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CHAPTER 1

THINKING ABOUT ENERGY

1.1 INTRODUCTION

Solving the energy problem is very different from solving problems in energy. The latter--solving problems in energy--consists of calculations, such as imparting to an assistant secretary of energy of mass m kg an upward acceleration of y m/s^2 in a gravitational field of g m/s^2, then asking at some later time t about the secretary's kinetic and potential energies. The former--the energy problem itself--is much more, and involves additional questions such as: "Was it a good idea?" and "Compared to what?" It is a socio-technological condition that we did not want but brought upon ourselves nevertheless; having it, we hope to ameliorate it. But amelioration to some people means enhancing supply; to others, reducing demand. To some it means national independence; to others, reducing global tensions via international interdependence. To some it means environmental consequences of over-use; to others, economic consequences of doing without.

The difficulties are as much political as intellectual, because even when a myriad of facts and their interconnectedness are reasonably well understood, the procedures that have been developed to make collective decisions and to implement them don't work very well.

Dealing with energy in this broader sense means dealing with and accomodating to continuing paradox, not trying to suppress it, and seeking broad and often unspectacular gain rather than narrow victory for some narrow view. Some activists perceive villains behind every opposing view; but the villains are fewer than that, more often found in the ranks of those who would paint the multi-colored panorama of energy only in colors of black and white. As Proust wrote, "The truth is so variable for each of us, that other people have difficulty in recognizing what it is."

The search for energy has occupied the attention of civilizations since ancient times. Wood, then coal, fed the industrial revolution in Europe, and until recently cheap oil and natural gas fed its successors. Understanding energy therefore means understanding resources and the technologies of using them.

The consequences of using energy have also been with us equally long. Plato writes in Critias*:

> Contemporary Attica may accurately be described as a mere relic of the original country . . . in consequence of the successive deluges which have occurred during the past nine thousand years . . . there has been a constant movement of soil away from the high altitudes . . . what remains of her substance is like the skeleton of a body emaciated by disease, as compared with her original relief. All the rich soft soil has moulted away, leaving a country of skin and bones.

Plato's description is correct, but his ascription of the cause is not. Wood was the energy resource in classical Greek and Roman times; the Greeks and Romans (and the Carthaginians, Chinese and others) cut their forests for firewood, and often introduced goats onto the cleared land. Much of the Mediterranean littoral remains barren to the present day. Where are the cedars of Lebanon? Cut down. The Arab is not only the child of the desert, but in part its father.

Lack of wood (and grain) within easy transport distance of Rome contributed to its decline, and helped to shift technological dominance to the more heavily forested and amply watered Northern Europe. The Roman historian Tacitus wrote (with some hyperbole) that a legion could march for a month beneath the trees in Germany without ever seeing the sky. Those historic events have modern public and economic counterparts, for example in OPEC oil. Understanding energy therefore also means understanding historic parallels and perspectives.

The relation between energy availability and social conditions sometimes appears in startling retrospect. Singer, Holmyard, Hall and Williams in their History of Technology (Singer et al, 1954) tell the story of the horse collar, in which ancient technology assessment profoundly affected the social structure. In Roman times it was well known that a horse was basically a higher-output and more adaptable work animal than an ox. But yoking a horse as an ox tends to choke it. Under those conditions, a horse could do four times as much work as a man, but ate four times as much; so horsepower and manpower were a standoff, and the Romans had no rapid road transport. Many inventions were tried for several hundred years; finally, the horse collar (used in China about A.D. 300) was adopted in Europe about A.D. 900. Thereafter Europe enjoyed more rapid road transport, and slavery declined as a raw power source.

Besides deforestation, a topic to be revisited in contemporary context in Chapter 8, energy brings other problems with its many benefits. Most air quality degradation arises from transformation of fossil fuels, a fact well known but too little heeded. Not so well known in the United States is a principal hazard to the lungs of village women in India: smoky chulas (primitive and inefficient stoves) which burn dung and twigs. Understanding energy therefore also means understanding the environmental, health and social consequences of its provision and use.

From cars to cookstoves, rational and effective use of energy still receives insufficient attention, though its rewards can be handsome and socially extensive. Thus, understanding energy also means understanding the possibilities and limitations inherent in the myriad of uses to which it is put, an activity which the logically and dictionally diminished word "conservation" fails to describe.

Measured in dollars, energy in the U.S. comprises more than 15% of the GNP: in 1981, it was $200 billion for oil, more than $20 billion for coal, $50 billion for natural gas, all for raw fossil fuels alone, plus the vast processing, conversion and distribution network that led to a $100 billion electric power bill, and many other things. Similar fractions exist for other industrialized countries. Even that 15% represents an arbitrary cutoff; should we include part of the cost of cars, toasters and steel mills? Their designs testify to past and present energy policies. The entire agricultural food processing and distribution sector is about the same size. Understanding energy therefore also means understanding capital formation, economic tradeoffs and other cogent matters.

Holistic, extensive thinking and re-integration stand in contrast to the selective inattention implicit in disciplinary reductionism or bureaucratic fragmentation, in which intellectual, social or technological sectors become subdivided for ease in manipulation or special understanding. These latter activities, necessary and desirable in themselves, led progressively to careers in natural philosophy in the eighteenth century, physics in the nineteenth, nuclear physics in the early twentieth, and charmed quarks and chromodynamics today. Academic or bureaucratic specialization is insufficient preparation for dealing adequately with large and extensive problems--energy, food and many others.

These energy difficulties did not come upon us unheralded as, say, an invasion from outer space. Long before the "Oil Crisis" of 1973, plenty of information and thoughtful analyses were available, in addition to what should have been obvious to thoughtful people from the time of Plato onward. Turning to recent history, we can read today with profit Palmer Putnam's (1953) Energy in the Future, in which he reviewed estimates of world population growth, plausible future per capita demands for energy, and known renewable energy resources; he concluded that difficulties of provision would occur, that solar and other renewable energy resources would be required, and that nuclear power in various forms would also be needed. Three decades later, it is easy to criticize his work in detail, especially his lack of attention to some economic and environmental considerations; but an important message was there, virtually ignored by the U.S. Government which commissioned it,* by private industry and by the public at large. Since the 1950s, M.K. Hubbert had been predicting, on the basis of decreasing yield per foot of exploratory oil drilling, that U.S. oil production would peak by about 1970, at a time of increasing demand for it.

Unlike food, housing and transportation, which are used for their own sake, energy is an intermediate good, not valued in itself but for what can be done with it to provide warm (or cool) houses, transportation, industrial heat and so on. But, like these and many other things, it is a public good, and in this respect perceptions about it changed in the 1970s. Those perceptions have been determined by changing circumstances, modified by various political and social outlooks in different parts of the world.

Not all public goods receive public attention. Air and water are public goods, in the sense of being universally essential. But in the U.S. and many other countries, until air became polluted and water both regionally polluted and scarce, little attention was paid to them.* Land is a public good, whose ownership and trade is left mainly to the private sector in the U.S.; but in the U.S.S.R., land is state-owned; and in the U.S., when the native Indians had it to themselves, land was common property.

Until the 1970s, both providing and utilizing energy were left almost entirely to the private sector in the U.S., and in most of the other OECD countries. Two major effects--the increasing awareness of needless and costly environmental damage from injudicious energy-related activities, and the transformation of OPEC attitudes toward their oil monopoly as a manipulable public good--coming in quick succession in the late 1960s and early 1970s changed all that. No longer was the private sector seen as capable of resolving by itself the problems that arose. Not only did governments find themselves deeply involved in schemes to supply energy, but also to control its effluents; in addition, often with querulous beginnings, the U.S. and other governments perceived an essential role for themselves in stimulating development and making regulations designed to use less energy to accomplish what had been done before. How far should the government go in this direction? Attitudes change, with one federal administration constructing large programs of one kind and the next administration attenuating them in favor of others.

Whatever the outcome in detail, the general trend is clear: the public view of energy as a public good requiring effective public participation is here to stay. Many of the present confusing debates, when reduced to their fundamental issue, relate to how that task is to be accomplished.

1.2 INITIAL FACTS AND COMMENTS

Here are some facts and comments about energy, some of them in capsule form, others in more detail to vivify them and to prepare the way for later chapters.

1. Energy is not a material commodity; it is an abstract concept invented by physical scientists in the nineteenth century to described quantitatively a wide variety of natural phenomena. In the language of physics, it is a quantity that obeys a "conservation principle." The First Law of Thermodynamics asserts that the total amount of energy in the universe is fixed; all that can happen to it is that it can be changed into other forms. Thus,

the chemical energy in a lump of coal is transformed into the heat energy of a flame, part of which is turned into the kinetic energy of motion (mechanical energy) of a steam energy--and so on.

2. Besides the chemical energy stored in fossil fuels, useful energy occurs in many different forms in nature, e.g.,

- o Kinetic Energy of wind and waves;
- o Potential Energy in the dammed-up waters of a lake. When the water is liberated to flow down to a lower level, an equivalent amount of
- o Mechanical Energy may be generated in a turbine. This in turn will yield (apart from frictional losses) an equivalent amount of
- o Electrical Energy, which is transported via conducting cables to load centers and distributed.
- o Radiant Energy of sunlight is not merely a source of heat; it can be converted into chemical energy by photosynthesis or into electrical energy by photovoltaic devices.
- o Nuclear Energy is released by changes in the structure of nuclei, just as chemical energy is released by changes in the structures of chemical molecules.

3. Although the First Law of Thermodynamics guarantees the exact equivalence of the various forms of energy (and therefore allows all forms to be measured in a common unit such as joules, quads (10^{15} BTU or 1.05×10^{18} J), or terawatt-years (3.16×10^{19} J or about 30 quad),* it does not guarantee interconvertability. Thermal energy ("heat") is in a peculiar and unique position,

for whereas all other forms can be completely converted into thermal energy, the reverse process is impossible; only a portion of the heat from, say, a nuclear reactor, can be converted into mechanical energy in a steam turbine. The rest reappears as less useful heat at lower temperature, for example, as a large outflow of lukewarm water. This is a physical law, not mere practicality, and is expressed in the Second Law of Thermodynamics. Thus,

First Law: Heat and Work are the same;

Second Law: Heat and Work are different;

or all quads are equal, but some are more equal than others.

4. The energy sector can be visualized in many ways, a principal one being based on following what happens as energy resources at the bottom of Figure 1.1 are variously manipulated to provide desired services (at the top of the figure), together with the inflow and outflow of other things along the way.

5. What the world is running out of is not energy per se, but cheap oil and natural gas which are versatile in end-use, convenient to use and transport, relatively clean, and able to be used with moderate to high thermodynamic efficiency. The major use of oil that is least amenable to inter-fuel substitution at present is in transportation.

The global (and U.S.) coal reserves are about ten times those of oil and gas. The energy potentially available in uranium or thorium in the ground (by fission) or deuterium in the seas (by fusion) could in principle suffice for millions of years, and sunlight lasts forever (on our time-scale); but all of them are harder or costlier to capture, or harder to convert to useful forms, or bring environmental or other complications.

Figure 1.2 shows some of the principal energy shifts in the U.S. up to 1980: wood to coal to petroleum and natural gas to increasing uncertainty about what next. Note that the characteristic time for each new major energy mode to grow from a small to a large fraction of the total is about 50 years, and the period of decline is similar. The energy system is ponderous and shifts slowly, even with strong incentives, a topic to be revisited in several later chapters.

6. Heat is the form of energy for which there is by far the greatest demand. Liquid fuels for transport are in second place. The uses for which electric power is essential are third; but electricity's controllability and cleanliness at point of use, plus its appearance as the most natural product of many modern non-fossil technologies, cause its use to grow rapidly worldwide.

These words introduce Table 1.1, which shows where the primary energy resources in the U.S. are used. Ignore the electricity row at the bottom for the moment (but not the electric power generation column). Notice the total of 82.3 quads in 1979, a number which could be disputed $\pm$ 2 quad or so depending on how some of the sources are accounted for in detail. This total grew approximately exponentially from 20 quads in 1920 to 72 quads in 1972 (convenient to remember), at almost 2.5%/yr, with variations along the way. U.S. energy use grew more slowly after 1973; it peaked at about 1979, and declined to 72 quads (the 1972 level) in 1982, to the astonishment of many energy forecasters.

From Figure 1.2, Table 1.1 and the numbers just given, we can conclude that coal production in tons/yr must have stayed relatively constant during the past five or six decades. That is so; coal lost its relative importance during the period 1920-1970 because of the vast increase in oil and gas use.

Petroleum supplied 42% of the 1979 energy market, and in that year, over 40% of it was imported; since then it declined, to about 20% in 1982. The implicit vulnerability and outflow of money are common knowledge. Europe and (especially) Japan, among industrialized countries depend even more on imported oil; some less-industrialized countries are similarly dependent and in severe financial difficulty on account of high oil prices.

About one-third of primary energy went into U.S. electricity production in 1982, up from 25% in 1971, a fraction which also increases worldwide. Electricity is an intermediate energy good, an end-product from the viewpoint of primary resources, but an energy source as seen by end users. The 24.3 quads of input energy in Table 1.1 produced 7.1 quads of delivered electricity, an efficiency of conversion plus distribution of about 30%. Thus, we encounter the bottom row of Table 1.1 which shows where it is used. Note the tiny amount for transportation; that fraction is higher in Europe and Japan.

If industry is charged with its fraction of electric power generating losses, it would be found to have used 33 quads, or 40% of all U.S. energy in 1979.

Thirty-four percent of primary energy went to generating electricity. Table 1.1 tends to highlight the losses inherent in electric power generation via thermal cycles (see topic 3 above). The losses are real, but similar and even larger ones also appear in the use of most of the other energy forms. That they do not appear obvious in this and similar tables is in part an accounting peculiarity, to be taken up at length later.

7. Patterns of energy consumption do not change easily in the short term, but in the longer term many opportunities exist to use energy more efficiently and rationally, most prominently in the industrialized countries, but also in less industrialized ones. This is often inaccurately called conservation.

8. The energy problem is global and must be treated that way. It also must be treated in a dynamic context. That is, the world population and labor force are growing. Aspirations for amenity are growing (in Daniel Bell's phrase: "the revolution of rising entitlements"). National economies grow, and for the population of the global South, this growth must be rapid if they are to achieve reasonable living standards in a reasonable time.

Figure 1.3, Table 1.2 and several other exhibits to follow support these views. The International Institute for Applied Systems Analysis (IIASA) in Austria (Häfele et al 1981) completed a series of global energy studies, with various projections of future energy demand. There is no such thing as a unique authoritative projection (as the IIASA authors remark), but we can learn from this and other analyses.

The IIASA group divides the world into seven regions, to make their analyses tractable:

I. North America (NA) with developed market economies, many resources.

II. The Soviet Union and Eastern Europe (SU/EE), with developed centrally planned economies and many resources.

III. Western Europe, Australia, Israel, Japan, New Zealand, South

Africa (WE/JANZ), with developed market economies, but fewer resources than other developed regions, with some notable exceptions (Australia, South Africa).

IV. Latin America (LA), a developing market economy, rich in resources.

V. South and Southeast Asia, and Sub-Sahara Africa (AF/SEA), developing regions of mostly market economies, but with fewer resources (with some notable exceptions).

VI. The Middle East and North Africa (ME/NAF), a special case with economies in transition, rich in oil and gas.

VII. China and other East Asian centrally planned countries (C/CPA), developing regions with modest resources.

Other groupings could be imagined, but this will serve the present purpose well.

Table 1.2 shows some recent and present data on these groups. Region I (NA) has relatively few people, uses much energy per capita, and grows economically more slowly than the rest. At or near the other extreme we find most of the people in the world using little energy, with fewer developed resources, growing much more rapidly. All the data are historic or recent, except for a population projection for the year 2030, which, together with the present growth rates, emphasizes the intent and intensity of purpose in the less-industrialized countries to improve their circumstances.

Figure 1.4 shows this global inequality dramatically, as measured in the mid-1970s and continuing into the 1980s. The closer the curve hugs the axis, the greater the global disparities.

The relative weakness of international institutions compared to those with national objectives complicates these global tasks.

9. Besides becoming more populous, the world becomes more urbanized. Figure 1.5, taken from the IIASA study but originally from Keyfitz, shows 8 billion people in 2030; there were 4.5 billion in 1980. Figure 1.6 shows the global trend toward urbanization. With increasing population, this is inevitable. If the world's present population were distributed evenly over the earth's agriculturally productive land, there would be about two persons per hectare. Everybody cannot go rural, raise goats and firewood and recapture an imagined spirit of ancient times.

10. The less-industrialized world uses much <u>non-commercial</u> fuel --i.e., wood, dung, straw, etc., that is not bought and sold on the commercial market. Figure 1.7 shows one estimate of the fractions; if China had been included, it would have dominated even India in the center of the figure. Most energy demand forecasts have failed to take account of these non-commercial fuels, whose amount not only cannot easily be increased as population increases, but will probably decrease as more land is converted to intensive food crops and populations become more urbanized. These circumstances aggravate the difficulty of meeting expected energy demands in the less-industrialized countries.

11. Many energy "projections" exist, some made with great show of authority; the art of making them improves with time and experience. But except for certain clear trends, they should be regarded more as "if-then" scenarios. Figure 1.8 illustrates the difficulty of seeing only a few years ahead, let alone far

into the future. Actual energy consumption in the U.S. is plotted, 1955-1982, according to a U.S. Department of Energy convention about electricity. That is, electricity made from fossil-fueled power plants was not counted, but the primary fuels themselves (with about three times the energy value) are counted. Electricity from hydropower is counted as energy; so is electricity from nuclear power plants, but not their waste heat. If the rules pertaining to fossil fuels had been applied to nuclear plants, the 1972 total would have been 1.8 quads higher, and the 1982 total would have been 77 quads rather than 71.

Consider now the various projections. Up to about 1972, the approximate 2.5%/yr growth was usually assumed to continue, despite contrary warnings; the top curve of Figure 1.8 is typical of the upper limits. For example, Shell Oil projected (1972) U.S. consumption at 124 quads in 1985. But the National Petroleum Council was somewhat more cautious: 110-120 quads. The year 1973, a year of unsettled outlook, brought downward modifications--for example, 114 quads by 1985, according to Shell (1973)--and other projections fell even lower. The Ford Foundation study (1974) generated much controversy; its "technical Fix" was regarded by many in the energy sector as daringly low, even indecent.

The effects of the oil price rises in 1973 and again in 1979-1980 can be clearly seen in Figure 1.8. By 1978, different views were emerging, albeit cautiously. The National Academy of Sciences Committee on Nuclear and Alternative Energy Systems (CONAES 1980) shows a whole range of scenarios (as of 1976); the figure shows three of them. Near the top was fairly vigorous supply (D). Almost at the other extreme was "strong conservation" (A). The lowest (A*) was made by the only sub-committee that had a substantial infusion of sociologists, who judged that significant changes in lifestyle could occur.

None of these projections is categorically forbidden (although U.S. society has rejected the highest ones). What will happen depends not only on technology and market economics, but also on changing social desires and values, and political events. The passage of time, increasing costs, new technology and political pressure move us lower on these curves, but it would be foolish to predict more than the general direction. Nevertheless, some who claim clearly to see the future appear unable or even uncaring to see the past, though it be laid out before them.

Areas on Figure 1.8 represent total quads of energy (quad/yr times years). Notice the small areas covered by 20 trillion cubic feet of natural gas (U.S. output in one year), 5 billion barrels of oil or one billion tons of coal (each much more than the U.S. 1980 annual output).

1.3 OPTION SPACES AND TECHNOLOGY ASSESSMENT OF ENERGY

The phrase "option space" stands for the range of allowable technological, economic, environmental, political and other conditions within which resolutions of particular issues are likely to be found. For one extensive topic, many option sub-spaces may exist, and all the essential ones must overlap for a satisfactory resolution. For example, consider Figure 1.9 and the prospective development of power for controlled nuclear fusion. At the very least, success depends on the favorable resolution of problems in physics, development of very advanced technology, and all this to yield an affordable product. But (for example), will the physical laws of plasma confinement, when they are finally unraveled, require magnetic field structures that can be built in practice? That is, do the permissible physics and permissible technology overlap, as in the upper part of Figure 1.9? Or will things turn out as in the lower part? The latter now appears more likely, at least until the mid-twenty-first century, but much research was necessary to find out. Questions like these need to be continuously re-asked, as circumstances change.

Figure 1.9 provides convenient opportunity to remark further on selective inattention and paradoxes, topics raised in the introduction. Too often, practitioners in one of the arts, say physics, will try to use up all the option-space, or to define unilaterally where it is. The physicists then imagine that technologists, engineers, economists and others will extend their skills to fill the gaps. Other arts and crafts have their limitations which, if ignored, can lead to grief.

Regarding paradoxes, many of the option sub-spaces are in conflict, and something must stretch, or give, for any overlap to occur. In general, cheap energy in abundance and good environmental quality do not go together.

What is being discussed here (and much of the rest of this book) is often called technology assessment, a term coined in the late 1960s. Arguments have raged over whether technology assessment is a new art or a re-statement of an old one. It is the latter: the horse-collar example of the introductory section is a fine example from ancient times, and plenty of others could be cited. A considerable disciplinary literature appeared on the subject in the 1970s, some of it too specialized for an endeavor so broad by its very nature. Notwithstanding its occasional practice by ecumenical obscurantists, the idea of technology assessment--by which is meant the assessment of both technological and non-technological parts of important issues that involve technology--is a good one.

1.3.1. Some Principles

Three main principles guide the work. First, energy pervades so many sectors of society that special care must be taken to prevent too-narrow sectional representation of ideas. In addition to technology, international relations, trade and national security, energy involves also the allocation of other basic resources such as capital, labor, land and water, and social conditions such as human health and safety, environmental preservation, and individual and institutional traditions.

A second guiding principle is also a caveat: in selecting an assessment group, special care must be taken not to prejudge unconsciously the character of the result. The task is not easy. For example, when the Federal Government publishes a "request for proposal" to study particular or general aspects of energy, the most organized, prestigious and therefore most apparently attractive responses often come from groups that already have experience in what they believe are appropriate activities. This seems (and is) reasonable, but the danger exists of the group bringing with it into the assessment a substantial freight of opinion and expertise along various previously worked lines. This is no general condemnation, but a recognition that people see things in the context of their experiences. Organizations and people generally have a past to defend, a present to support and a future to prepare for. Ask a lawyer how he envisages dealing with smoking deisel trucks, and he thinks of enforcing regulations; ask a mechanic, and he suggests making the mixture more lean. They are both right and wrong at the same time; the real problem was that the truck driver gets a little more power on hills that way, and he was anxious to finish early. If we cannot decide whether this simple case was a technical, regulatory or behavioral problem, we should be particularly careful about unconsciously and precociously judging much more complex issues.

If freshness and breadth in new directions are important to the assessment, then it is often advisable to convene a special group for the assessment purpose alone, relatively immune to the trap of pre-judgment. It is better to err on the side of excessive diversity; it is easier to argue against what at worst may be irrelevant nonsense than to try to intercalate new opinions into a completed intellectual structure.

A third guiding principle relates to time horizons of social, technological and economic concern. The energy problem, like many others, consists of issues having a multiplicity of time horizons, which stretch from very short (e.g., response to an oil embargo) to very long (e.g., planning for a world without natural petroleum). Special care must be taken that neither the usual short-range considerations nor planning for some singular date overwhelm the assessment, but rather that options and consequences over extended times (centuries when necessary) be seriously considered. That subject will be revisited in later chapters.

Violation of these principles has been and continues to be common; here are some illustrative examples. Most energy groups violated the first principle, because of self-interest, or short-sightedness. The Federal Executive Branch until 1973 looked upon energy as the technology of supplying it, plus watching a (mainly) free market economy. The former Office of Science and Technology, in a 1972-1973 study leading to a large shopping list for the Energy Research and Development Administration (ERDA) formed in 1974, did not consider environmental factors or energy utilization and conservation in any substantial way. The former Atomic Energy Commision persisted in judging for itself whether its activities affected other sectors. Self-judgment is laudable, but requires augmentation from outside critics; otherwise, false assurance and false conclusions follow via positive internal feedback. In 1974-1976, ERDA demonstrably reached further, via internal planning and analysis, assisted strongly by the MITRE and Thompson-Ramo-Wooldridge Corporations, the Institute for Energy Analysis, and other groups. Even so, the outreach was inadequate because of undervaluing societal and other non-technological issues. The Federal Energy Administration, in its Project Independence Blueprint, violated all three principles, especially in aiming its work toward a solitary date--1985; see the coal chapter (6) for some more specific material, and how attitudes generated then affect affairs in the 1980s.

The Congressional Office of Technology Assessment (OTA) tried to avoid the various pitfalls as it entered the energy field in 1974-1975. Rather than depend heavily on outside private or public contractors (the National Academies being an example of the latter), or on developing internal expertise (which would have taken too long), it assembled temporary assessment groups whose members came from many societal sectors.

no ¶

The groups had no organizational past or future, were supposed to be broadly representative and capable of responding on various time scales, and also capable of operating on a self-correcting basis.

no ¶

OTA did this twice in 1975 (OTA 1975), each time successfully. Using this and other assessment techniques, it has since done outstanding work on energy and many other topics.

1.3.2. Four Option Spaces

Ex hypothesi, the whole energy fabric of society is joined, hence the need for assessing it as a whole. In principle, picking any thread and following it and its connections will lead one over the whole fabric, but there are better ways.

Sets of rubrics are needed which allow orderly and efficient entrance into the logic space. One speaks of sets of rubrics, not just one set, because the metaphoric fabric of energy is folded and connected to the body of society in complex ways. Different starting points on the fabric lead to different parts of the whole with different relative ease. Thus appear different kinds of useful option spaces.

Four useful classes of methodological rubrics each give somewhat different insights into energy.

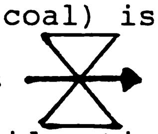
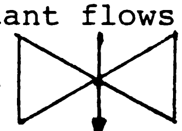
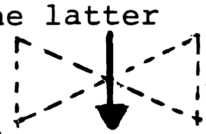
1.3.2.1. Modeling Two major species exist, each with incomplete and complementary features. Substantial effort now goes into attempts to join them.

The first species deals with material flows. Several prior studies have identified and followed energy use--from production through conversion and/or transmission to consumption and ultimate rejection of the waste heat. Figure 1.1 showed the scheme in outline. A small conceptual step brings us to real analyses along this line.

Figure 1.10 shows the U.S. energy data listed in Table 1.1 as a set of flows, with width of each track and sector proportioned to the amount. The right side of the figure shows a division into "Wasted" and "Used" according to two different methods of thermodynamic accounting, discussion of which will be postponed to Chapter 4, on rational and effective energy use.

At the working level, the flows show much more detail; Figure 1.11 shows a summary of the Brookhaven National Laboratory's Reference Energy System for the U.S., representing energy flows in 1972. Similar diagrams were worked up as scenarios for 1985 and other years in the (then) future, principally in aid of the 1972-1973 Office of Science and Technology Study mentioned a few paragraphs ago. Actual material flows appear, and one can see in the mind's eye things happening along every path and at every starting and end-point. Particular strengths of this approach are: it permits easy recognition of processes and new possibilities, thus tending to minimize the chance of omitting energy sectors; also, it forms a natural display on which to pin effluents and environmental impacts, all along the many energy and material flow paths. Some possibilities and effects of substitutions can be traced out. Weaknesses are: as it presently exists, this is awkward for quantitative economic analyses, elasticities, or demand forecasts. Figures 1.10 and 1.11 represent a kind of snapshot in time of what happens.

The layout of these figures can be extended into different sectorial dimensions, a necessary property in any model that attempts to approximate reality. This quality is shown schematically for an extension into the environmental-health sectors in Figure 1.12. Every kind of energy flows across the top, here compressed for discussion into a single path, with suggestive inputs and outputs from other energy sources. The classic energy technology sector deals with these flows, their control, and increasingly with their advertent and inadvertent outputs.

Starting at the upper left, a resource (coal) is mined, and its amount is controlled by a gate, shown thus  . The gate is controlled by environemntal and health considerations (black lung disease, sulfate and particulate emissions, etc.) and by other considerations (economic competition from other fuels, depopulation of Appalachia). Its mining leads to both controlled and uncontrolled effluents. The former are shown by the pollutant flows shown as solid lines with "solid" controls, shown thus  and the latter by solid lines but dotted ("imaginary") controls, shown thus . Note that the distinction between controlled and uncontrolled emissions is largely a matter of societal decision, whether certain costs will be recognized and included, or not.

Next on the energy flow, the fuel is shipped (railroad accidents) and may be refined or converted. Here, competing fuels enter (coal versus petroleum for electric power provision), and the resource may go to several intermediate destinations (coal to synthetic fuel plants, coal to be burned au naturel for electric power provision). Environmental and potential health costs flow out at this stage (particulates, acid sulfates, heavy metals, degraded water supply). Next, distribution and storage lead to final utilization, and new choices appear, as indicated by more decision gates (oil versus gas for heating, electricity for heating versus electricity for industrial motors). Controlled and uncontrolled emissions occur here too (unburned hydrocarbons from inefficient home heating units).

All these effluents permeate the environment, some for short distances only (coal dust in underground mines or carbon monoxide near gas stoves), some for long distances (acid drainage, acid rain). The middle part of Figure 1.12 represents the transport of these materials, and their eventual reception. The transport phenomena are partly understood, but not nearly so well as the main energy backbone at the top of the figure.

Finally, at the bottom of the figure appear health effects, which are discovered not only by measurement on exposed groups (as shown) but also by more basic biomedical research. Both these paths suggest needs for and sometimes types of monitoring and control strategies shown by the various dotted lines in the figure. For example, active receptor protection is one route (dust masks for miners, and pollution masks for residents of some cities) which could represent the two local control strategies shown at the bottom of Figure 1.12.

Because the environmental health hazard is often widespread, control strategies lead back to the energy processes themselves, and to decisions about exercising one energy option or another (above-ground retorting of oil shale, hence the mining of it in the first place, versus synthetic fuels from coal). Thus appears ideally the holistic control strategy imagined in the figure, but which does not yet exist in reality. Some other dimensions can be grafted onto the model, for example disaggregation into geographic regions and subregions. Assessment groups with large computing facilities will have overwhelming advantage in carrying out these intricate and data-intensive activities, provided they use them wisely. However, useful information can appear rapidly from simple versions of this model, especially when large differences exist among the various effects.

All that foregoing discussion referred to the materials-flow variety of modeling. The other main variety is economic and econometric, which cuts across other dimensions. It asks such questions as: "How much capital investment will be needed to increase energy production by 20% in the next five years?" <u>or</u> "Given a list of petroleum, natural gas and coal reserves available at various prices, what is the actual demand in 1990 expected to be?" Answers to questions of this sort require understanding of the physical energy system and the energy technologies, but are more concentrated on economic and other societal issues. This sort of modeling contains time, costs and feedback paths as essential components, but the perspective is more defined by economic rules. Energy models and their associated computer programs which combine these approaches were being developed by the early 1980s, and are now able to provide considerable insight.*

Typical economic studies are input/output or input/consequence, and Figure 1.13 shows a highly over-simplified version of one kind. Imagine a simple world, with one petroleum source, one natural gas source, etc. The petroleum sector uses steel, labor, rail facilities, and even some of its own petroleum. If the amounts are known, it is then possible to write an equation for the flow of materials into the petroleum sector, picking up various inputs from known coefficients in each of the boxes on the first row in the table: so much petroleum, so much natural gas, so much steel, etc. Similarly, the steel industry (fourth row in the table) uses some petroleum and natural gas, much coal (directly as coal), some of its own steel, coke in its blast furnaces, and so forth. Coefficients of use can in principle be found and inserted, so an equation can in principle be written for it too. One can imagine doing this for every sector, including the inputs to and outputs from each sector, including end-use.

Figure 1.13 is an elementary input-output matrix; if there are N rows and N columns, it is an N by N matrix, representing N different equations describing the whole system. In principle (also) it can be solved; if prices and various economic elasticities (change of demand or supply with changing price) are known and included, one can solve for equilibrium of the system, for effects of changing one part on all the others, etc.

Actual systems are very complicated; in reality, many kinds of crude oil, of refineries, of reactions and types of coal, of steel plants and so forth exist. Many models include as adjustable inputs ("exogenous" inputs) future demand, different actual or hypothetical technologies, arbitrary constraints, time rates of change, and other things of interest to the modeler. The number of rows and columns need not be the same, and the numbers can be several thousand each way for an energy-related matrix alone. Manipulating such large assemblies of equations with their (literally) millions of coefficients requires large computers, and great care must be taken to ensure that the computations are mathematically stable.

Strengths of these systems are that they permit insertion of new suboptions, and calculation of effects of incentives and trade-offs, especially between various economic sectors; their weaknesses: they tend to miss new opportunities that arise from outside the matrix formulation, tend to miss unquantifiable issues (e.g., international and societal consequences), and may yield outputs whose validity is difficult to establish by tracing back through the complex formulations.

<u>1.3.2.2. Political Option Space</u> This approach fits most naturally into the spirit and work of government groups, especially of the Congress, and could be imagined by it as the principal assessment mode into which the others eventually feed.

The U.S. energy policy will in fact be constructed of a mix chosen from a small number of relatively "pure" strategies; this assessment mode considers the acceptability, possibility of implementation and consequences of various option mixes. Of course, no set of pure isolated strategies exists, but it is remarkably easy to recognize main ones that have substantial independence.

The approach has these advantages: it is closely connected to the real decision world; leads to recognition of non-quantifiable issues; is easily interpretable to decision-makers; if well done, tends to preserve intellectual balance. Its main weakness: it is hard to quantify. It tends to make the political nature visible from the start, which could be advantageous or not, depending on the circumstances.

Pale examples of this assessment mode appear in "scenarios" constructed by the Department of Energy and others, of futures with "business as usual," "more conservation," etc.

Now follows the set, consisting of 11 general categories. Not surprisingly, they overlap somewhat; this is policy option-space, not mathematically perfect multidimensional space.

(1) There is no problem, and contemplation of it should be discouraged. This is not an imaginary option; until mid-1973, energy conservation and many environmental issues were non-discussable topics in the Federal energy agencies, and in many groups they supported. Even in the early 1980s, work progressed in some of these areas only in the teeth of inspired apathy. In some other countries, lacking the equivalent of the U.S. Freedom of Information Act, discussion of energy policy by government employees at other than official levels can lead to dismissal.

(2) Laissez-faire, an extreme form of business as usual. Resources will become scarcer, prices will rise, and supply equals demand at some price. Some of that strategy applies as the U.S. changes from a policy of too-cheap energy. However, the social costs of too much laissez-faire will be high.

(3) Study the problem. That's all; we don't know enough, etc. Maybe that is true, maybe not. If applied as a more or less pure strategy, it can be merely an academic pacifier and inaction legitimizer. However, none of this should be interpreted as a criticism of study per se or a defense of brave action supported by ignorance. See Chapter 3 on acid rain and the global carbon dioxide problem.

(4) Propaganda. This can be good or bad, but the connotation unfortunately favors the latter. It is, in its objective sense, the attempt to persuade others of particular points of view. This option is rarely seen alone, but rather in aid of some other strategic goal, which the propaganda identifies.

(5) Buy more overseas petroleum (or other resources), without serious attempt to manipulate the price or availability of foreign supplies. The U.S. necessarily adopted some of this strategy, which cost about $90 billion for imported petroleum in 1980. Thus the question arises of how to pay for it.

(6) Attempt seriously to manipulate price and/or availability of foreign supplies. This option contains suggestions ranging from incentives for OPEC members to cheat on each other (weakening OPEC, in the eyes of the suggesters), to fanciful nightmares to taking over part of the Middle East by force. The U.S. can weaken international oil prices significantly by its own internal strategies of provision and conservation, thus lessening international demand.

(7) Apply pure regulations. These could range from not selling gasoline on Sunday (ineffective) to implementing tax incentives and penalties to regulating energy use. This is the only option with

instantly available components.

(8) Provide incentives for new domestic conventional provision. Here lies one of the two large U.S. efforts--to mine more coal, build pipelines to Alaska, open offshore regions for exploratory drilling, etc.

(9) Provide incentives for new technology of energy provision. Here is the other large U.S. effort--to develop solar power, controlled fusion, synthetic fuels, breeder reactors, etc. This differs from item (8) by introducing new approaches, usually on longer time perspectives.

(10) Incentives for "conservation." By this we mean not just curtailment, but more importantly, wiser uses of energy. Examples are tax incentives for storm windows, easy access to reliable advice by energy "county agents."

(11) Technology for rational and efficient utilization. This differs from (10) in the sense of deliberately sending for new ideas, as item (9) differed from (8). A classic example was the replacement of steam trains by diesel-engine trains; the efficiency increased by a factor of several, and the maintenance costs declined.

These categories fall roughly into several classes: mainly social (1, 2, 3, 4, some of 10); mainly political (5, 6, 7, some of 8 and 10); mainly technical (some or most of 8, 9, 10, 11). Policies within classes tend to compete, but across classes can more easily cooperate.

1.3.2.3. Hierarchical Arrangements Many assessment schemes are valuable as aides memoires or logical ways of arranging work. That is true even for econometric modeling; for once the heavy computational work is done, the results must be understood from simpler publicly understood arguments.

This scheme--hierarchical arrangements--does not by itself provide any numerical answers, but serves as a convenient set of hooks on which to pin computations, issues, pro-con arguments, and so forth. Inspect Figure 1.14, which looks like a mobile (most of them do), showing only one way of representing the energy sector: supply of energy in various forms, and use by various sectors. Each major item can be divided into sub-items, as for example whether to heat a house with oil or gas, or some other scheme. Comparisons are usually easy and easily understood for adjacent items near the bottom, and more difficult toward the top.

Other sectors can be similarly drawn, most profitably where the same material or service in question can be produced or performed in several ways. The electric sector is particularly amenable to this treatment, and Figure 1.15 shows one possible version of it, arranged by energy options, with the direct solar option and some others embellished. Figure 1.16 shows detail of the coal and nuclear sectors. The arrangement could have been different to suit different purposes; concentrated vs. dispersed, for example.

To see how issues arise as one studies these arrangements, consider for example the nuclear sector in Figure 1.16 (and implicitly in Figures 1.14 and 1.15 as well). Comparative merits and demerits of various light water reactors can proceed mainly at technological levels where the issues are relatively objective, although by no means simple. But at higher levels in this "mobile," the issues become more and more societal (costs and benefits of the breeder reactor, fusion as a long-term answer, etc.). Nuclear-fossil tradeoffs with associated social costs arise. At the top, a position befitting its importance, exists the issue of more provision versus better utilization, the subject of many unbalanced debates. At each stage one assigns costs, benefits, opportunities, etc.

Principal advantages are: a simple way to start at the bottom with relatively straightforward technological issues, plus gradual introduction of more complex societal ones, by ascending the hierarchical structure. The principal disadvantages are: difficulty of judging economic issues, especially tradeoffs and elasticities, and of introducing normative content.

Over what fraction of these figures (in a more complete and complex version) does there exist any present rational basis for decision? Not much. In the nuclear sector, timing and extent of convertor reactor options vis-a-vis breeder development has been a lively subject for debate, fission vis-a-vis fusion is not understood at all well (fusion may not be ready until after A.D. 2050, if then), and the issue of nuclear power vis-a-vis fossil fuels has been scandalously misunderstood and misrepresented.

1.3.2.4. Societal Goals Until recently, these issues lay somewhat outside technology assessment itself, but they now become increasingly incorporated. That is, the technology is presumed to serve some broad social purpose, and not vice versa. Here, one starts with normative questions, such as present and future desired quality of life, societal time horizons, concepts of security (hence in this context the permitted dependence on imported resources, among other things), and so forth. Trial decisions about these aspirations then lead to trial social goals, the existence of which helps to define and limit the range of the technology assessment itself. The work is of course iterative, because trial assessments shed light on the technological, economic and other social costs of achieving the trial goals, and on whether they can be achieved within given time horizons.

Assessments based on these ideas have these advantages: they facilitate recognition of hitherto unconnected parts; and permit easy inclusion of social purpose and non-quantifiable issues. Their weaknesses: it is hard to make numerically dependent decisions in the early stages, there is a tendency to degenerate into opinion and hortatory oratory. Good examples are unusual, but now become more common. Decions about global energy strategies made on the basis of an expected "greenhouse" effect of carbon dioxide buildup in the atmosphere would be an excellent example. To be sure, the environmental effects would follow from analysis of energy consequences, as one could see by following the logical paths of (say) Figures 1.14 to 1.16. That shows, as pointed out earlier, that the same total fabric can be explored, starting from any place on it; it is often useful to start at more than one place. The advantage of a starting place in societal goals is that the social time perspectives necessary for real appreciation and affection about this problem come easiest that way, not derivatively from the modeling analyses.

Despite its seeming weakness and real difficulties, this approach is the most basic; in a technologically sensible society the others are subsidiary to it. It guides decisions even unconsciously, because attempting to ignore this approach is itself a decision within its framework. Thus arose the mistake made earlier by me and others that the U.S. had no energy policy based on such considerations; it had one indeed, of selective inattention, and the fact that no one thought much about it until recently made it no less a policy.

The seeming weakness of this approach mirrors the weakness or strength of the civilizations that contemplate these matters, and the real difficulties are those of finding consensus on fundamental issues.

1.4 GOALS AND POLICIES

These words appear throughout the text, and it is important to understand the difference between them. Roughly speaking, one can have many goals in the sense of desiderata; they may and often do conflict. One can also have many trial policies, and they too may conflict. But once embarked on some course of action, the policy is more explicit--what is to be done, to reach as many of the goals as possible, to accomodate the paradoxes in disparate goals, and so forth. The policy may be good or bad, a success or a failure, fixed forever or subject to change tomorrow, but it is not goals, it is not desiderata, it is policy.

A good example of how such matters become confused came in the opening statements of the Energy Research and Development Administration's first National Energy Plan (1975), Report ERDA-48, referenced earlier (OTA 1975). It listed these five U.S. energy goals:

1. Maintain the security and policy independence of the

nation.

2. Maintain a strong and healthy economy, providing adequate opportunities and allowing fulfillment of economic aspirations (especially in the less affluent parts of the population).

3. Provide for future needs so that future life-styles remain a matter of choice and are not limited by the unavailability of energy.

4. Contribute to world stability through cooperative international efforts in the energy sphere.

5. Protect and improve the nation's environmental quality by assuring that preservation of land, water and air resources is given high priority.

These were rightly stated as goals, but in the context were often read as policy, leading to confusion of purpose as different groups tended to concentrate on one or another of them at the expense of all the rest. For example, item 3 implies much cheap energy, and item 5 says that its provision and use should be environmentally benign. Item 1 might imply not importing oil, but item 4 might imply surrendering some of the independence to serve a larger cause.

But suppose for the moment that all those goals could be satisfied simultaneously, say via limitless electricity from wall plugs, with a magical, free non-polluting source behind them. Would that guarantee a better world? Very likely not, because so much free energy would tempt people to use it to manipulate the world as never before, to dig vast holes in the ground in search of the merest baubles, to leave us to live in polluted quarries. Proper use of energy requires social caring as well as technology.

Nevertheless, those goals were better than the de facto energy policy of even earlier days:

1. Energy should be as cheap as possible.

2. Energy could be considered separately from other major societal issues.

3. Energy could be considered chiefly as the business of supplying it.

4. Plenty more energy is around, from the same type of sources we have used before, perhaps at some increased cost, but not to worry.

5. No change in life-style need be discussed, let alone implemented.

6. The private energy sector would solve the energy problem pretty well, particularly if left to do it.

Though they were either false or at best poor guides, they worked in earlier times because energy was plentiful, no one asked about public costs, and no one thought very far ahead. Opportunity will appear elsewhere in the book to reflect on whether some of those attitudes reappear in the 1980s.

FOOTNOTES - CHAPTER 1

1.2 Plato, Critias III A-C, as quoted by Arnold Toynbee, "A study of History," revised and abridged ed. 1972, Oxford Univ. Press (1972), p. 115.

1.5 A term originally used by the psychologist Harry Stack Sullivan, to describe a patient's filtering of information too extensive to incorporate.

1.6 The U.S. Atomic Energy Commission.

1.7 A social comment on this was written by Peter Rideman, in 1545, as relevant today as it was then. See the last section of Chapter 7 on nuclear power.

1.9 See the unit conversion tables.

1.27 For example, by the Institute for Energy Analysis, Oak Ridge, Tennessee.

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4. Häfele, W. et al. (1981). Energy in a Finite World, Vol. 1, Paths to a Sustainable Future. Prepared by Inst. for Applied Systems Analysis (IIASA), Austria; Ballinger Publ. Co., Cambridge, Massachusetts.

5. OTA (1975). Office of Technology Assessment, U.S. Congress, "Analysis of the FY 1976 ERDA Budget" (March); "An Analysis of the ERDA Plan and Program" (October). U.S. Gov't Printing Office, Washington, D.C. 20402.

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7. Putnam, Palmer C. (1953). Energy in the Future, D. Van Nostrand Co., New York.

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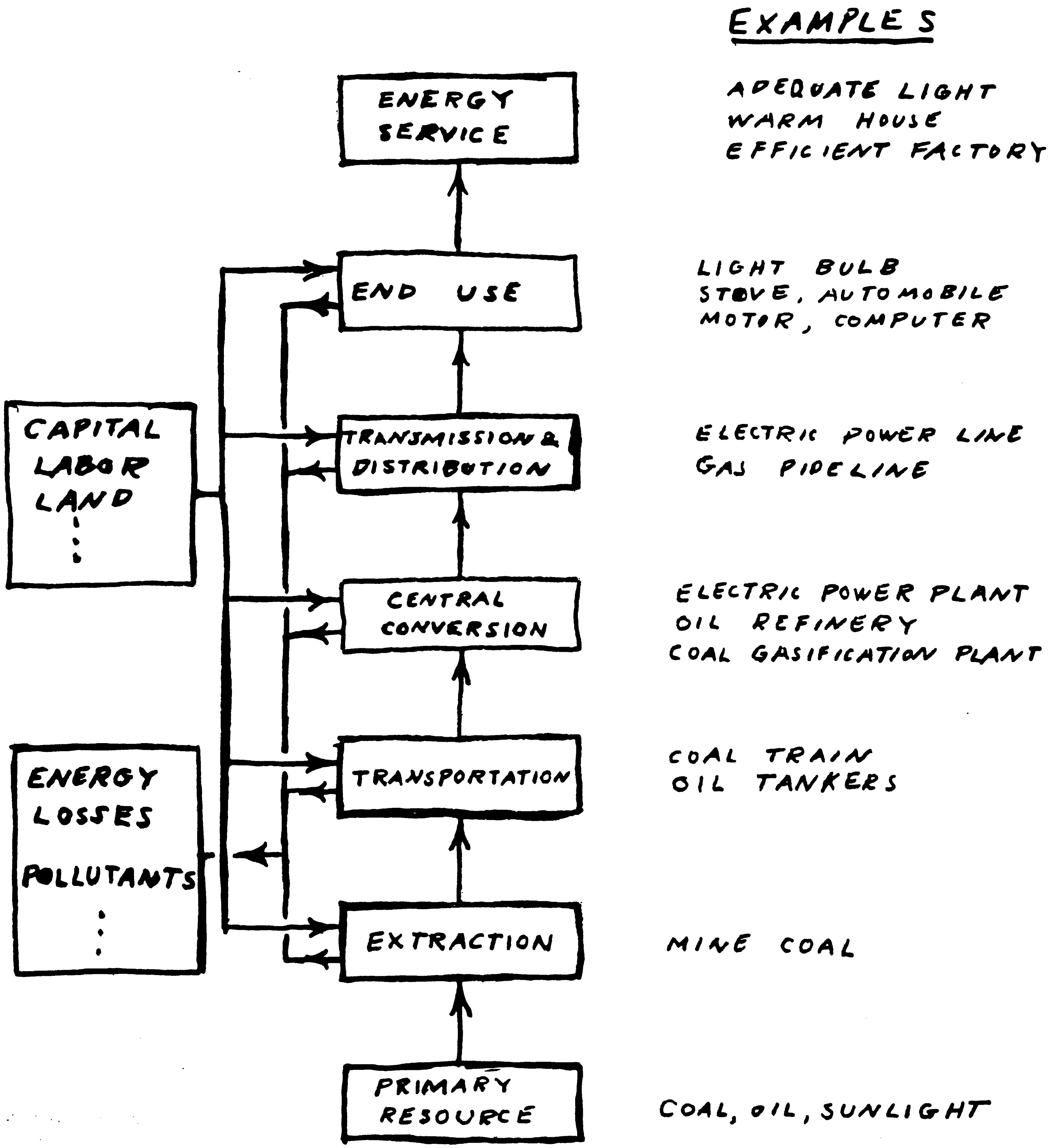
10. Singer, Charles; Holmyard, E. J.; Hall, A. R.; and Williams, Trevor I. (1954-58). History of Technology, Oxford Univ. Press.



A SIMPLIFIED ENERGY FLOW DIAGRAM

FIG. 1-1

U.S. FUEL USE PATTERNS

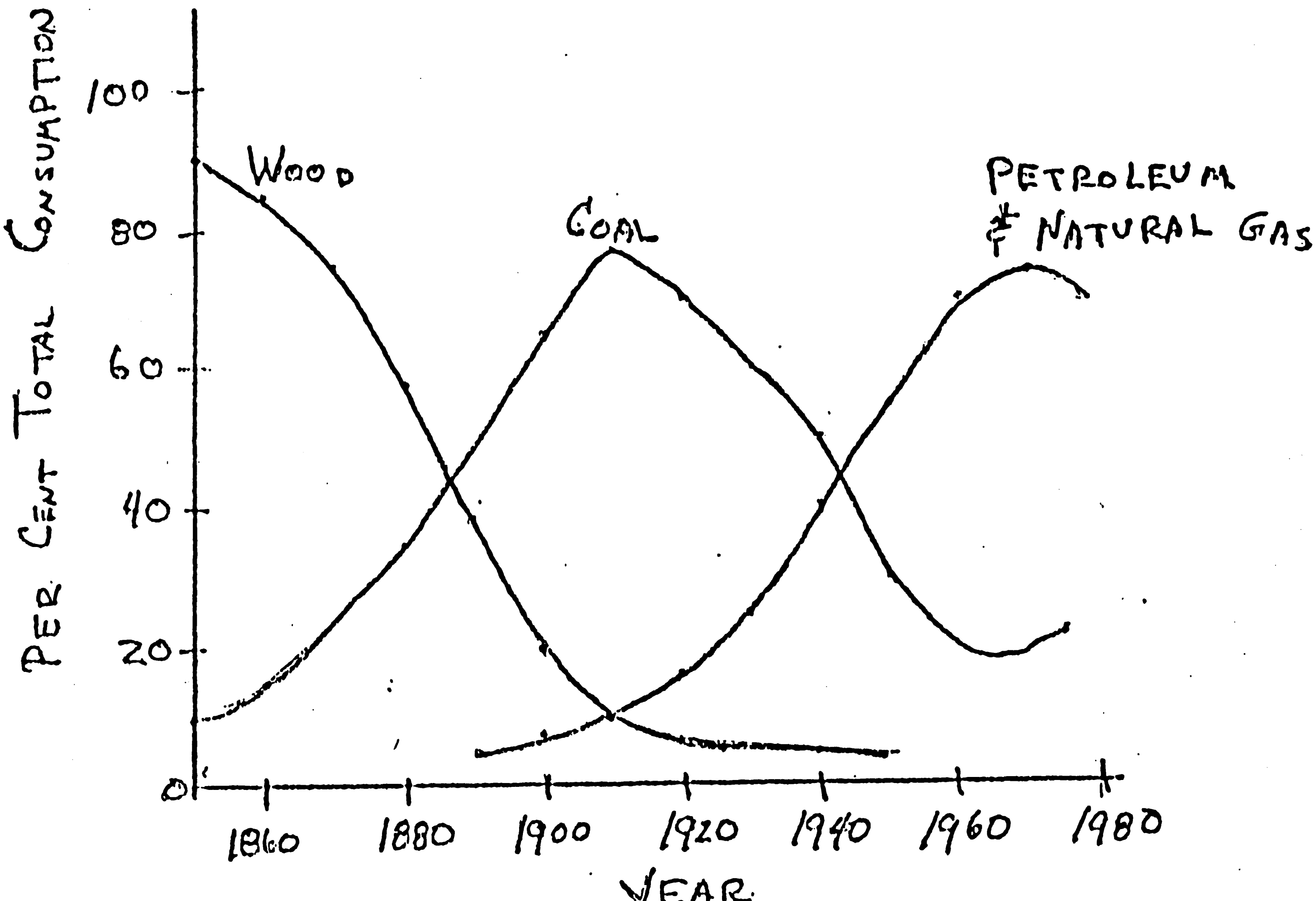
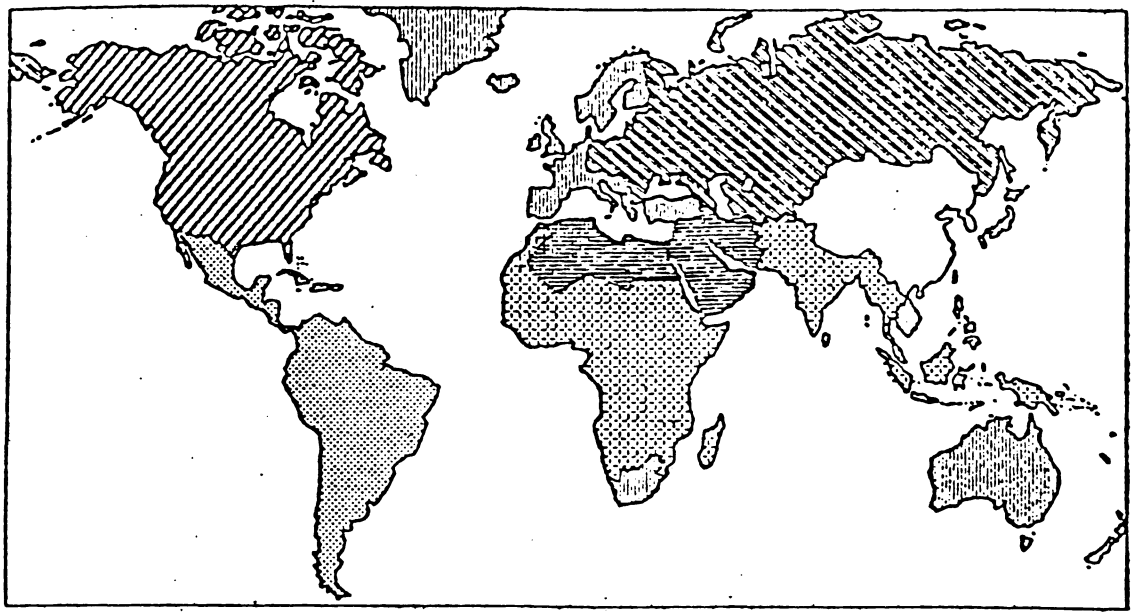


Figure 1-2



	Region I	(NA) North America
	Region II	(SU/EE) Soviet Union and Eastern Europe
	Region III	(WE/JANZ) Western Europe, Japan, Australia, New Zealand, S. Africa, and Israel
	Region IV	(LA) Latin America
	Region V	(Af/SEA) Africa (except Northern Africa and S. Africa), South and Southeast Asia
	Region VI	(ME/NAf) Middle East and Northern Africa
	Region VII	(C/CPA) China and Centrally Planned Asian Economies

(Häfele et al 1981)

FIGURE I-3: The IIASA world regions. Adapted from Energy in a Finite World, Vol. I: Paths to a Sustainable Future.

Prepared by the International Institute for Applied Systems Analysis (IIASA). Ballinger Publishing, Cambridge, MA, 1981.

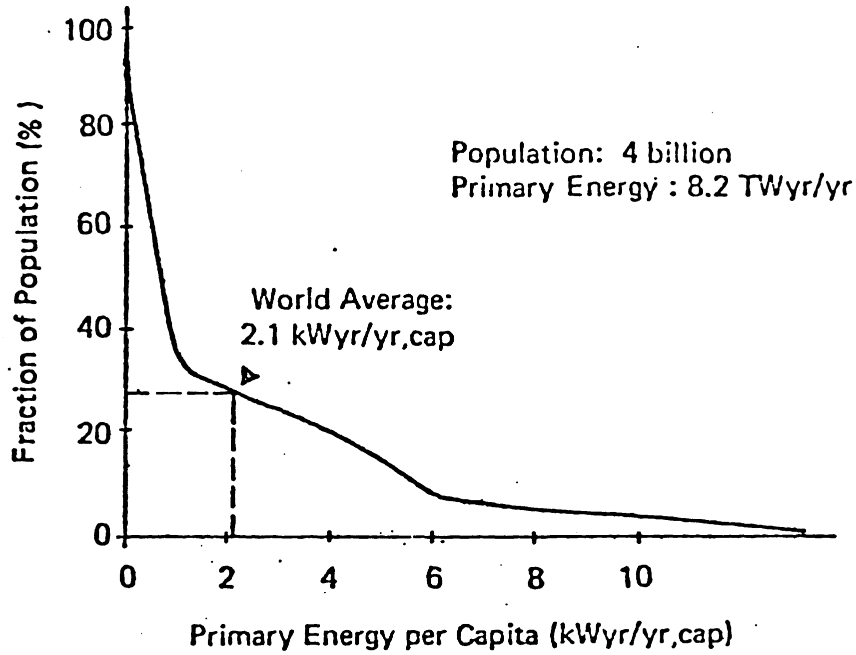


Figure 1-4: The global distribution of energy, ca. 1975.

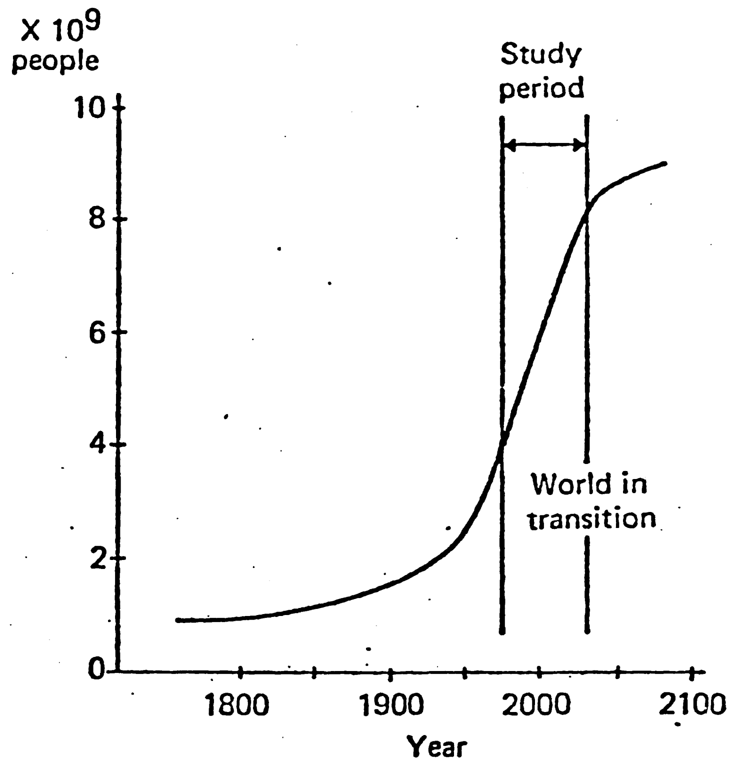


Figure 1-5: World population. Projections to 2030 based on data from Keyfitz (1977).

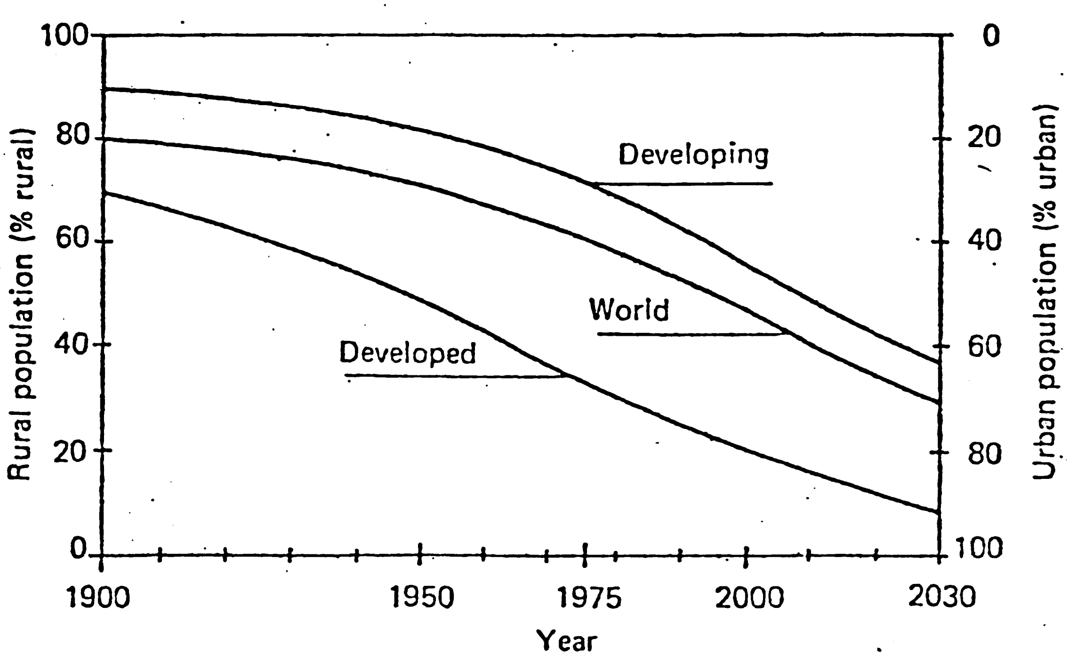


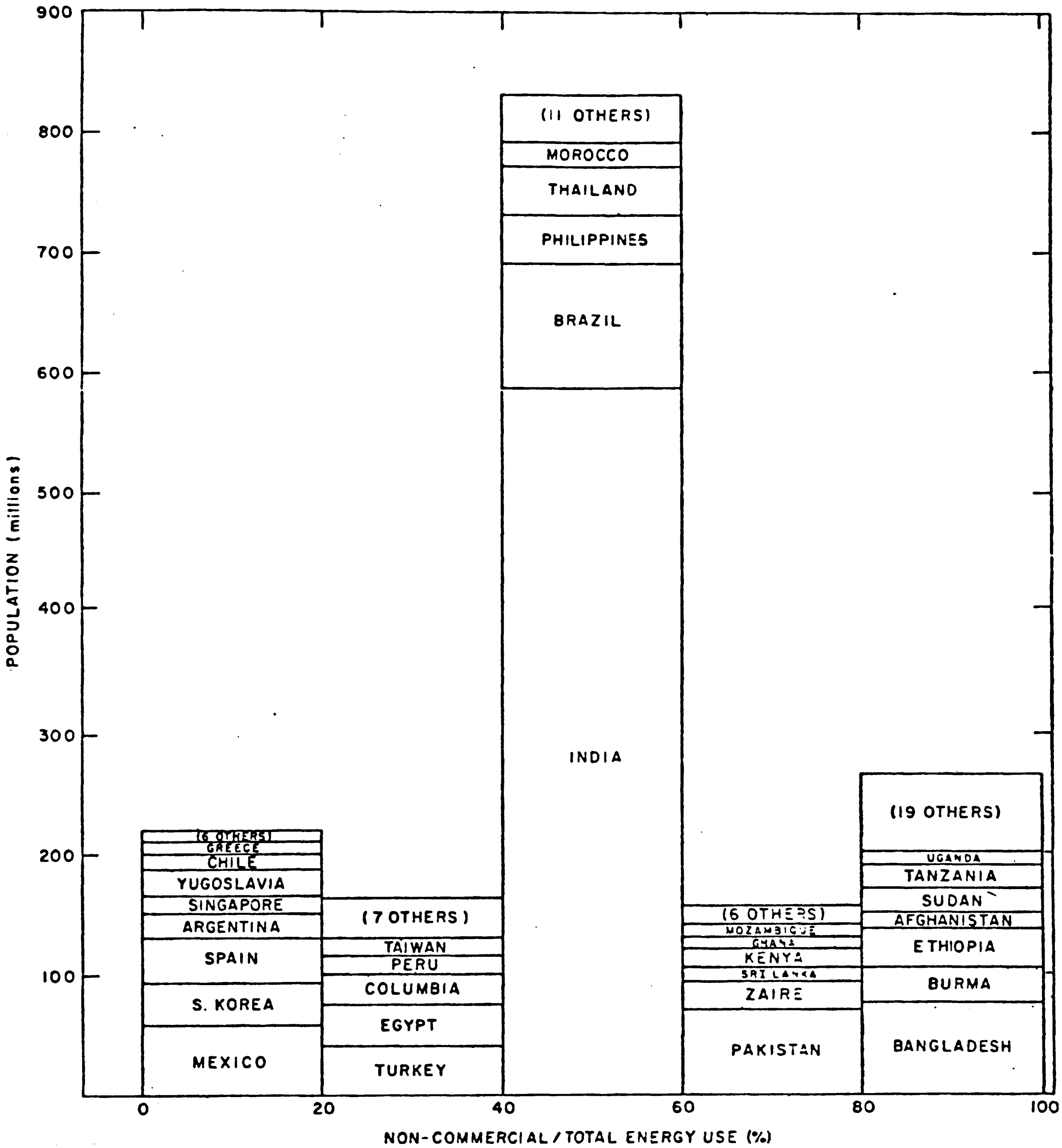
Figure 1-6: Estimated distribution of rural/urban population, 2030. Based on papers submitted to the UN Population Conference, Bucharest, 1974.

FIGURE 1-7

NONCOMMERCIAL ENERGY USE

AS A PERCENTAGE OF TOTAL ENERGY USE,

vs. POPULATION, BY COUNTRY



Sources:

- 1974 (est.) Population (Table 18, U.N. Statistical Yearbook 1975.)
- Commercial Energy Use: (U.N. World Energy Supplies 1971-1975, 1977)
- Noncommercial Energy Use: 400 kgce/ rural population

Taken from Report BNL - 50784: "Energy Needs, Uses and Resources in Developing Countries"

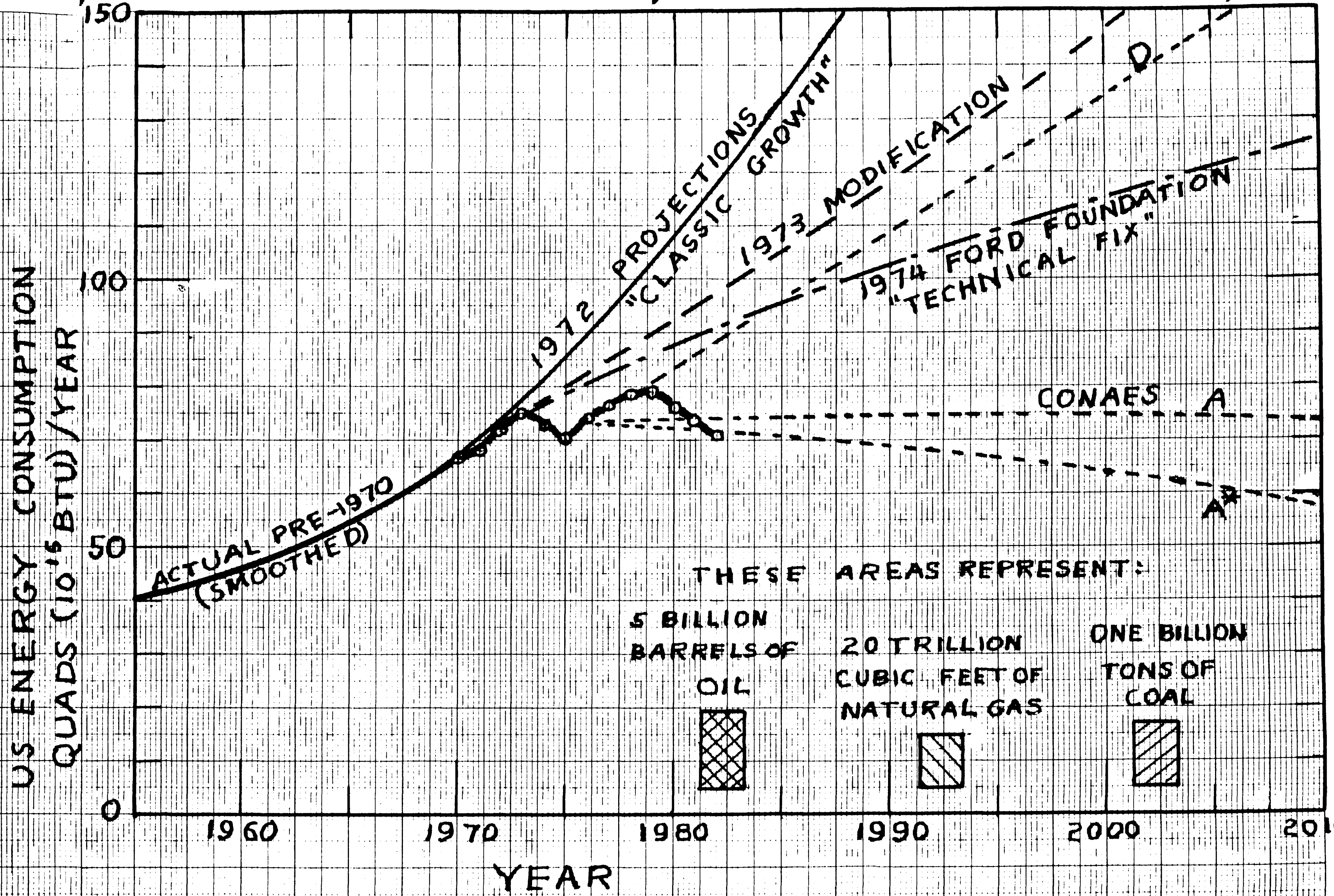
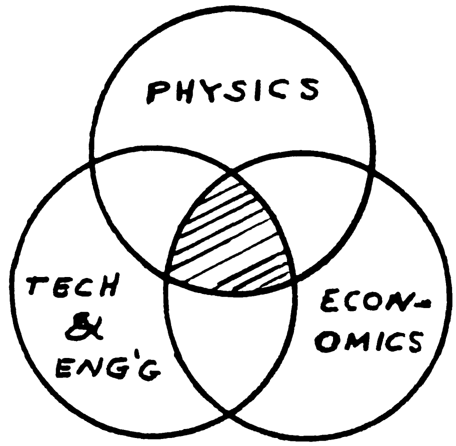
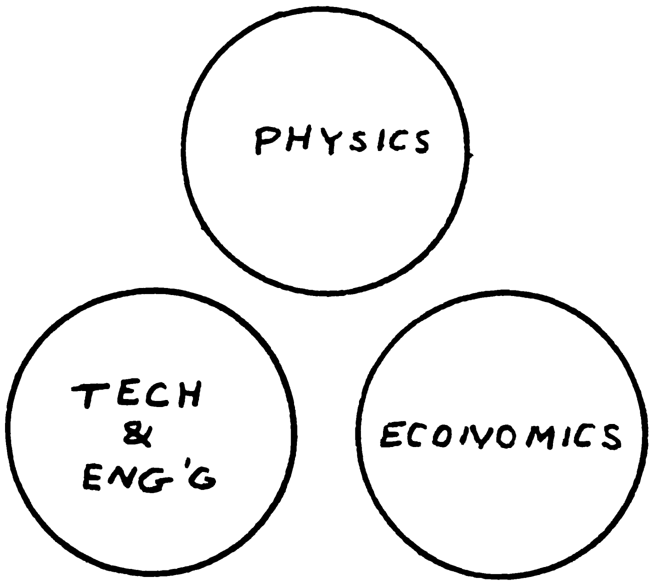


FIGURE 1.8 U.S. ENERGY CONSUMPTION 1955-1982, PLUS PROJECTIONS MADE IN THE 1970s. SEE TEXT FOR DETAILS.





OPTION SPACE EXAMPLE: DO THE LIMITATIONS IMPOSED ON CONTROLLED FUSION BY REQUIREMENTS OF PHYSICS, TECHNOLOGY + ENGINEERING, AND ECONOMICS PERMIT A REGION OF OVERLAP, SO THAT FUSION IS FEASIBLE AT LEAST FROM THESE CONSIDERATIONS (TOP THREE CIRCLES)? OR DO THEY NOT OVERLAP, SO FUSION IS INFEASIBLE (LOWER CIRCLES)?

FIG. 1-9

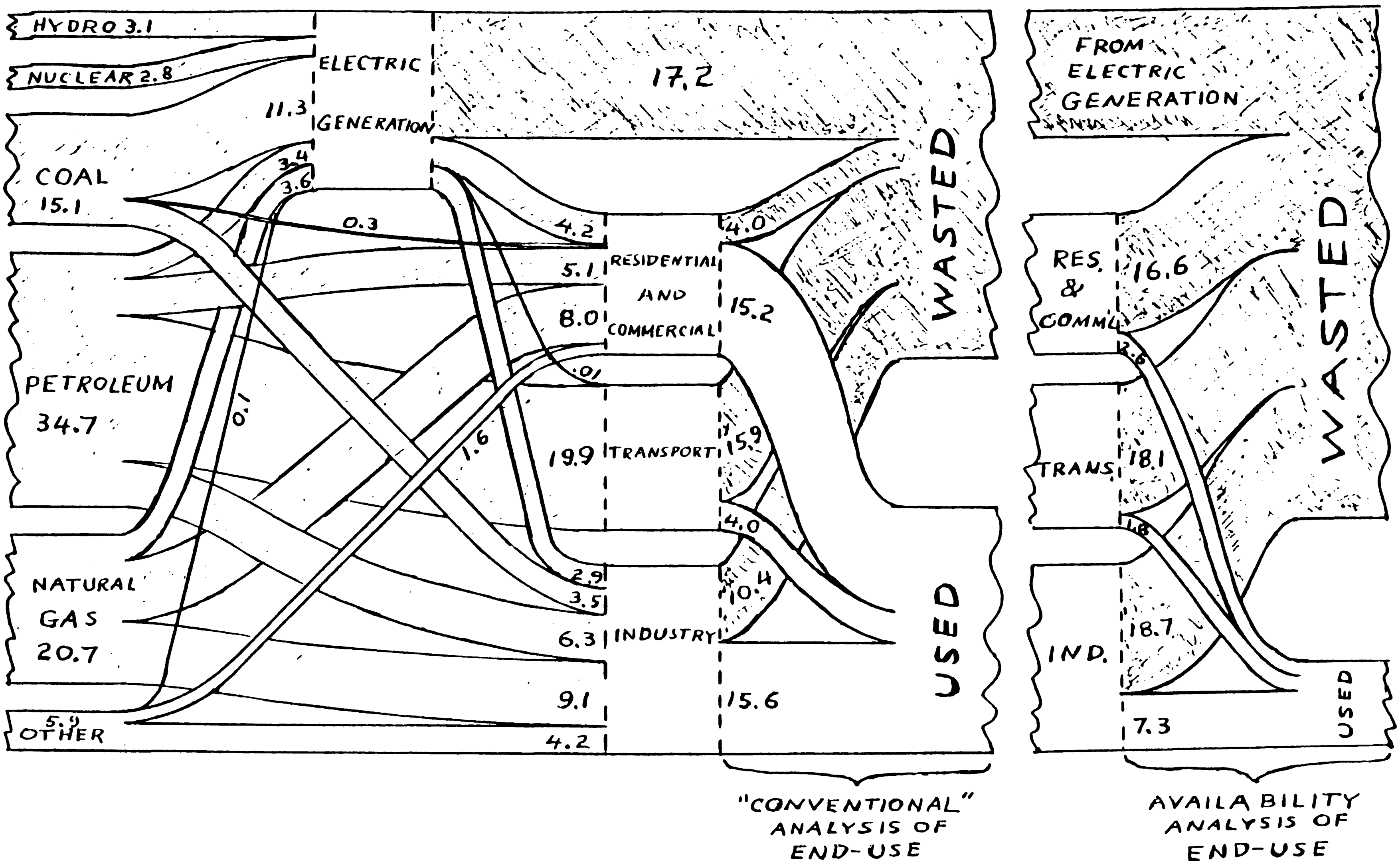


Figure 1-10. Principal Energy flows in the US., 1979. Data from Table 1.1, except for ~~end use~~ which is discussed in Chap. 4 (use vs waste,)

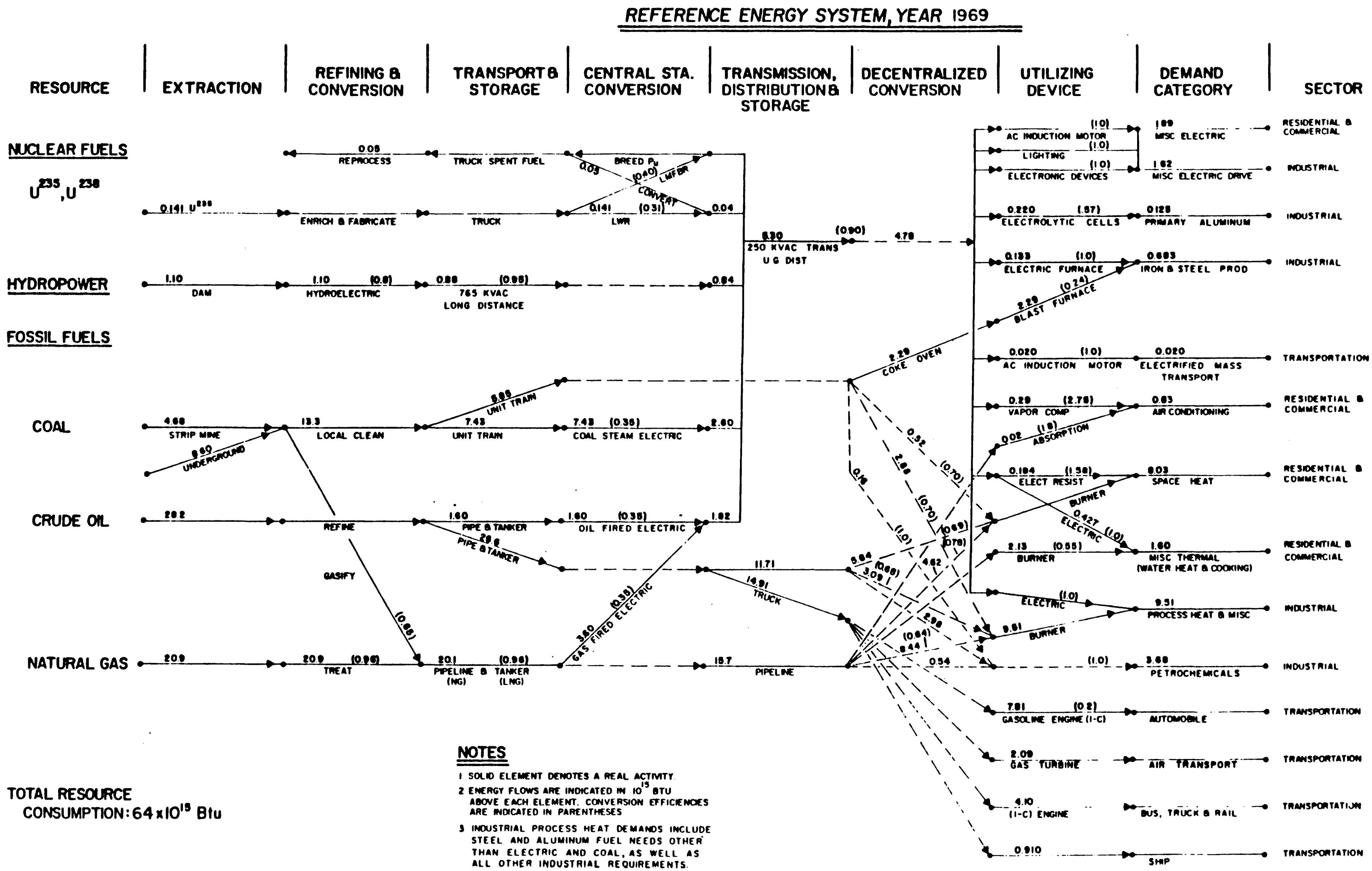
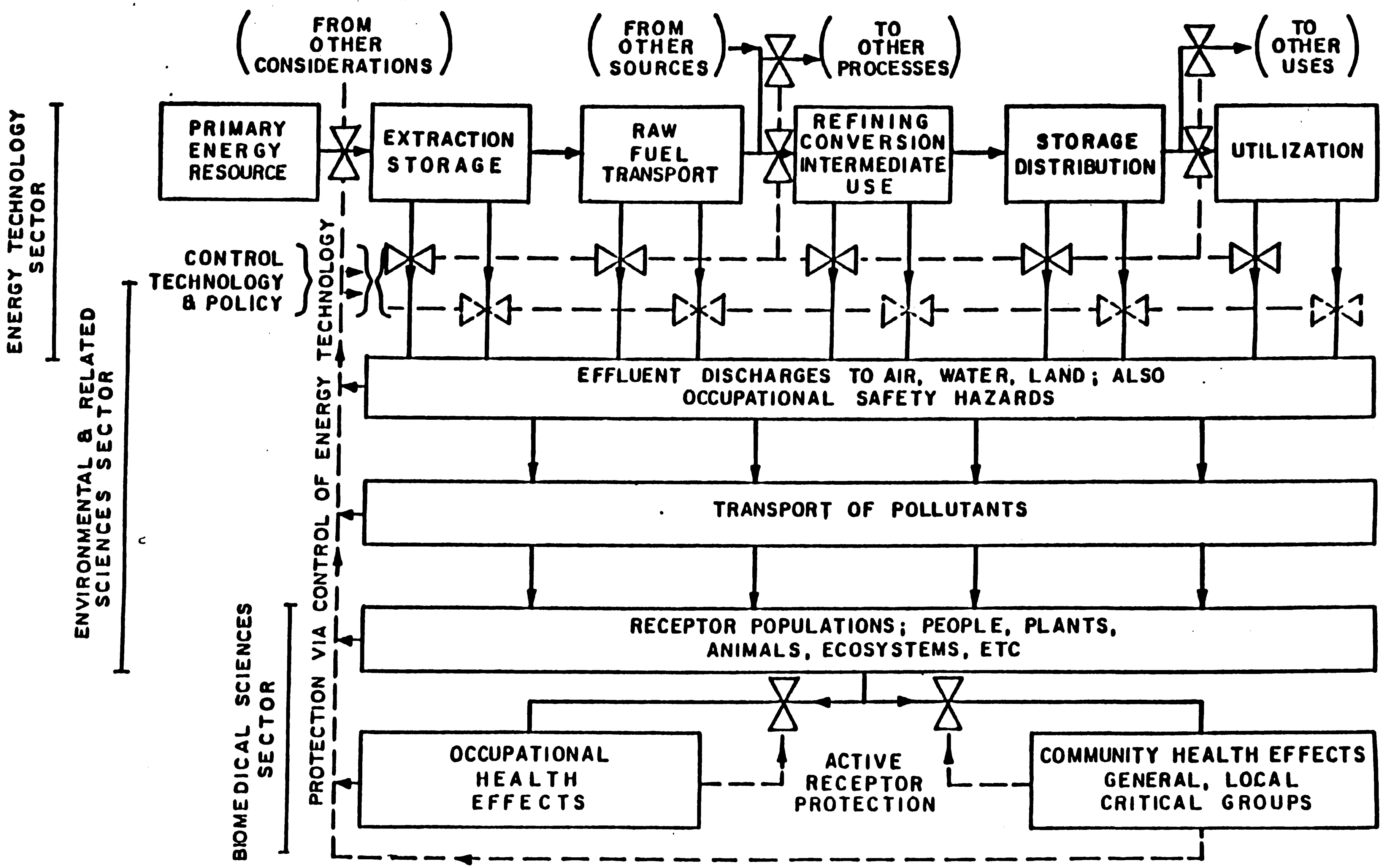


Figure 1-11: The Brookhaven National Laboratory Reference Energy System for 1972. ~~From~~ "~~Sourcebook~~ For Energy Assessment," Beller, M. (ed). Report No. BNL-50483, NTIS, Springfield, VA, 1975.

Figure 1-12: An illustration of how environmental effects might modify energy flows of Figure 10.



Products from these sectors → are used by these sectors ↓	PETROLEUM	NATURAL GAS	COAL	STEEL	COKE								
PETROLEUM													
NATURAL GAS													
COAL													
STEEL													
COKE													

Figure 1-13: Part of an elementary input-output matrix.

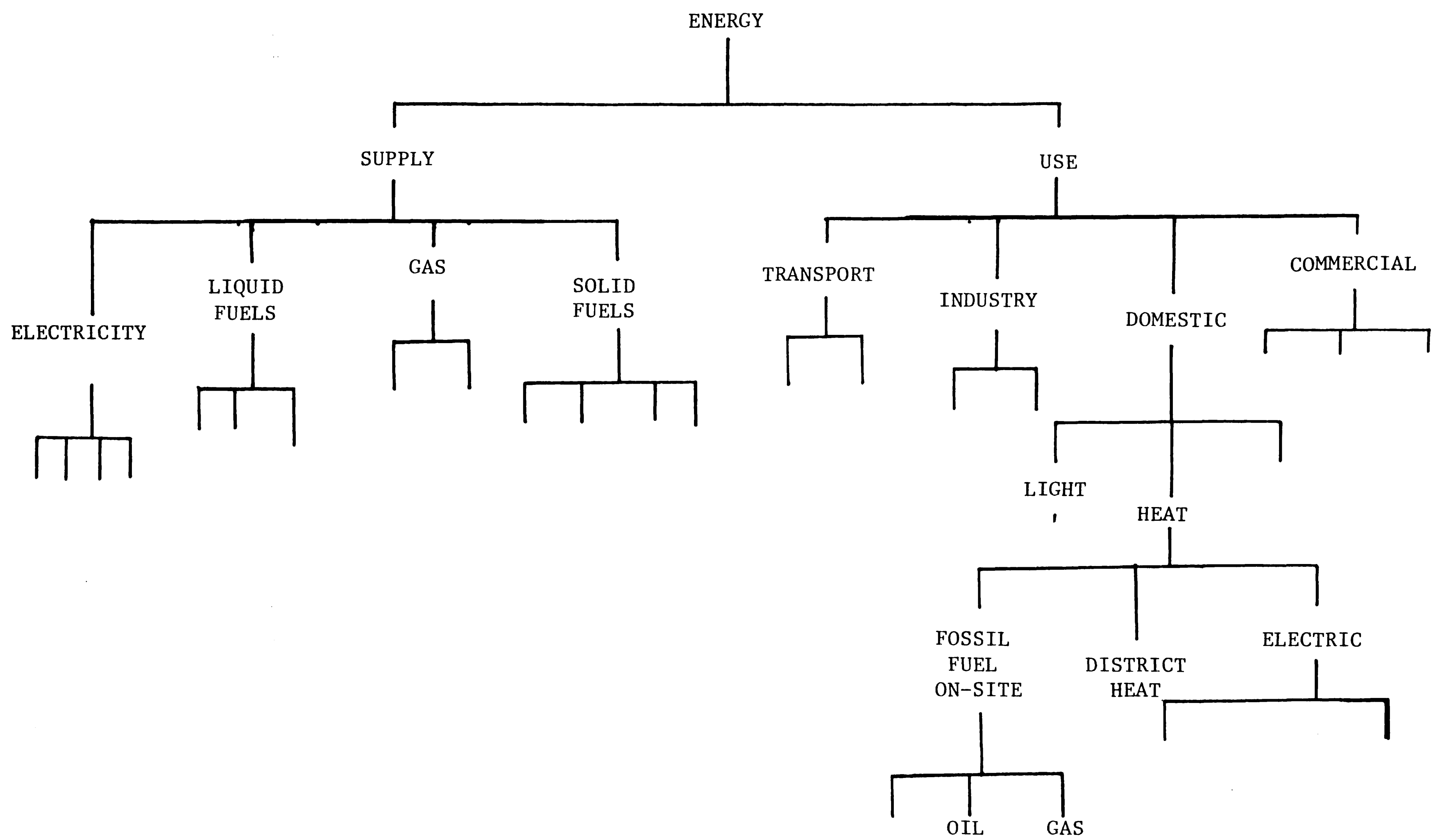


Figure 1-14: An arrangement of energy options as a hierarchical mobile.

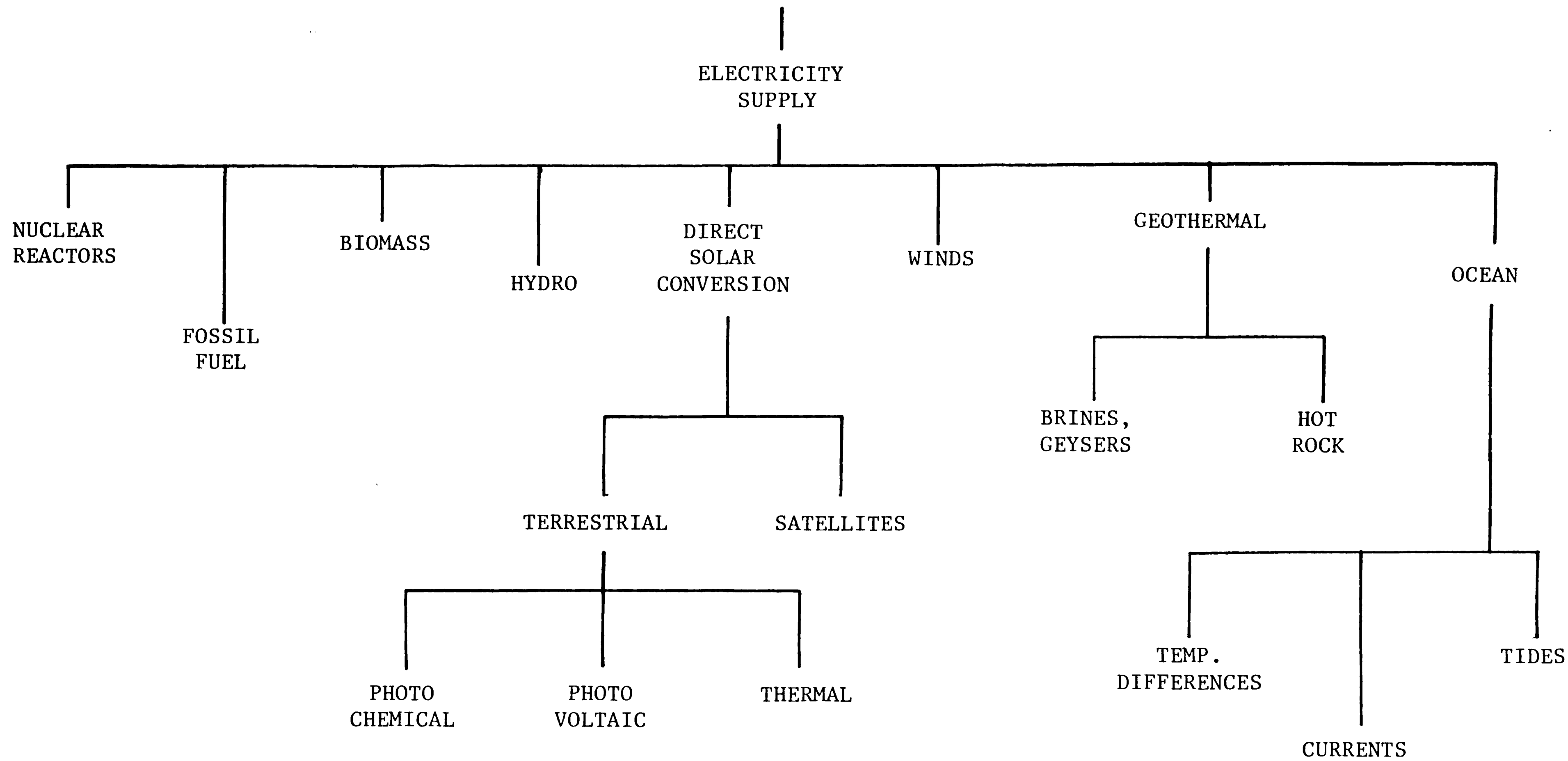


Figure 1-15: An arrangement of electric supply options as a hierarchical mobile.

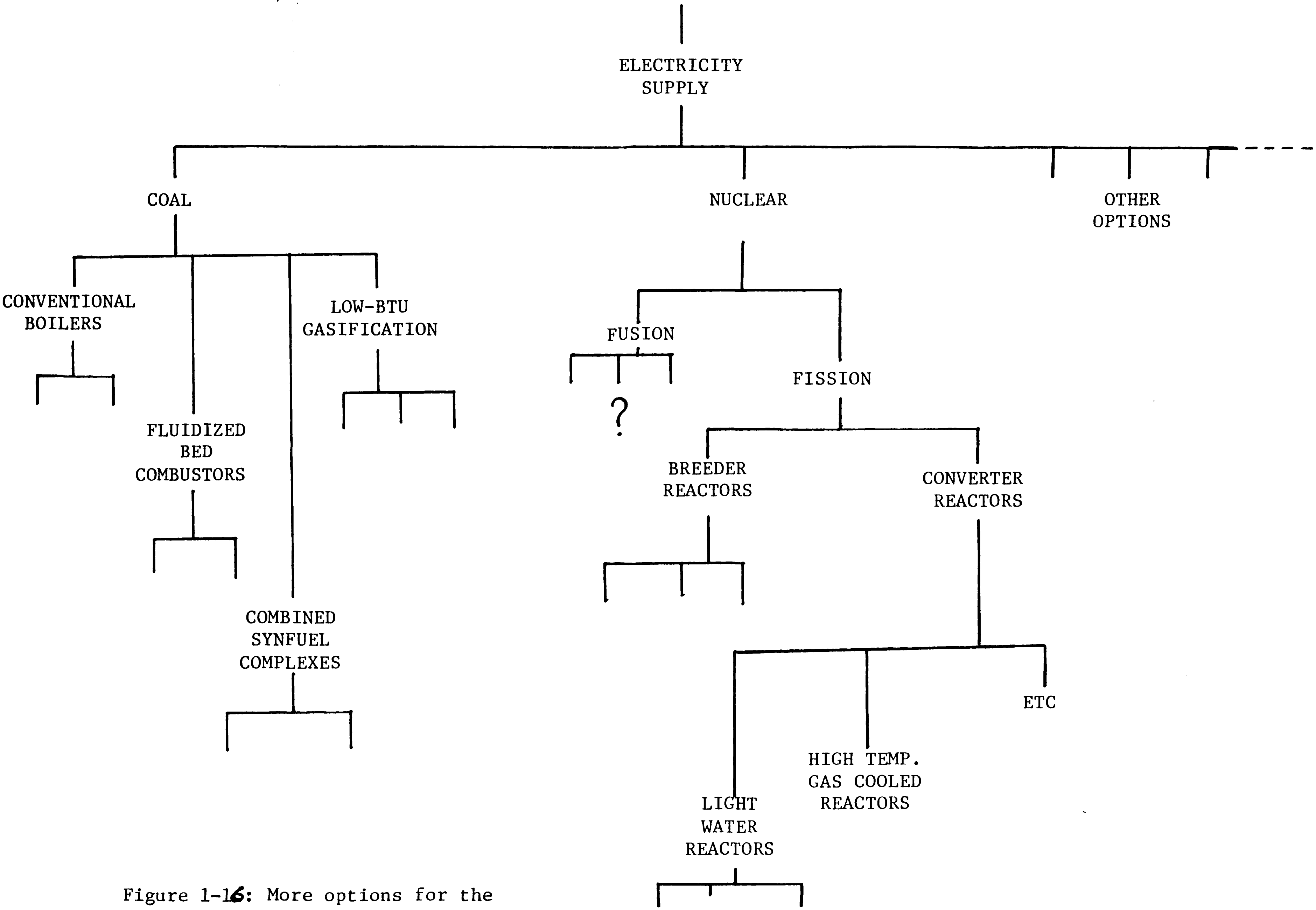


Figure 1-16: More options for the electric supply sector

Primary energy source ↓ / Where used →	RESIDENTIAL	COMMERCIAL	INDUSTRY	TRANSPORTATION	ELECTRIC POWER GENERATION	TOTAL
COAL	0.1	0.2	3.5	-	11.3	15.1
PETROLEUM	3.0	2.1	6.3	19.9	3.4	34.7
NATURAL GAS	5.5	2.5	9.1	-	3.6	20.7
NUCLEAR					2.8	2.8
HYDROELECTRIC					3.1	3.1
OTHER	0.3	1.3	4.2*		0.1	5.9
TOTAL	8.9	6.1	23.1	19.9	24.3	82.3
(ELECTRICITY)	2.5	1.7	2.9	0.01	X	X

* Includes about 2 quads of wood used by the forest products industry.

PRIMARY FUEL USE BY SECTOR, 1979
(quads)

From Department of Energy 1980 Annual Report to Congress (April 1981).

TABLE 1-1

IIASA REGION	PRIMARY ENERGY/CAPITA KW-YR/YR (1975)	POPULATION MILLIONS (1975)	PROJECTED POPULATION MILLIONS (2030)	GROSS DOMESTIC PRODUCT GROWTH RATE %/YR 1960-1975	ENERGY GROWTH RATE %/YR 1950-1975
I. (NA)	11.2	237	315	3.4	2.7
II. (SU/EE)	5.1	363	480	6.5	5.2
III. WE/JANZ	4.0	560	767	5.2	4.3
IV. (LA)	1.1	319	797	6.1	6.8
V. AF/SEA	0.2	1422	3550	5.5	6.7
VI. ME/NAF	0.9	133	353	9.8	10.4
VII. (C/CPA)	0.5	912	1714	6.1	10.8

DATA ON THE SEVEN IIASA REGIONS (Häfele et al 1981)

TABLE 12

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CHAPTER 2

REFLECTIONS ON TIME PERSPECTIVES AND ECONOMICS

2.1 Introduction

Energy - its economics, its technology, its effects on the natural ecosystem and on the artificial one called civilization - has within it many different natural time perspectives. As with other ubiquitous activities in this world, many of these different perspectives lead to different opinions of what should be done. Should we plan for the short term or the long term? The plans will probably be different, and perhaps even conflicting. What is a short or a long term? Different time perspectives involve different social groups. The selective involvement of or inattention to these various groups cause much of the difficulty with energy decisions, as already described in Chapter 1.

The important time perspectives extend from a few years, determined chiefly by economic and some political considerations, to centuries and even millennia, determined not only by exhaustion of long-lasting resources, but also by the fabric of cities and civilizations, and by long-lasting environmental and world-climatic effects.

Conventional economics conversely concentrates interest on a much smaller range of time perspectives. The cost of money, that is the rate of interest, defines a characteristic time, a time often short compared to those important in energy. Here lies the source of several of the paradoxes mentioned in Chapter 1, and what follows here gives some body to their hitherto more etherial claim of existence.

The energy problem has often been described in economics terms which, when put in the form of advice, leads to such phrases as "let the market decide," "clear the market," "charge the marginal cost," "internalize the externalities," "ensure a proper return on investment," and so on. The first phrase generally refers to keeping the government out of the business; the second refers to letting supply catch up with demand (or vice versa) so that a hoped-for equilibrium follows thereafter; the third refers to the costs of providing or (obtaining) the next incremental unit of the product (e.g., the next barrel of oil or kilowatt-hour of electricity) rather than the average of all presently provided; the fourth refers to incorporating the true and whole costs of doing something (e.g., operating automobiles) into the cost of those receiving the benefit (e.g., by taxing gasoline sufficiently to pay for all environmental and public health damage arising from the operation); the fifth is superficially self-evident. All these terms have meaning, but not always in the simple way they are often used. Some are unattainable even in principle, and even thinking of them in terms of attainable goals causes trouble, to be described in later sections.

But before that, we need some simple formulas about compound interest, payback times and other things used in simple calculations.

2.2 Compound Interest and Related Formuals

The concept of compound interest underlies much of present economics and many practical economic calculations. To the extent of its validity, it determines future worth of present things, present worth of future things, and therefore time-perspectives themselves. The idea of interest is intuitively appealing: with diligence and intelligence we expect to have later more of whatever we value (or maybe more for our children); we usually value the present more than the future.

Suppose the interest rate is $\underline{i}$ per period (e.g., 0.1 per year, or 10% per year). Then we need some formulas for determining present values $\underline{P}$, or future values $\underline{F}$, as a result of making investments all at once now (or later), or by investing a fixed amount $\underline{A}$ at the end of each period, for some set number $\underline{N}$ of periods. Conversely, given $\underline{N}$ and $\underline{P}$ or $\underline{F}$, what should be the periodic payment $\underline{A}$? Table 2.1 and its simple diagrams show the various factors that relate all these quantities. The usual period is one year, so that interest is $\underline{i}$%/yr and the total time is $\underline{N}$ years; but the formulas are not so restricted.

The first line of the Table says that one dollar put into the bank at 10% per year compound interest (i.e., the interest earns interest) will give \$2.59 after ten years. The second line says the inverse: \$2.59 ten years from now, discounted 10% per year, is worth \$1.00 now. The third line says that one dollar put at the end of each year into that account, with everything earning 10% per year, will yield \$15.94 after ten years (for the \$10 put in over the period). The fourth line inverts the process of the third: to build up a sinking fund of F = \$15.94 in ten years (for example to replace equipment that will be worn out then) at 10%/yr interest, will require \$1.00 input at the end of each year. The fifth tells the present worth of the investments described by the compound amount factor of line 3; it is line 3, discounted by the present worth factor, in our simple example, \$6.15. The sixth and last line is the inverse of line 5: to recover a capital investment of \$6.15 today, requires \$1.00/year at 10%/yr interest, for ten years.

Uniform-payment mortgages are more complicated, not shown in this simple table: there, the sum of capital repayment plus interest on the remaining balance is constant. Thus, the amount $\underline{A}$ increases with time over the period as the unpaid balance and interest shrink.

Often it is easier to calculate the answer by continuous compounding -- "daily interest." By convention, the coefficient is called $\underline{r}$ instead of $\underline{i}$, and we can develop an entirely equivalent set of formulas; Table 2.2 shows them. Figured this way, the one dollar invested at 10% per year (or more precisely 0.02738% per day) gives \$2.718..., the number $\underline{e}$ after ten years. The amount is slightly larger because in this case the money did not have to wait until the end of each year to be eligible for interest. To the extent that $\underline{i}$ (or $\underline{r}$) is small per period, the two tables yield identical results in all cases, a consequence of the relationship

$$\underline{e}^{\underline{x}} = \lim_{\underline{i}\to 0} (1+\underline{i})^{\underline{x}/\underline{i}}$$

We are now in a position to appreciate some economic time-perspectives, and to comment upon some economic policies. Let us use the simple exponential continuous compounding formula, at a rate $\underline{r}$ per year, for convenience. The present value of something in the future is discounted by the factor exp(-rt) where t is measured in years. This gives a simple exponential decline of future value (as measured now); see Figure 2.1. The entire area under the curve can be fitted into the rectangle that extends out to time T = 1/r; the two shaded areas are equal.

How long is this time T? At low interest rates (i.e., small discounting of the future) it can be long: at 3% per year, it is 33-1/3 years. But at 14% per year, it is about 7 years. In an inflationless world, many businesses expect to make a net profit of about 10% per year after taxes. But to do this after paying taxes, they must make on their investment about 15 or 16 percent per year, which gives a time-perspective of 6 to 7 years. Many economists claim that the higher interest rates caused by inflation do not shorten the time perspectives, because the prospect of cheaper future money increases the attractiveness of longer-term indebtedness so as to compensate. But the economic system is not so simple and perfect. Uncertainty itself leads to anxiety, and to shorter times for return on investment. Thus at 9% inflation per year, the business must hope for 19%/year dollar profit after taxes to make an inflation-free 10%. The before-tax return on investment then becomes 30%, and the time perspective shrinks from the previous 6-7 years part-way toward the new mathematical value of a little over three years. The recent U.S. experience of "double-digit" inflation, and the frenzy of attention on short-term return on investment, illustrate this feature. An extreme example was Germany after WWI; the government printed money at an ever-increasing rate, so that millions of marks bought only a loaf of bread. The time-perspective shrank to hours, the time a person took to spend the money before it became valueless. So the system collapsed.

Here arises a dilemma which the economists seem to answer only ambiguously. In a period of inflation (for instance) should one restrict the flow of money, say by increasing the interest rate, or conversely lower the interest rate? Raising the interest rate actually shortens the time-perspectives of those who decide to stay in the market: they seek an even shorter pay-back. That presumably reinforces the original disease, which was too much discounting of the future. Only those who drop out contribute to longer time-perspectives, and to them it seems unfair. Conversely, lowering the interest rate leads to longer time-perspectives; but it leads also to more entries into the market, and an expansion of the money in circulation, which won't cure inflation, either. This text does not pretend to resolve such dilemmas, except to remark that the cure must be at least partly attitudinal, and not just fiscally manipulatory.

2.3 Some Important Time Perspectives of Energy

Times as short as weeks or months, measured by fluctuations in the spot market for oil or in the winter weather in Europe will affect energy prices and deliveries. Those of more concern here, that affect longer term decisions, are themselves longer, but sometimes not by much.

1. <u>The Economic and Political-elective Time Perspective, T_1</u>

These are the shortest time perspectives important in energy policy; not coincidentally, they are similar, and together tend to determine the over-emphasis on short-range solutions.

The political-elective time perspective is easier to understand; according to a common aphorism, the future is the next election, and infinity is the one after that. Thus depending on particular circumstances, the political-elective time perspective tends to be 2, 4, perhaps even 8 years, but rarely longer, and often approaches the shortest times. Notorious examples in the U.S. Federal Government in the late 1970s and early 1980s were the protracted debate and predictably unsatisfactory decisions on natural gas pricing, and the ambiguous enthusiasm to develop synfuels from coal.

Politics does good things too; these few paragraphs are meant to illustrate the difficulties that arise from paradoxes, not a need for some basically different system. Among good things is the grace that often arises from the politician's sense of history -- a sense sometimes more highly developed in senior politicians and leaders than in junior ones. What politician wants to be remembered for causing some particular or general long-term mischief? Mercifully few; and coupled with this reflection is a corollary conclusion that the amoral politician who cares not at all about future judgement might be a worse political risk than an immoral one. The ambition to be remembered well is a generally visible and constructive motivation.

From this, one might conclude that the political time perspective would be longer if the period between elections were increased, or if the elective system were to be replaced by a long-term dictatorship (or a hereditary absolute monarchy), or if the political system itself had better institutional memory (for example, as some churches tend to have). Cursory study of history shows this conclusion to be generally true - the monuments of ancient Egypt and Greece, the Roman roads and aqueducts, medieval cathedrals, Franco's Spain, Hitler's plans for a thousand-year Reich - but at social and intellectual costs that suggest we seek to introduce conscience some other way.

The economic time perspective considered here arises from the normal market expectation of rate of return on investment, already derived in the previous section - a time of typically five years, and usually not more than ten.

This economic time horizon T_1 tends to work against both long-term research and development and against many ancillary energy conservation activities in business and industry. Regarding long-term research and development, the reason is obvious: the payoff is too far away. To be sure, exploratory research can be justified, but its cost must be low if normal market rules and rates of return apply.

The disincentive to ancillary energy conservation (or other side-line activities) is more subtle. Those activities are new to the company, in its view uncertain and therefore riskier than its normal business; therefore the company must devote a disproportionate fraction of its management and/or technical skills to the effort. These skills tend not to be diverted from the company's main line except with unusual incentives. If the incentives are purely economic, the company must expect an even better payback on its energy conservation investments than it gets from its normal business. It is not unusual for business firms to demand 30-40%/year return on internal energy conservation investments, corresponding to a two-year time horizon. This unfortunate but real circumstance, which tends to divert attention from long-range conservation strategies, was for a long time unrecognized both by academic economists and by both State and Federal Governments. All investments yielding the same in-principle return are not equally attractive in the marketplace.

Governments have substantial ability to change these economic time horizons: tax relief and subsidies encourage what would otherwise be unattractive investments; that is, the time horizon T_1 can be artificially extended by appropriate policies. Conversely, taxes and punitive regulations discourage other investments. Here is part of the political option-space described in Chapter 1.

That the economic and political time perspectives are comparable is no accident. These two groups, business and politics, often sharing common time perspectives, find many interests in common. This is no denigration per se, but a positive necessity; the civilization cannot afford to have such powerful groups at odds for very long. The almost essential congruence of views between these two sectors suggest that if the independently dominant member - politics - held longer-term views, either by inclination or by inherent governmental structure, then the business sector would tend automatically to correlate. Casual observations of business practices in countries with very different governmental forms tends to support this hypothesis.

2. The Technological Time Perspectives, T_2

Consider now the next longer typical time perspective T_2 needed to develop and introduce cycles of new technology. It exceeds the economic and political time horizon T_1 substantially. Analyzing solar power, a new coal technology, nuclear power, even a mature set of technologies emphasizing better energy utilization, we discover times that vary somewhat with the option, but all take twenty years or more except under most exceptional conditions and strong government incentives. For example, civilian nuclear power was first seriously explored in the U.S. about 1950, by the early 1970s accounted for only one or two percent of the U.S. electric power generation, and by the late 1970s about ten percent. Figure 1.2 of Chapter 1 shows the effect of this inertia for several energy options, an inertia that arises partly from technology alone and partly from additional factors discussed in the next several paragraphs. The slow recovery of the U.S. coal industry from its 1950-1970 decline and the continuing illness of its railroad partner provide further examples.

Comparable minimum characteristic times appear in other capital-intensive sectors, for example housing, heavy industry, and machine tools. Thus appears a societal inertia, which impedes turning from one energy strategy to another, be it either provision or rational utilization. The U.S. automotive industry appears on casual inspection to be exceptional but it is not: frequent cosmetic and less frequent engineering changes gave the appearance of rapid advance even in the 1960s, and individual vehicles last an average of eleven years. But the basic industry - particularly its mode of energy dependence - persisted for decades and (it now appears) intellectually and managerially declined for at least a decade also.

The inequality $T_2 >> T_1$ leads to work neglected until very late, and too few long-term reserve options prepared in advance. Consequently, development finally proceeds via short-cuts with excessive social costs. This over-driving of technological headlights has become notorious in reference to coal technology and appeared also in parts of the solar power sector, to be recounted in those later chapters.

The time T_2 has been estimated to exceed 20 years. To be sure, more rapid changes can be impressed upon an unwilling or slowly-responding civilization, but at least in the energy sector it usually leads to equipment turned off or abandoned before the end of its natural useful life. Occasionally that is good, for example upon the discovery of hitherto unsuspected hazards associated with the operation. But forcing too fast a pace usually means non-use, lower productivity, and accompanying social troubles. In other words, energy use and societal health are fairly closely coupled in the short term; but as we shall see in Chap. 4, they are much more loosely coupled in the long term, with time constraints related to T_2.

A bizarre perversion of this technological time T_2 sometimes arises in institutions that have developed comfortable client-patron relationships, for example, as between some government laboratories and supporting government agencies. The specific activity is that of pursuing complex, often expensive, sometimes even arcane technological goals that therefore have built-in barriers against casual scrutiny; but the goal lies so comfortably far in the future that neither the laboratory participants nor the federal civil service patrons expect to be challenged during their tenures for real results. By no means do all - even a majority of - national laboratory projects fall into this category. However, too many projects of doubtful quality persist in mutually advantageous cooperation between the clients (who get de facto tenure support) and the patron (who points to supporting long range research for valuable social goals, disproving the allegation of no long-term governmental interest).

3. The Resource Time T_3

No resource runs out absolutely; simple economic forces raise its marginal price as it becomes more scarce while any demand still persists for it. But often something else starts to become more attractive, then further technological and economic development makes the new mode increasingly more popular than the older one. Not every resource follows such a pattern; but this common replacement - coal for wood, oil for coal (and some now propose wood for oil) - and increasing scarcity for resources that continue to be useful tends to define an effective resource lifetime, here called T_3. For oil and gas domestically, it has been estimated as about 25 years, and for the world as a whole perhaps

50 years. But of course there is no sharp cut-off date.

The perception - true or false - that this resource time T_3 for oil and gas has shrunk so far as to be comparable to the time T_2 to develop new technologies causes anxiety in some government and academic circles, and stimulates the present energy debate. It leads to political vulnerability; see section 2.6 of this chapter. Other groups with interests more closely aligned with the economic or political-elective times T_1 see no pressing problem here. The energy crisis depends on who describes it.

This shrinking resource time horizon is particularly visible and worrisome to the electric utility sector, whose internal time horizon is made long by regulation, by limitation to low but guaranteed rate of return on investment, and by expensive capital equipment built to last for 30 or 40 years. In previous decades, the electric utilities took into account as well as they could the price of fuel, in making least-cost decisions. To be sure, the price of coal or oil might rise in ten years, but in their planning, coal or oil would always be available at <u>some</u> negotiable market price: provided the electric utility company knew its business, it could always incorporate the fuel price into the rate base. But the genuine unavailability of fuel is quite another matter, because now the equipment itself becomes inoperable, and questions arise whether it should, under such conditions of resource uncertainty, be built in the first place. The availability of natural gas, oil, coal and uranium - principal fuels for generating bulk electric power by present technologies - have all been called into question, some because of impending scarcity, others because of environmental, regulatory or other social concerns. The consequences of this proliferation of uncertainty on the electric sector have been severe, and will be discussed elsewhere.

4. The Time Scales of Cities and Civilizations

Cities last for centuries, unless wars or other calamities destroy them. Some Romans still live in buildings built during the Roman Empire. Once built, their technological infrastructure is hard and costly to change, for example to thread a subway system through existing foundations, pipes and tunnels with minimum disruption. Sometimes the energy resource times outlasts the civilization (e.g., wood in the pre-Greek empires) and sometimes matters are the other way around (e.g., in Greek times). These very long time perspectives receive attention more as occasional social fashion than as part of rational exercises.

5. Some Geophysical Time Perspectives

We cause profound effects lasting very long times; here, inattention is very selective, determined by many factors ranging from short-term economics to fashion.

Present burning of fossil fuels and the world's major forests runs the natural cycle of photosynthesis and gradual accumulation of organic matter backward at high speed, with long-term changes likely to come within a century. But social attention to economics and politics as usual, plus incentives to build new technological systems to oxidize more fossil fuels and biomass, involve mainly the time horizons T_1 and T_2, to the neglect of such considerations until the past few years.

What would be amusing, were it not another sign of general intellectual and societal incapacity to comprehend the energy problem, is the selective concern about the long-term hazards of nuclear wastes buried in the ground, coupled with apparent unconcern about what would remain from underground gasification or liquefaction of coal, shale oil, and other deposits too difficult to extract by normal methods, plus the vastly larger present burden of toxic chemical wastes. The hazards of both the nuclear wastes, fossil fuel residues and many toxic chemical wastes relate to the same human ailments - cancer, genetic defects, birth defects. One comes from radioactivity and has been highly publicized. The others come from the millions of tons of biologically active molecules (anthracenes, phenols, alkenes, etc.) that could remain in a relatively unmonitored condition, often in geologically unfavorable strata; the prospect seems to appall few, and there is little public outcry.

2.4 Economics and Tensions between Dimensions

From the Greek word oikonomis, meaning originally the proper management of the household, and hence by extension the proper and holistic management of all our activities, we have the words "ecumenical" and "economy". Economics is then the proper management of things, and the field known by that name (known more as "political economy" in Europe) deals with rational and efficient allocation of resources and labor in that broad sense. Expressing everything or almost everything in terms of money brings problems, along with obvious complications and benefits. Money is often a valuable surrogate for labor raw materials, finished goods, etc. At its limit, the idea assumes that the value of tangible and intangible things has been decided upon in terms of money, or at least that an agreed-upon method exists for deciding.

Viewed this way, usual business economics leads to a money theory of value, in particular to time perspectives related to the cost of money. But many disparate time perspectives exist, related to technological development, environmental change, and resource depletion, for example. In mathematical metaphor, the whole subject is, with these many dimensions, a vector, one direction being technological, another economic, another environmental, and so forth. As with multi-dimensional vector functions, it is not possible to ignore any of the important dimensions without losing something essential,any more than it is possible to climb the two-dimensional picture of a mountain. Yet the attempt is often made, sometimes to re-cast the problem as one of technology almost exclusively(as did the Energy Research and Development Administration in the 1974-77 period), or as almost exclusively business (as does most of the business sector), or in academic seclusion. In an ideal society, some argue, no great problem will arise because the economy will sort itself out so that monetary expectations are a good measure of social, technical and other expectations. But, as with Plato's ideal Republic, that is impossible: different time-perspectives lead to different valuations of the future. Thus, the reduction to one dimension is not possible, even in principle.

Two consequential questions now arise.

1. Can the costs be internalized?

One can try, often usefully, often successfully. On the positive side exist many pollution abatement schemes: sulfur oxides and particulates from power plants, radioactive releases from the nuclear power industry, automobile exhausts, reclamation of strip-mined land. But even here there are limits. Note the importance of social decisions that the costs will be met in one particular way and not in another (e.g. emission limits vs pollution taxes) and even that the public damage will, in fact, be prevented or limited. Social awareness changes with time in these matters: until the middle 1960s, air and water pollution in the U.S. received relatively scant attention. Energy shortages in the early 1980s stimulated calls for relaxing the environmental standards.

Pollution taxes illustrate both the possibilities and the difficulty. Figure 2.2 shows several possible strategies. Curve A might be adopted by a group that wanted to control pollution at all levels, but considered the various social, epidemiological and other costs to be relatively small. Another group, with a different outlook, might choose curve B. Yet another, believing that some pollution is almost unavoidable but that excessive pollution should be strongly discouraged, or perhaps realizing the impossibility of controlling every small polluter, might adopt something like curves C or D. Which is correct? More information gives only partial resolution.

Probably the most intractible problem of this class is known as intergenerational equity, as with (say) burning fossil fuels now to cause increases of carbon dioxide in the atmosphere and consequent substantial climate changes in the next century (a topic discussed at length in Chapter 3. The various winners and losers exist not only in different places, but at different times, generations apart. How much of our resources to leave for later generations concerns conscience as well as technology or money. No agreeable discounting scheme exists to resolve such problems, which cannot be stretched or cut to make them fit one Procrustean bed.

Also, attention to exact equity and equality in even the simplest of these internalizing issues can lead to ridiculous exercises, makes the society destructively litigious over dividing the last scruple, and in any event cannot be achieved. The only way to achieve absolute internalization of costs even at one single time (i.e. ignoring the intergenerational question) is for each person to live completely independently. In our civilization, people cooperate to do many things, creating a complex flow of costs and benefits. That is not a zero-sum game, so at least in principle everyone gains by the collaboration. The best that can be done is to attempt conscientiously to even out the total goods and bads among individuals and groups, with a generous and occasionally forgiving and occasionally thankful attitude.

2. <u>Social and Commercial Discount Rates: Should they be equal?</u>

One conclusion <u>inter</u> <u>alia</u> to be derived in this and subsequent sections is the necessity of thoughtful and effective public involvement in important energy tasks. This usually means some degree of government involvement. It must be made clear at the outset that this does not extend to federal governments taking over the tasks that should and could be performed better by local ones, nor to governments displacing private initiatives, except in cases of likely default. Government success in "picking winners" that will eventually belong mainly or wholly in the public domain is poor.
A favorite question that shows the inadequacy of simple discounting is whether the public and private sectors should figure their investments using the same rate of return (taking into account the probability of success). Everyone will agree that the government must engage in some activities (public education, public safety, national defense, etc.) on purely social grounds; rate of return on investment has nothing to do with the question -- the activity doesn't suit the private sector.

The interesting questions relate not to those clear-cut cases, but rather to those in which both the private and public sectors could, in principle, be competent, for example liquefaction of coal to make synthetic crude oil, or running the railroads or the telephone system. One important reason exists why the government must assess even these opportunities differently than does the private sector, even though the risks experienced by the private company during its life may be exactly the same as those experienced by the government (or the difference is somehow compensated). In briefest abstract, the difference arises because a company has limited liability, but a reasonable government does not. The economic consequences will then be to make the social and commercial discount rates different.

Ahead of the main points of this section, here is first a summary of the points of view of those who hold that the social and commercial discount rates for similar activites should be the same.

Suppose the private sector invests money in an enterprise with some assumed risk of success, and expects a return at rate r. The flow of capital in the marketplace then makes all similar-size and similar-risk enterprises equally attractive; thus, if the government wishes to invest in something, it should do so at the same rate, modified only by its capability to reduce risk, e.g. through regulation of competition, etc. In coal gasification, for example, private industry must face the hazard of being undercut by maintenance of controlled low prices on natural gas, and expects a higher rate of return (or government assurance of protection); the government can settle that risk question for itself. Except for factors of that sort, the public and private investment rates should be the same (according to this concept). If the government invests in projects yielding lower rates of return, it misses the chance to invest somewhere else at a higher rate, and is, therefore, derelict in its duty. As a corollary, if a private sector doesn't find a risk-adjusted investment in coal liquefaction attractive, the government should not get into the business either; then it is but a short step to conclude that the government should not be in such businesses at all.

A very clear statement of that view was written into "Proposed

Principles and Standards for Planning Water and Related Land Resources," 36-FR-245 (24144-24194) by the Water Resources Council (Washington, D.C., 21 December 1971). Their concern was originally about investments in water reclamation projects (partly with the laudable objective of ensuring that the Corps of Engineers did not engage in projects whose main social attraction was return on investment maybe in the next century), but the guidelines have been used to judge other government activities, for example, Federal development of energy resources. This "opportunity cost" of proposed Federal investments should also include the taxes that the private sector would have paid (says the proposal); if the government supports it, the taxes on the erstwhile private business are forgone, and we must be fair to the Federal taxpayer who must finance the Federal investment. The proposal discusses whether the government should do its calculations on the marginal or average costs and rates of return, favoring the latter as being more equitable; it ties its logic to the price of government bonds, whose value changes according to the interest rate, which itself responds to the average business level and rates of return.

That reasoning fails, and the one dimensionalizing of social problems via money caused the difficulty. Money is a tool for solving perceived social problems, and not an end in itself. On the day these sentences were first written, the U.S. Treasury was borrowing money at 16%/year. Our social problems do not disappear on a six-year time scale. As simple example: the Federal government maintained coal research on a virtual starvation diet (about $10 million per year) until the early 1970s; thus, through the 1960's and early 1970's, almost nothing was done; by 1972, when the need for more and better coal technology had become apparent, neither the private nor the public sector had done much; the problem itself, which requires more effort for a longer time, remained real even in 1980, and the legacy of inaction two decades ago remains.

Neither does the private sector live by such a narrow investment philosophy. The prestigious Harvard Business School charges high tuition and gives appropriate value for money by teaching its students how, after graduation, they can go into the world and make much money by running businesses with high rate of return on investments, i.e. with short time perspectives. The HBS then duns these graduates enthusiastically for contributions to the School. If it took its own economic philosophy literally, it would use the money to build tar-paper shacks with ten or twenty year life. On the contrary, it builds to a standard so high that, when the rest of Boston has decayed to dust, the HBS will remain as a monument to its principles.

2.5 Going Bankrupt Profitably: A Tragedy of the Commons

Here is a particular quantitative illustration of these ideas, that has a surprising policy sequel to be developed in the next section. Suppose that all the "usual" externalities have been internalized. One cost remains that cannot be internalized by any limited-liability company: the costs, social and economic, to other sectors that may arise if it ceases operation. West Virginia is littered with abandoned strip mines whose corporate owners no longer exist.

A private company can, if disaster comes, declare itself bankrupt, walk away, and lose not more than its total investment; stockholders have no responsibility other than paying for the stock. Social or other costs persisting thereafter must fall on other sectors, often public ones. This limit on liability is not open to socially responsible governments, whence arises the fundamental difference.

The idea is easily developed by example. Suppose a company can make just two kinds of investments: (a) it can invest money at present time $t = 0$ in a venture that yields a high rate or return r_1 for a certain period $\underline{T}$; then it will assuredly collapse and the investment will be worth nothing thereafter; (b) at any time, it can invest money in a safe continuous activity, yielding a lower rate of return $\underline{r_2}$. If the period $\underline{T}$ and the ratio $\underline{r_1}/\underline{r_2}$ are large enough, strategy (a), with the profits invested in (b) is preferable, as follows:

The company invests unit capital in the doomed enterprise at $t = 0$, writes off the capital investment, and reinvests the $\underline{r_1}$ profits in option (b). Then its total assets y at any time t are governed by

$$\frac{dy}{dt} = r_1 + yr_2 \tag{1}$$

with the proper initial condition $y = 0$ at $t = 0$ (the plant written off as unrecoverable at the start), we find

$$y(t) = \frac{r_1}{r_2}\,[e^{r_2 t} - 1] \tag{2}$$

The total assets at time $\underline{T}$, when the game ends, must be discounted back to time $\underline{t}=0$ at rate $\underline{r_2}$. Thus present net worth $\underline{P}$ of the whole action is

$$P = \frac{r_1}{r_2} [1 - e^{-r_2 T}] \qquad (3)$$

The present worth of strategy (b) is (by definition) unity. Thus, the question becomes

$$1 - e^{-r_2 T} > \frac{r_2}{r_1} \qquad (4)$$

If the inequality holds, then the doomed strategy yields more.

The criterion is plotted in Figure 2.3. For example, if the "safe" rate of return is 10% per year and the "risky" rate of return in 16% per year, a doomed enterprise lasting 10 years or longer is the better one to invest in.

This simple example makes no attempt to optimize the company strategy: it just points out that a real difference exists in the two cases, and that the company can take advantage of the doomed activity _if_ it can abandon the enterprise without cost. On the other hand, if a social cost of abandonment had somehow to be included, then a charge at time _T_ suitably discounted to $t = 0$ would have to have been figured in at the start, making the doomed strategy less attractive.

We see in this example the difference between the social and commercial discount rates: it is a matter of time horizon differences between the public and private sectors, and the transferred social costs of failure, _NOT_ just a simple risk about profitability.

Central to this example is the presence of a large, stable economy where the operator can safely invest at rate $\underline{r_2}$, and where he can dump his social costs, without the general economy appreciably damaging him in return. But clearly, if a large fraction of economic operators tried to behave this way, the system would falter, or even collapse. The term "Tragedy of the Commons" is often heard respecting such matters. It comes from England in its prosperous sheep-raising days in the seventeenth century, but when pastureland was still public property. A sheep-raiser could then calculate that if he put one more of his sheep in the common pasture, he would reap the benefit of one more sheep, but the loss of pasture for that sheep would be shared by all the farmers, and his share would be a small fraction of it. So each farmer figured, so each acted, so the pastureland was overgrazed and failed for a time in England. Thus arose English enclosure laws, and the phrase comes down to us today. Many environmental issues have this "tragedy of the commons" feature, from grand examples of atmosphere and water pollution to individual ones of why people want exhaust pipes of their cars pointing backward rather than elsewhere. ?

This demonstrated difference between governmental and private sector attitudes toward investment involves also risk of failure in not doing something, as well as in doing it. For instance, the "safe" investment may have been one of several necessary activities that keeps the country going; yet the private sector, seeing less profit in such an operation, eschews the opportunity. The government, applying a similar analysis to the one performed here mutatis mutandis with failure costs included, then finds it not only attractive to pick up the lower return investment, but also necessary.

2.6 An International Strategy to be Aware Of

The material of the previous

section suggests a game that at least could be seriously studied; it may have been (inadvertently?) played. The effect of Mid-East oil on our own economy and on our policies is too obvious to need comment here. Do opportunities exist for playing that game elsewhere, say by the U.S.S.R.? Let us generously grant them a somewhat better state of organization and competence than they probably possess, and proceed.*

It is possible to imagine strategies of two kinds: (1) constructed principally by, and in the interests of, the Western nations; and (2) constructed by and in the interests of the U.S.S.R. Interestingly, it seems possible that the U.S.S.R., while seeming to acquiesce and co-operate in this first kind, actively implements the second.

The strategies are based on the immense U.S.S.R. reserves of fossil fuels, especially gas. Exact numbers are not needed to debate the possibilities. A large fraction of the world's gas resource lies in the West Siberian basin. Of course, it can be argued that more is to be discovered in the U.S.A., in the North Sea, in North Africa, etc. To be sure; but that is not the point: predictions show a long-term dearth of natural gas (in relation to the demand for it) in the U.S. and Europe, despite new discoveries and new incentives. More to the point is the fact that the U.S.A. and Europe are, on the whole, more fully explored than is the U.S.S.R.; thus the U.S.S.R. advantage persists, and the U.S.S.R. possesses a resource not easily depletable in the next several decades by whatever strategy, and coveted by the West.

For petroleum, things are not seemingly so favorable to the U.S.S.R. General reasoning leads one to imagine, however, that the reserves might also be very large: the geologic structures of West Siberia are part of a continuous series of similar ones forming an oil crescent that extends

* This passage was written in 1973 and used for teaching since then, and has some relevance to the 1981-82 controversy about the USSR-Europe gas pipeline.

from North Africa, through the Middle East, Russia, and even as far north as Novaya Zemlya. The difficulty seems to be getting it out, in very inhospitable terrain and climate.

The West-favorable strategy. Actually, the strategy is to the advantage of the U.S.S.R. also, therefore can be argued as viable. It is simple: Western Europe and Japan depend on imported oil, and the U.S.A. imagines that it could benefit from an assured foreign supply. The U.S.S.R.'s petroleum and gas constitute, at least physically, a credible alternative to O.P.E.C. resources. The U.S.S.R., xenophobic as it is, is very unlikely to join O.P.E.C. The U.S.S.R. finds itself falling behind in modern technology, in agriculture, in development of consumer goods, and faces at home a growing popular pressure for more and better things. It fears an increasingly powerful China. The U.S.S.R. appeared to seek détente in the 1970's with the U.S., partly for those very reasons. Suppose, for the sake of argument, that détente reappears. What could be more logical than for Western nations to propose the development of U.S.S.R. petroleum and gas resources, as a credible alternative to O.P.E.C., offering to the U.S.S.R. the opportunity for needed industrial development, etc? To the Western nations and Japan, the strategy appears as an escape from the tyranny of monopoly, in the same sense that having Ford and General Motors competing as suppliers is healthier than having one alone.

The strategy is, of course, already being implemented, albeit indirectly, in the gas sector. Italy and Germany obtain an increasingly large fraction of their gas from the U.S.S.R.

The U.S.S.R.-favorable Strategy. The U.S.S.R. can take much more advantage of the strategy just outlined, particularly in respect to supplying natural gas. Three more topics enter the discussion:

a. Natural gas seems more or less substitutable, but it is not, particularly over the short term.

b. Natural gas could be supplied by the U.S.S.R. to Europe and Japan at a price low enough to capture a large fraction of the energy market, except for hesitation on account of security and danger of cut-off.

c. A sub-strategy exists for the U.S.S.R., in dealing with limited liability financial institutions, to overcome hesitancy about insecure sources, while in fact the U.S.S.R. entraps the institutions, even in the face of knowledge in the target institutions about the danger.

These matters will now be discussed more amply.

A. Substitutability of natural gas. A natural gas distribution system has little inherent storage; unless favorable opportunity can be taken of natural underground reservoirs (e.g. depleted gas fields), providing storage is much more expensive than it is for petroleum. Thus, interruptions tend to be promptly felt.

Natural gas is methane; burning is so easy that very inexpensive equipment can be developed for the purpose. Until natural gas came into short supply, it was used in steam-electric utilities in the South and

Southwest, in very cheap plants. Thus, many installations cannot switch to alternate fuels except by way of lengthy and expensive retrofits. It costs less to switch to light fuel oils (e.g. kerosene) than to switch to heavier oils. But this distribution in costs and opportunities must be amended by the fact that more sophisticated refining capacity is required to produce high-grade light fractions. As a rule of thumb, new refineries take three years to build.

Anent the insubstitutability question, note also that in all-pipeline systems, the customer is wired in, so to speak. Liquid natural gas (LNG) tankers cannot substitute on short notice: the transport is high-cost, thus both tankers and terminals will not be built in large numbers except for already contracted routes. This circumstance stands in sharp contrast to the movement of petroleum, where much of it is accustomed to going to sea, so that a large tanker fleet exists; the cost is low, and the possibility exists to divert and re-route a substantial fraction of the world supply, even on short notice.

The short-term insubstitutability becomes even more evident when one considers the uses to which natural gas is put: home heating, urban use, plastics and petrochemical industries, etc. Either the installations are rudimentary and have no substitutability built in; or environmental circumstances preclude the use of other fuels; or the material itself is needed for feedstock; or a combination of these restrictions applies.

It is not possible without more analysis to predict how difficult it is to shift from natural gas to other fuels in any given time. Certainly, several years would be needed for an orderly transition; thus, the potential exists for substantial mischief by the U.S.S.R. See below.

B. Low-priced gas. An assumption essential to the analysis is that the U.S.S.R. would be willing to provide gas at the boundaries of its empire at a price low enough to implement its plans. Just how low this might be will become more apparent soon.

C. Entrapment economies. The strategy to be described depends essentially on there being available a spread of risks and corresponding returns on investment, and more precisely on a difference between "safe" and "risky" rates of return, in the sense of the previous section. Refer again to Figure 3, showing the safe and risky rates of return and the calculated investment times.

The U.S.S.R. strategy is then as follows. It determines the prevailing safe rate ($\underline{r_2}$) in the target countries; then it finds from the figure (more realistically, from more complicated calculations) a "risky" rate $\underline{r_1}$ and investment time $\underline{T}$, on which to make an offer of gas to the target countries. (Thus, for example, suppose the prevailing safe rate was 14% per year. Then the U.S.S.R. could decide on a 10-year guarantee of gas at a price calculated to give the target countries a return equal to or greater than 18.7%.)

Having done this internal calculation, the U.S.S.R. now stimulates the target countries to see a long-term supply that (they calculate themselves) will yield very attractive return on investment r_1 (>18.7% in the example above). After some negotiation, the U.S.S.R. makes real and believable commitments to supply the gas, up to the time T (10 years in the example above). In fact, the U.S.S.R. will actually supply the gas.

Companies in the target country, having no penalty costs exceeding their capitalization, opt for the strategy if the guaranteed performance persists for a time _T_ or greater, and ignore the consequences. Note in the figure, the higher are the expected rates of return, the quicker and easier is the U.S.S.R. strategy to implement.

Thus the bait is taken, and after the interval of years _T_, the U.S.S.R. has one more weapon at its disposal with which it can achieve some degree of hegemony over its neighbors. It can raise prices, cut off the flow, impose conditions, etc., all to the discomfort of its victims.

Of course, the actual chain of events will be more complex; the market grows with time, strategies are more numerous and so forth. The U.S.S.R. itself becomes dependent on the investment transfers from the West, which may contribute to a more stable and unified world after all. But a basic advantage rests with the U.S.S.R., by virtue of its having an extra degree of freedom: plentiful natural gas and flexible time horizons.

It can be argued that private companies would not behave that way, but the evidence is not compelling. Certainly the company must have (or believe it has) a "safe" investment place, which its own actions do not destroy. Such a place could exist (in the company's imagination) in a number of ways: (1) the U.S.S.R. wouldn't spring traps--note that the real calculations would be much more complex, considerable lead-time would be required by either country to calculate the strategy really well, and the U.S.S.R. has an advantage of several year's work on the problem; (2) the government "wouldn't let it happen"; or (3) there are other investment opportunities elsewhere--a particularly attractive thought to a multinational company whose home base is not in the target country.

Regarding whether governments would permit the events imagined here to happen: (1) Can the government resist pressure from the private sector sufficiently well? (Note that a more business-oriented government is more vulnerable than other kinds); (2) Does the government see the long-range threat in its true light, and take action in time to develop alternate fuel sources?--To do this, it must undertake activities whose expected rates of return (or equivalently, present discounted net worth) were by definition unattractive to the private sector.

Perhaps these events will remain hypothetical; but to repeat the question posed at the start of this section: was it already inadvertently played by the Arabian O.P.E.C. states vs O.E.C.D.?

2.7 Short, Intermediate and Long Terms: Resolving Fuzzy Thinking

Those three convenient terms -- short, intermediate, long -- educate us about the time perspectives of people who use those terms; but they may not relate rationally to the characteristic times that we have found in previous sections. Even worse, those times and the strategies to meet them sometimes become thought of separately, as if each existed in isolation of the others. One does not wake up some future morning to discover that the short term is over, and the utopia of the long term has arrived. To put the matter another way, a strategy valid in the short terms may preclude achieving what we want in the long term, and vice versa.

The resolution of this difficulty is to rephrase the topic, by asking: beyond what termination date do we cease to care (at present) about the civilization, or do we wish to believe that we need not worry because something new will have turned up to save us? Having chosen a terminal date - which itself is a salutory exercise and forces the civilization to inspect its own intentions - the civilization can then inspect its present activities and plan future ones at best it can to achieve its goals. This very different interpretation draws prompt attention to the fact that no civilization throughout history consciously planned for its own end. Terminations came by accident, conquest, or patterns of paradox woven into their own makeup. Even if societies and civilizations planned to be ephemeral - as the present one does, de facto - only a schizophrenic one would imagine that it had several terminal dates.

Some will aver that this criticism is mere semantics - of course the planners had the long term in mind, that we need a multiplicity of strategies, and so forth. Even so, the harm is done, because failure to ask the question properly invites ill-considered ventures.

Faced with limited resources, the logical strategy aims toward long-term sustainability, and shorter-term goals appear in their proper light as tactics which, if successful, make the long view possible. Whether the strategy and tactics suffice to meet the challenge then becomes the appropriate topic to explore.

This line of thought leads directly to such questions as - sustainability for whom? Here again history becomes a useful guide, for almost no civilization has sustained itself very long by adopting principles of social injustice. Finally, we arrive at what seems to be the proper social goal on which to base energy policy — a more just and sustainable society, embracing of necessity and *ex hypothesi* all the participants.

Searching for the route to a just and sustainable society again leads to consider several time perspectives, but now they differ both qualitatively and quantitatively from what has gone before.

1. Options for a Short Time Only - A Nonsustainable Society

At the meagerly short end, for example 25 years (but still sufficiently longer than appears in most U.S. energy plans), redistribution of present petroleum supplies and intensified use of natural gas and coal would suffice. Neither nuclear nor solar energy nor any other major option need be developed, although some may be desirable. Energy conservation, rational utilization and increased efficiency would be relatively unimportant. For energy, at least, our society could last 25 years in the face of almost any combination of circumstances.

The trouble with this view is that disaster impends in the 26th year, so to speak. No preparations will have been made for what to do when oil and gas run out; different groups will fight over the remaining scraps. Despite the dismal prospect, normal economic perspectives often restrict thought and action to even shorter periods. At this moment, we live in the future of 25 years ago, when today's energy problems were predicted, but beyond the horizon of action.

2. Options for a Longer But Still Insufficient Time

Suppose now 50 years; issues and actions will be quite different. It is not just a question of making a 50-car train out of a 25-car train by merely adding 25 extra cars. The train itself must be different.

World-wide, petroleum and natural gas will be substantially depleted in most places unless other options have meanwhile been introduced; coal assumes a more important role, bringing a multiplicity of problems and also temporary opportunities. The nuclear debate will surely have been resolved on some basis; but for this termination it is still not absolutely essential. The carbon dioxide level in the atmosphere has not yet caused substantial climate change, but the large fossil fuel technological infrastructure almost guarantees that the changes will occur. All fossil fuels would eventually run out: although the U.S.A. has 1,000 years' supply of mineable coal at present rate of use, a 2%/year energy growth based on coal would exhaust the resource in 100 years. Truly sustainable energy sources - solar, fission, maybe fusion - will not have been properly perceived let alone developed. Civilization will not collapse in the 51st year, but it will have been sorely wounded, open to disintegration by rot from within or challenges from without.

A Real Sustainable Future

Now suppose a 100 year (or preferably longer) view. Petroleum and natural gas will make a small contribution, averaged through the period. Continued principal dependence on any fossil fuel brings so many difficulties in its train that coal appears better as a raw chemical resource for present and later ages. More rational energy utilization, increased efficiency, and other energy-minimizing strategies will dominate the scene. On the supply side, the three long-term world-wide options appear: solar power, nuclear fission, maybe nuclear fusion. These can and should be augmented by attractive regional energy sources, whose importance will vary with time: geothermal power (in tectonically active areas), wind power and biomass in limited but valuable amounts and so forth.

This time perspective also requires some early decisions and a conscious beginning; otherwise one of the shorter-time scenarios comes by default. On the one hand, oil, gas and coal -- bridges to the future, as they are sometimes called -- cannot be saved to serve their essential bridgely functions unless the main supply alternatives are available soon. But all three have peculiar problems. Controlled fusion is scientifically and technologically very complex, may be late, and might not even be eventually attractive. Solar power will have large low- and intermediate-technology uses of great value (direct solar heating and cooling of more rationally-designed buildings, for example); in bulk it appears presently difficult and expensive, but cheaper later. Nuclear power, if it is to have long-term prospects, must be cured of several ills real and imagined, extending from uranium resources through cost and safety to proliferation of nuclear weapons, and more, as discussed at length in chapter 7.

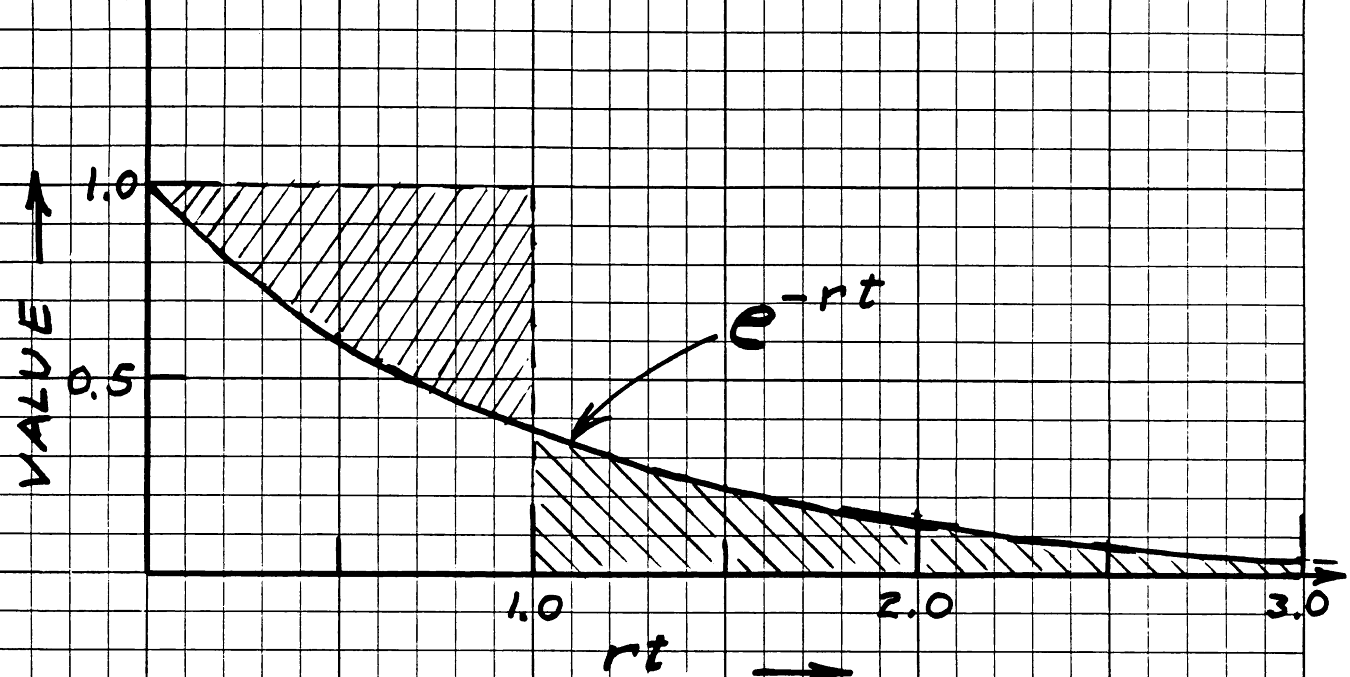


Figure 2-1 Curve of e^{-rt}, illustrating present value. The two areas are equal.

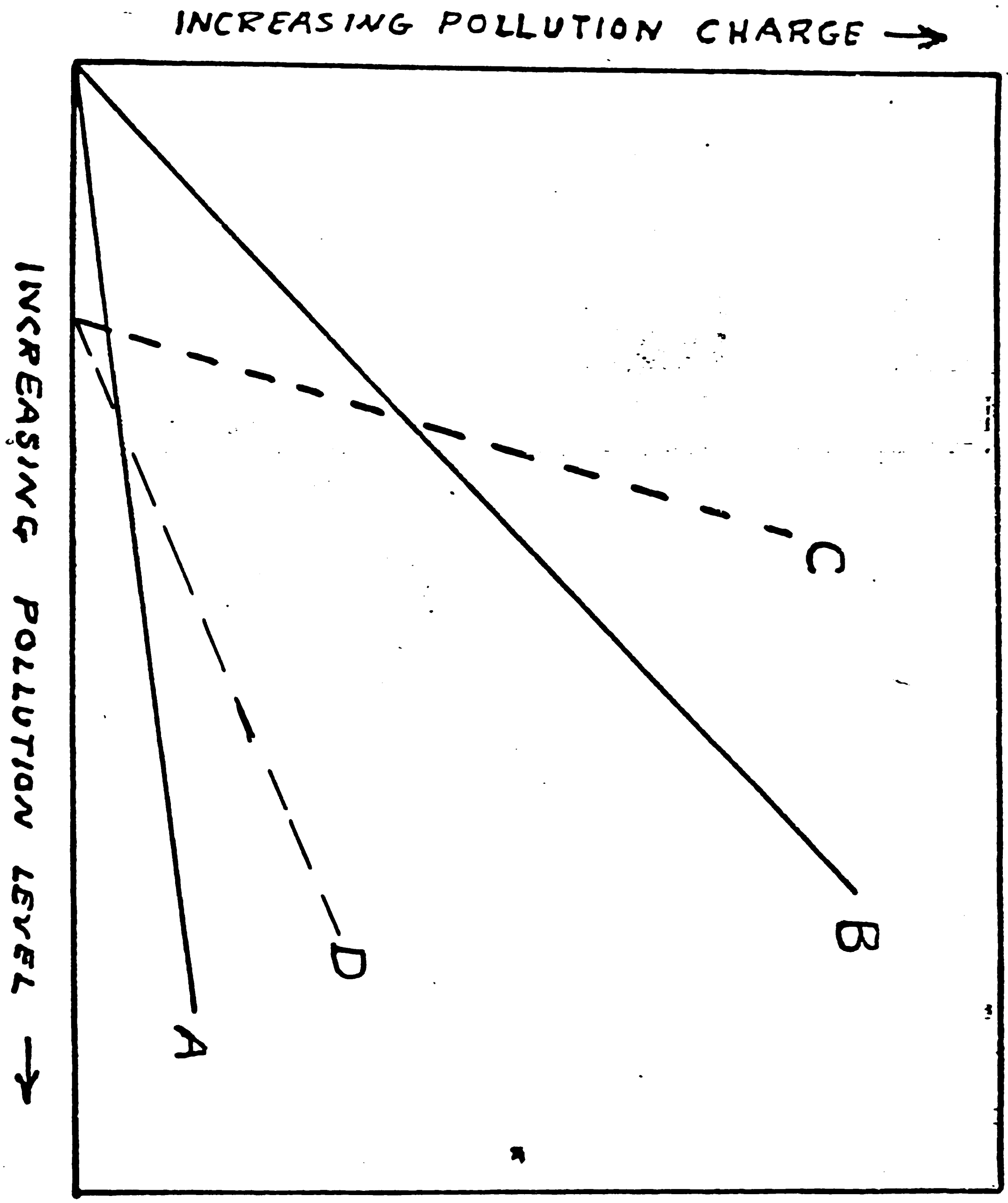


FIGURE 2-2. SEVERAL POSSIBLE STRATEGIES FOR POLLUTION TAXES

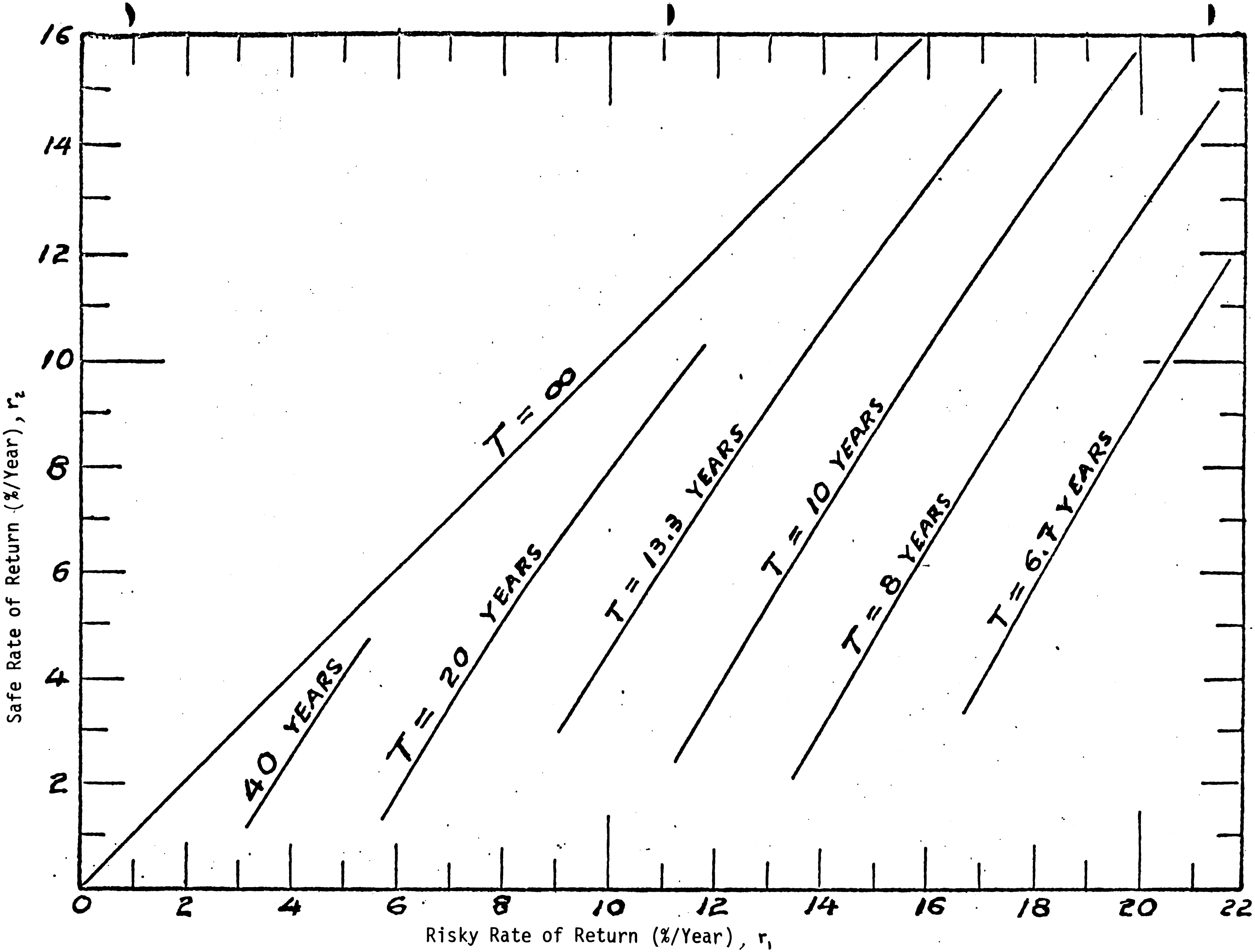


Figure 2-3 TIME T THAT A "RISKY" INVESTMENT MUST LAST, TO BE AS ATTRACTIVE AS A "SAFE" ONE.
(See text for details.)

Table 2.1 DISCRETE COMPOUNDING INTEREST FACTORS

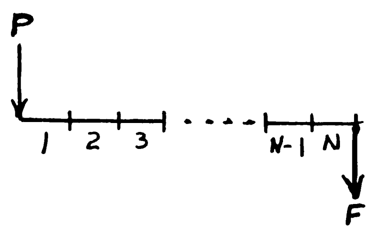
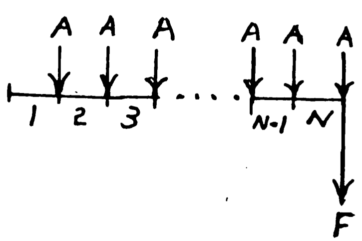
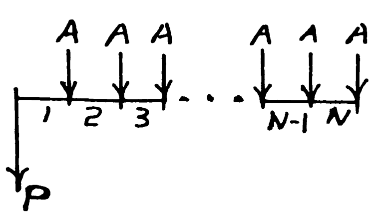
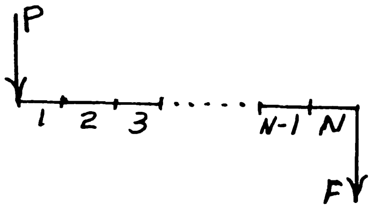
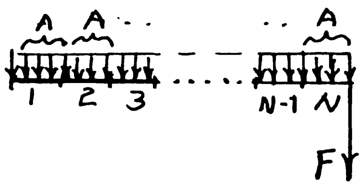
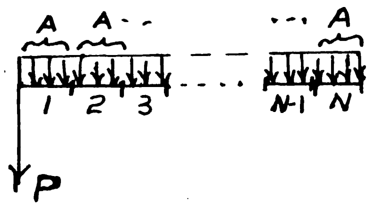
Cash Flow Diagram	Given	To Find	Factor Name	Factor	Factor Symbol
	P	F	Compound Amount Factor	$(1 + i)^N$	$(F/P, i\%, N)$
	F	P	Present Worth Factor	$\dfrac{1}{(1 + i)^N}$	$(P/F, i\%, N)$
	A	F	Compound Amount Factor --Uniform Series	$\dfrac{(1 + i)^N - 1}{i}$	$(F/A, i\%, N)$
	F	A	Sinking Fund Factor	$\dfrac{i}{(1 + i)^N - 1}$	$(A/F, i\%, N)$
	A	P	Present Worth Factor --Uniform Series	$\dfrac{(1 + i)^N - 1}{i(1 + i)^N}$	$(P/A, i\%, N)$
	P	A	Capital Recovery Factor	$\dfrac{i(1 + i)^N}{(1 + i)^N - 1}$	$(A/P, i\%, N)$

Table 2.2 CONTINUOUS COMPOUNDING INTEREST FACTORS

Cash Flow Diagram	Given	To Find	Factor Name	Factor	Factor Symbol
	P	F	Compound Amount Factor	e^{rN}	$(F/P, r\%, N)$
	F	P	Present Worth Factor	e^{-rN}	$(P/F, r\%, N)$
	A	F	Compound Amount Factor --Uniform Series	$\dfrac{e^{rN} - 1}{e^{r} - 1}$	$(F/A, r\%, N)$
	F	A	Sinking Fund Factor	$\dfrac{e^{r} - 1}{e^{rN} - 1}$	$(A/F, r\%, N)$
	A	P	Present Worth Factor --Uniform Series	$\dfrac{e^{rN} - 1}{e^{rN}(e^{r} - 1)}$	$(P/A, r\%, N)$
	P	A	Capital Recovery Factor	$\dfrac{e^{rN}(e^{r} - 1)}{e^{rN} - 1}$	$(A/P, r\%, N)$

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Gnomon

CHAPTER 3

LARGE ENVIRONMENTAL EFFECTS: ACID DEPOSITION AND GLOBAL CARBON DIOXIDE

3.1 INTRODUCTION

As shown in Chapters 1 and 2, environmental effects accompany both energy provision and use, and hence play a role in energy decisions. Unintended environmental consequences tend to be harmful, partly because benefits can be made profitable, hence institutional and intentional. Therefore, most environmental effects to be described in this book are harmful. Some are local and/or quite mode-specific, for example nuclear waste or coal-mine dust, and many such topics appear in later chapters that deal with more specific energy sources or uses.

On the other hand, some environmental effects involve very broad classes of fuels, uses and regions, good examples of the "commons" problems mentioned in Chapter 2. Among those, two major ones stand out, can usefully be considered together and prepare the reader to approach other broad tasks of environmental degradation. Both acid deposition (more often called "acid rain," despite some of its precipitating in other ways) and the probable climatic disturbances caused by carbon dioxide buildup are atmospheric phenomena which involve burning fossil fuel; but those similarities yield precedence to a more profound common set: much future trouble, but mainly delayed beyond the time horizon of most economic or political analyses; no large public sector affected early--indeed, few early obvious effects at all, though fairly clear and early evidence herald their coming; non-local, even international in scope; expensive enough to ameliorate so that strong incentives arise to delay or even suppress serious consideration.

Of the two, acid deposition is far simpler and better understood--less widespread, less delayed in effect, easier to detect, diagnose and cure. Regarding such phenomena and the onset of ameliorative action, one can usefully define a response lag as the time between possession of enough knowledge to permit counteraction and the start of the counteraction itself. For acid deposition, the response lag exceeds a decade at the present time. In every respect, the CO_2 problem will be worse--harder to understand, involving disparate groups, some winners among the losers, much more expensive to ameliorate and so forth. How much greater might the response lag be in that case?

Thus acid deposition, important in itself, serves also as an introduction to the complexities of global CO_2.

In most energy books, descriptions of technologies of provision precede descriptions of environmental and social consequences. But consideration of the latter two should moderate our attitude toward provision and use. Hence the present order of things; Figure 1-12 and its description set the stage for it. Reading this chapter ahead of the others (especially the coal chapter) should be a minor inconvenience, because the energy-specific details are kept to a minimum.

3.2 ACID DEPOSITION: SIMPLE CALCULATIONS AND EVIDENCE

Acid deposition arises principally from rainout or dry deposition of simple transformation products of sulfur and nitrogen oxides that came from burning fossil fuels. Its effects depend on how the winds blow, the capacity of soil, rocks and plants to resist the acidity, and hence are hard to calculate in detail. The National Research Council (1983) and others have published recent authoritative accounts, especially of the U.S.-Canada situation. Despite the complexities, some main effects can be calculated semi-quantitatively quite easily; furthermore, evidence pertaining to acid deposition has been available for many years; the phenomenon has received fashionable (but often fickle and fitful) public notice; corrective technological options are well known and available. Yet amelioration comes late in time and perhaps even not yet, often grudgingly, and is sometimes opposed on grounds that exhibit very selective inattention. Thus, acid deposition is worth studying, not only for its environmental damage, but also as an example of how society responds to such challenges.

3.2.1. Calculating the Acidity Approximately: A Problem for the Classroom

As the National Research Council book points out, the largest source of acid deposition in the U.S. and Canada is sulfur oxides. Figure 3.1, from that source, shows these SO_2 emissions; most of it comes from sources in the eastern part, principally from the Northeast, and most of it comes from burning coal; in this connection, see Chapter 6. Roughly speaking, the region is bounded by northern Alabama on the south, southern Canada (principally the province of Ontario) on the north, a line a little west of the Mississippi River, and the Atlantic Ocean. The region is about 1500 km on a side, 2.3×10^6 km^2. In it, almost 500×10^6 tons of coal were burned per year in the late 1970s, with an average sulfur content of about 2.0%. Ore-smelting and other operations brought the total SO_2 emission in that region close to 18 million tons. The prevailing winds blow from west to east, about 750 km per day, and on the average these combustion products reside in the atmosphere about five days before being rained out. The rainfall is about 1 m/yr. What is the average acidity of the rain? This is a good undergraduate class problem.

We need a little more information, and can afford to be carefully cavalier in deriving an approximate answer. Much of the SO_2 will be converted to SO_3 in the air, often aided by adsorption on fine particulates which make reasonably good catalytic surfaces, and by water vapor. Thus, the SO_2 tends to convert to sulfuric acid (H_2SO_4) the same way as it is made commercially; much of it combines with alkaline particulates present in the air. Assume that half the acidity so disappears. Also, the two-day travel time across the region and the five-day rain-out time imply that 60% of it drifted off the East Coast (to seek a fate to be mentioned in a later section). Not all of it waits for rain, but about 30% falls out by dry deposition. This contributes substantially to acidity at ground level, and affects things on and near the ground, but we will not include this complication.

We can now proceed. The annual average sulfur production over the area is 4.0×10^{-3} kg/m^2, and 20% of it (one-half of 40%) is effectively H_2SO_4 rained out in the area itself. It is dissolved in 1 m^3 of water, doubly ionized, i.e., $H_2SO_4 \rightarrow 2H^+ + SO_4^{--}$. Thus we find a molar density $[H^+]$ of hydrogen ions in the water of 4.9×10^{-5} mol/liter. Nitrogen oxides from both vehicles and power plants add an additional 30% approximately, bringing our total now to 6.4×10^{-5} mol/liter. The conventional measure of acidity or alkalinity being the quantity

$$pH = -\log [H^+],$$

we finally get the answer of pH = 4.2. The pH of pure water is 7.0, and of rainwater saturated with atmospheric CO_2 is about 5.6. A pH of 4.2 corresponds to 25 times the acidity of CO_2-saturated rainwater. While we cannot expect this average number to be very accurate, derived with assumptions which are individually inaccurate by as much as a factor of two (but some of the errors tend to cancel), it should give an idea of what to expect.

3.2.2. Checking the Answer

Now inspect Figure 3.2, taken also from the NRC report. The range of pH values and the geographic distribution correspond fairly well with our simple calculation. What goes up must come down. While more authoritative and better-documented than before, these results are not new; nor have they been hidden from public view. Likens et al (1979) in Scientific American published acidity contours similar in both amount and extent, and showed how the acidity had increased between the mid-1950s and mid-1970s.

With this in mind, what are we to make of such articles as "Tracking the Clues to Acid Rain" in the EPRI Journal (1979), published at the same time as the article in Scientific American; the EPRI Journal article states that:

> The idea has been publicized that fossil fuel combustion is the main source of the sulfates and nitrates that can produce

> acid rain. Acid rain has been given as the primary reason for acidification of surface waters, for decline in fish populations, and for decreasing forest productivity.
>
> The data on acid rain effects that were collected over the past two decades have validity, but the conclusions drawn from them are highly inferential. Too few avenues of the acidity network were traveled; too few scientific disciplines were included in tracking the facts.

This is the closest the EPRI author comes to identifying any source at all for the rain. It is a mystery, the article says; a program is underway to measure pathways by which acidity travels from rainwater to streams, to this or that kind of lake, and so on.

To emphasize both the existence of public knowledge and the value of school projects, Figure 3.3 shows results obtained by 16,000 high school students in the spring of 1974; details differ but the general trend is the same.

Some industrial concern is much stronger. Ember (1981) published an excellent summary of the situation, disagreeing with the EPRI views, supporting the NRC position and the one offered here.

Let us examine the matter further.

3.2.3. Further U.S.-Canada Facts

The acidity of rain in the Eastern U.S. has increased by a factor of about two or three since the mid-1950s, when reliable data began to be kept. This increase does not arise so much from the burning of more coal (up to the late 1970s) or an increase in its sulfur content, but probably mainly from the installation of tall smokestacks, in order to comply with local air quality regulations in the vicinity of the plant, for example an SO_2 limit of 80 $\mu g/m^3$, but no limit on acid sulfates.

While reducing local deposition or rainout, the tall stacks very substantially increased the regional and distant downwind concentration, and moreover of SO_3 and eventually acid sulfates themselves. Some of the increase can also be ascribed to increases in NO_x emissions, both from many kinds of industrial plants and from automobiles.

Here are more relevant observations regarding the acid precipitation problem in eastern North America.

o The Federal Aviation Administration reported 178 stacks whose height exceeded 550 feet built between 1970 and 1978, and few before that.

o The pre-1970 power plants, operating under special regulations, do not need to meet the new source performance standards of 1.2 lb $SO_2/10^6$ BTU; many of those plants will remain operating into the 1990s.

o Enforcement is largely up to individual states; some selectively ignore the problem. By far the largest and least cooperative polluter in the U.S. in the 1980 era was the state of Ohio (see Figure 3.1). Several of its large power plants in the Cleveland area have been granted relief from meeting emission standards partly by having the area declared non-urban. The Reagan Administration proposed in mid-1981 to turn back more control to the states.

o The various states now complain against each other. About 80% of acid precipitation in Massachusetts in 1980 came from outside the state, and about 30% comes from Ohio alone. The state of Pennsylvania has sued power companies in West Virginia for permitting excess sulfur oxides to enter Pennsylvania.

o In general, fish cannot survive in water more acid than pH 5.0, and in the Northeastern U.S., only perch survive at that level. In the Adirondack Mountains, about 300 lakes have fish no longer, and a much larger number of lakes in Canada are similarly affected. Many of the lakes in this Northeast region have little limestone or other buffering minerals in their vicinity (especially in Canada).

o The public press and also some popular scientific sources have picked up the theme, though late in time. A four-part series in the Boston Globe (Dumanoski 1979) is a good example.

3.2.4. Some European Observations

Acid deposition is not a just-discovered phenomenon in Europe either. At its contribution to the 1972 U.N. Conference on the Environment, held in Stockholm, Sweden, the Swedish government prepared and distributed in 1970-1971 its own report on the presence, effects of, and sources of acid rain in Sweden (Bolin 1972). Acidity comparable to that measured in the U.S. appeared in southern Scandanavia, especially on the western rainy sides of mountains. The acidity appeared to be carried by acid sulfates (and not SO_2). Fish populations had declined, Scandanavian pine trees grew about 15% more slowly, and metal test-pieces exposed to the weather showed corrosion corresponding roughly to the acidity of the rain. During the period 1950 to 1976, sulfur oxide emissions in Europe excluding the U.S.S.R. approximately doubled; tall stacks installed in English, French and German industrial regions apparently had contributed to the increase in far-downstream acid sulfates. While ameliorating the English condition, the tall stacks aggravated the Swedish one, downwind and across the North Sea.

Effects of acid deposition appeared outside Scandinavia, from various causes. Exterior carvings of marble and even sandstone in Paris show recent deterioration, as recorded by photographs taken during several decades. In Athens, the Parthenon and other marble structures erode, mainly because of NO_x from automobile exhausts. In contrast, in Persepolis in Iran, marble chips left on the ground by stone masons 2500 years ago appear as if cut yesterday.

3.3 MORE CONFIRMATION AND COMPLICATIONS

The effect of acid deposition on ecosystems depends on whether the soil and rocks are buffered by limestone, whether vegetation tends to thrive in naturally acidic soils (e.g., oaks and some conifers) and so forth. A NATO conference on this broad topic, held in Toronto, dealt with these phenomena in considerable depth (Hutchison and Hovas 1980).

Much has been written about the effect of SO_2 and acid sulfate on human health. Epidemiological data are hard to obtain and still uncertain; a short summary appears at the end of the chapter on coal. Despite large uncertainties, a consensus exists that these health effects are the largest of all associated with energy provision.*

Data obtained in the late 1970s and early 1980s hint that acid deposition may be even more widespread than hitherto suspected.

It has become fairly clear that tiny particulates from industrial regions in the northern hemisphere form a pervasive haze over much of the Arctic region during winter and spring (Kerr 1981). The particulates swirl at least 5000 km, from west to east counter-clockwise, and have been often observed at northern Alaska, at the Canadian Arctic Islands, and in satellite photographs. Do the sulfur oxides go that way, too? Acid rain has been detected at Hawaii and some other remote sites, but in a pattern which still defies understanding; some may arise from natural sources; the matter is still uncertain. But the largest difficulties lie not so much with the basic facts, incomplete though they are, than with economic pressures and social and political responses. Wetstone (1980) and Maclure (1983) give excellent accounts. See also Nanda (1983) and CONAES (1980). Some material from those sources is used here.

Regarding the economic and technological implications, consider this:

o Increasing the pH of rain from 4.2 to 5.2 (i.e., reducing its present acidity in many places to a value compatible with fish surviving for the long term, and much less damage to natural and manufactured systems) would require the acidity to be reduced by a factor of 10.

o Plans are afoot to double the use of coal.

o The present (1980) source performance standards will, when and if fully implemented, reduce the total SO_2 emissions per unit of energy to not less than one-third the uncontrolled emissions.

o 30-40% of the acidity comes from NO_x.

The implications are clear: ameliorating the environmental and other damages would require that the sulfur emission be reduced by a factor between 5 and 10 below the NSPS--that is, to somewhere between .12 and .24 lb $SO_2/10^6$ BTU, and much stricter control of vehicular NO_x emissions. Such reductions are not impossible, but would involve many things, for example coal washing (customary in Pennsylvania in 1980, but not in Ohio), fluidized bed combustors and/or coal gasification with stringent sulfur removal, electrified transport (including electric cars for short trips, etc.). The cost would be high. Many rough calculations like this have doubtless been made, by government, private industries and public interest groups, and the difficulties attendant on implementing any such large cleanup have been apparent to all.

These difficulties are reflected in the attitudes of the various participants in acid rain debates and decisions.

no ¶ Consider the U.S.-Canada problem. In the early 1970s, the importance of acid sulfates and similar pollutants carried over large distances received little attention from either of the federal governments; some who tried to excite federal response were ignored.*

However, concern in some U.S. Federal agencies had been growing during the early 1970s, but this was not matched by Canadian Federal interest. In contrast to the U.S., in Canada environmental regulations had been the prerogative of the provinces, and the federal role consisted of advice, guidance, some incentives, plus presumable adherance to international treaties. Each province seemed to have little incentive to support the establishment of federal standards, let alone international ones.

At Nanticoke, Ontario (on Lake Erie), is the largest coal-fired power plant in the free world; the International Nickel Company smelter in Sudbury, Ontario, had been the largest source of SO_2 pollution in the northern hemisphere; it appears in Figure 3.1, above Lake Huron. Non-ferrous smelting accounted for about 45% of Canada's sulfur emissions in the late 1970s, but electric power plants may be dominant in the future.

The Canadians until recently opted for tall stacks. In the late 1970s however, changes began in Canada, as a result of a combination of Federal pressure, realization that most of the endangered lakes were in Canada (and many in Ontario), realization that four times as much acid precipitation went from the U.S. to Canada as vice versa, plus a general increase in environmental awareness. Plans are afoot to reduce the Sudbury, Ontario, sulfur emissions by a factor of about two during the early 1980s, and the large coal-burning power plants receive attention also.

Thus, during 1979 and 1980, it appeared that the U.S. and Canada would agree on serious joint studies presumably anticipatory to formal agreements to start vigorous joint action. But in 1981 the situation partly reversed; the Reagan Administration gave little attention to the matter and seemed unconcerned about either the problem itself or the Canadian views.

In Europe and elsewhere, agreement is not much closer, despite vigorous calls for action, especially in Norway and Sweden. The U.N. Economic Commission for Europe (ECE, an association of 35 nations including the U.S.S.R., the U.S. and Canada, not to be confused with the European Economic Commission, or "Common Market") signed a convention on Long-Range Transboundary Air Pollution (ECE 1979) whose content shows both the hopes and the difficulties. It emphasizes pollution by sulfur oxides and their transformation products; the director of the ECE's Environment and Human Settlements Division summarizes some of its features in these words (Bishop 1980):

-- The Convention is the first legal instrument which directly applies, on a broad regional basis, Principle 21 of the Declaration of the Stockholm Conference; this principle expresses the common conviction that states have, inter alia, "the responsibility to ensure that activities within their own jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limit of national jurisdiction."

-- Despite its title, the scope of the Convention has a somewhat broader connotation; it addresses itself throughout to problems of "air pollution, including long-range transboundary air pollution."

-- The Convention legally binds the contracting parties to "endeavour to limit and, as far as possible, gradually reduce and prevent, air pollution, including long-range transboundary air pollution."

-- In this connection, each Contracting Party "undertakes to develop the best policies and strategies including air quality management systems and, as part of them, control measures compatible with balanced development, in particular by using the best available technology which is economically feasible."

-- Pending ratification of the Convention,* the Signatory States have (through adoption of the accompanying resolution) formally taken an unusual and far-reaching decision. Specifically, they decided to initiate, "as soon as possible and on an interim basis," the provisional implementation of the Convention and to carry out the obligations arising therefrom to the maximum extent possible, pending its entry into force. In this respect they will seek, inter alia, "to bring together their policies and strategies for combatting air pollution including long-range transboundary air pollution."

The ECE looks upon this Convention as an important advance in the development of both international law and in the development of effective institutions. The Convention recognizes the pollution problems, describes avenues of cooperation in monitoring and research, but sets no standards, obligates no one to any abatement policy, has no mechanism for enforcement of any future regulations, and delineates no responsibility for compensatory damages. Progress comes slowly with so many disparate groups. Regarding real transnational claims for real redress of perceived real damage, recourse can be had to the International Court of Justice; but the Court is permitted to rule on a case only after all involved nations have consented to the action.

One of the most important things that can be strained out of this discussion is the response lag, mentioned in the introduction to this chapter. The lag will vary, depending on the nature of the effect, how remote in space or time the consequences seem likely to appear, how many disparate groups need to be co-opted, and so forth. The acid precipitation problem is complex in this respect--many states, several nations, different economic interests, different groups receiving the benefits from those paying the costs, and so forth. Yet it is simple compared to other large international environmental problems; the countries involved are environmentally and technologically similar; the data are substantial; the strategies toward amelioration can be pretty well defined.

What is the response lag in this case? In 1982 it exceeded a decade, and it increases almost one year per year. This augurs ill for getting timely attention for a yet more complex and subtle problem of the same sort--buildup of atmospheric CO_2, the inaccurately but conventionally named global greenhouse effect.

3.4 INCREASING GLOBAL CO_2: INTRODUCTION

About the year 1970, some environmentalists became fond of asking whether heat from burning fossil fuels or from nuclear power plants would warm the earth appreciably. Simple calculations made then (and earlier) showed that while 10 TW of global energy generation would cause observable local effects in cities and some rivers, it was too small by a factor of at least 200 to cause the larger changes. But the exercise re-focused attention on something else: the earth intercepts 170,000 TW of sunlight, and small changes in the reflective, absorptive or re-radiative optical properties of land, sea or air could change terrestrial conditions much more than 10 TW of simple heat ever could, with great global consequences.

Carbon dioxide, water vapor and many man-made gases--fluorocarbons ("Freon," etc.) for example--all raise the temperature in this way. While almost transparent to incoming visible solar radiation, 0.4-0.7 μm wavelength, they are relatively opaque to outgoing infared radiation, 10-20 μm. These gases in the atmosphere trap the heat near the surface and in the lower atmosphere, so the temperature there rises to a new equilibrium, where re-radiation seeping out through the top of the atmosphere again comes into balance with the unimpeded incoming solar flux.

This phenomenon, commonly but imprecisely called the global greenhouse effect,* can be understood with the aid of Figures 3.4a and 3.4b, figures which will find important application here, in Chapter 4 (on solar houses), and Chapter 8 (on solar power). To the right (Figure 3.4b) is the solar spectrum, power per unit of photon energy. Blue-violet is at about 3 eV (0.4 μm) and ultra-violet beyond that. Red is at 1.8 eV (0.7 μm) and all to the left is infared. The incident solar flux at the top of the atmosphere has a spectrum close to that of a black body at 5700°K; its total is 172,500 TW, about 17,000 times the power produced, used and wasted by all the world's people. The cross-section of the earth facing the sun is $\Pi R_E^2 = 127 \times 10^6 \text{ km}^2$, where R_E = 6350 km is the earth's radius, so the incident flux at the top of the atmosphere is about 1360 W/m^2, a number which varies a few percent because of the earth's slightly elliptic orbit around the sun and because of small, mostly periodic variations in solar activity. Some is scattered back into space or absorbed, chiefly by water vapor or CO_2 as it descends through the atmosphere; about 1 kW/m^2 reaches the surface from an overhead sun on a cloudless day, as shown in the figure.

The earth loses this thermal input by re-radiating it in the far infrared, details of which are shown in Figure 3.4a on the left (the two parts of Figure 3.4 are plotted to different scales to show the phenomena most clearly). Note the substantial reduction in emission from the earth on account of various absorptions in the spectral regions shown, and especially the large effect of CO_2.

It is easy to calculate what the average global temperature would be if its visible and infrared reflective and radiative properties were the same. The total surface area of the earth is $4\Pi R_E^2$, four times the cross-section facing the sun. Thus, at mid-latitudes, we could write

output power (= 250 W/m^2) = σT^4

where = 5.67×10^{-8} $W/(m^2)(°K^4)$ is the Stefan-Boltzmann constant relating radiated power and temperature. Thus we would find in this approximation T = 257°K or -15°C (a more sophisticated calculation would give about 252°K). The actual temperature is higher, about 285°K, because water vapor and--especially--CO_2 absorb radiation strongly in the wavelength region of 10 μm and above, and so arises the topic of the next several sections. Carbon dioxide is the principal anthropogenic contributor, hence the principal prospective cause of change. The fact that this CO_2 is associated with combustion heat is incidental; if so much CO_2 had come from volcanoes or by desorption from the vast amount dissolved in the oceans, the effect would have been the same.

The possibility that carbon dioxide--hence fossil fuel burning--might in this way cause appreciable global temperature rise was first suggested more than a century ago (Tyndall 1861), and in 1896 the Swedish chemist Arrhenius included in his analysis most of the important complex phenomena to be described in these sections (Arrhenius 1896). Callendar (1938) proposed a two-degree global temperature rise for a doubling of atmospheric CO_2--a prediction remarkably close to present estimates; but extensive attention began more recently, for example with monitoring of atmospheric CO_2. Figure 3.5 shows the increase between 1958 and 1982 as measured at Hawaii; data from northern Alaska, the South Pole and elsewhere agree in all essential respects. The annual cyclic dips come from photosynthetic absorption during each growing season in the land-dominated northern hemisphere. As with acid rain, here is a history of ignored analyses and data, an issue to be exhumed later.

The CO_2 concentration rose from its pre-industrial level of about 290 parts per million by volume (ppmv) to about 340 ppmv in 1982, and now increases at about 1.3 ppmv annually on the average, corresponding to 2.8×10^9 tons (2.8 Gigatons or GT in what follows) per year of carbon. The 1980 rate of CO_2 release from fossil fuel burning was about 20 $\pm$ GT/yr, corresponding to 5.5 GT/yr of carbon.

Calculating the physical consequences of this atmospheric buildup and the prospects for their amelioration is very difficult, and can be divided roughly into four major parts:

1. The CO_2 cycle itself, including transport into and out of biomass and upper and deeper ocean layers, all of them with characteristic response times.

2. The climatic consequences of the CO_2 buildup, a problem intensively studied since the mid-1970s, using climate models which require not only many data, but large computers. These many climatic effects also have their own characteristic times, and react back on the CO_2 cycle itself.

3. The possible social, economic and technological response to anticipated climate changes.

4. Institutional and cultural issues, such as whether the problem gets timely attention, or whether prospective winners and losers can agree on what to do. The acid rain sections of this chapter showed the importance of such issues.

Much has been written on all this. Besides the natural-science aspects of climate determination and associated environmental consequences, some of which will be mentioned later, a substantial literature has developed on societal impacts and responses (McDuffie 1981). Particularly notable is the doctoral thesis of Araj (1982), which summarizes topics 1 and 2 above, explores deeply topic 3, and somewhat less deeply topic 4, in original work.

3.5 INCREASING GLOBAL CO_2: THE CARBON CYCLE

Figure 3.6 shows the major reservoirs and annual flows of carbon through the world. By far the largest amount resides in carbonate rocks (e.g., limestone), but movement in and out of them is so slow as to be negligible on the time scales of interest here, say 1000 years.

The 5.5 GT of carbon from burning fossil fuel is small compared with the approximately 95 GT transferred between the troposphere and the upper mixed layer of the ocean (about 100 m deep) and the flows in and out of biomass. But those flows had been in close balance; before the advent of fossil fuel burning, the principal net source of new atmospheric CO_2 was volcanoes, contributing less than 0.1 GT/yr. Therefore, 5.5 GT/yr is a large forcing function.

Among the many questions that can be raised about CO_2 sources and sinks, Figure 3.6 suggests an important one: the net contribution of biomass to the atmospheric reservoir. If fossil fuels comprise the only appreciable CO_2 source, the retained atmospheric fraction is (from the previous section) 2.8/5.5 = 0.51. Where the rest goes is uncertain. Most of it surely augments the burden in the upper ocean, and raises slightly the air-ocean rate of interchange, but probably some of the remainder stimulates growth of biomass (Bjorkstrons 1979).

Despite such stimulation, tropical deforestation, loss of accompanying humus and similar processes might produce a net flow of (say) 1 GT/yr of atmospheric carbon from the biosphere.* Then the calculation becomes modified via a total source of 6.5 GT/yr, and the retained atmospheric fraction becomes 2.8/6.5 = 0.43, the larger remainder presumably being temporarily eaten by the upper ocean.

Informed opinion in the early 1980s was mixed on this matter; the data are not good, despite ground surveys, attempts to interpret resource satellite data, and so forth. Much better data could be obtained by using spy satellite technologies, but that is unfortunately classified. Clark et al (1982) estimate the airborne fraction (AF) to be about 0.4, corresponding to a net biomass loss near 2 GT/yr rather than 0.5 - 0.6, corresponding to approximately zero net biomass change. Revelle (1982) seems to prefer a value in the range 0.4 - 0.5. The calculations are so complex that every opportunity should be taken to resolve and eliminate uncertainties like these.

Most of the calculations to follow were made using AF $\simeq$ 0.52, which may be correct, but also may be 25% too high. If the latter be true, the resulting energy-CO_2 scenarios would correspond to using about 25% more fossil fuel than shown, or stated.

Where does the CO_2 eventually go? Into the deeper ocean, surely, but the downward diffusion time is centuries and perhaps longer, so we can virtually neglect it. The effects to be discussed happen faster, with time constants of the order 10-100 years.

3.6 PREDICTIONS OF THE CLIMATE MODELS

The general trend of effects has already been described, and important complications are easy to add by title. Here are some:

o As CO_2-induced radiation trapping starts to warm the troposphere and the oceans, the water evaporation (which is very temperature-sensitive) increases. But water vapor also traps infrared radiation and what we discuss here becomes more truly a CO_2-H_2O greenhouse effect. Water vapor provides positive feedback, tending to augment the effects of CO_2 alone.

o The upper mixed layer of the ocean has large heat capacity, which introduces a time delay in observed temperature rise, estimated to be about a decade.

o The radiation trapping, changing evaporation and other effects tend to increase thermal transport from the tropics toward the poles, leading to expected temperature increases larger by a factor of two to three at high latitudes than in the tropics and sub-tropics.

o The polar accentuation tends to melt more Arctic sea ice, especially in the summer; the polar albedo decreases thereby, which augments the Arctic warming, another positive feedback mechanism. The Antarctic sea ice would also retreat, and a further complication then is the possibility of the Antarctic Western ice sheet, which is grounded mainly below sea level, melting; that would raise the ocean level by 5-6 m, and thoughtful opinion is divided over whether this might happen during a time as short as a decade (albeit at some uncertain time after the year 2000) or only after centuries. The much larger ice masses of the Antarctic Eastern ice sheet and the Greenland ice cap are solidly grounded on land, and would surely take centuries to melt. Indeed, it is still unclear whether they could shrink or grow under the new conditions of changing precipitation and still-cold temperature.

o Tropospheric and stratospheric aerosols affect the atmospheric reflectivity and transmissivity in complex ways; in general they reflect sunlight back to space, but the effect depends on size and composition. Some major volcanic eruptions can lower the global temperature measurably, thus making difficult the interpretation of historic temperature data. It is fruitless, even mischievous, to imagine offsetting the greenhouse effect by aerosols; the effects could not counterbalance either geographically or for any long time, and the pollution level would be unacceptable besides.

o The sun's output changes with time, for example cyclicly but not uniformly with the 11-year/22-year sunspot cycles, which further complicates the interpretation of past data.

o Most man-made gases unfortunately have infrared optical properties similar to CO_2--especially nitrogen oxides and fluorocarbons. The temperature increases more, and the total phenomenon might best be called a CO_2-H_2O-trace-gas one-way blanket effect, surely a term with little public appeal.

Figure 3.7 shows some of these interactions, plus others.

What do the climate models suggest, and with what certainty? Hansen et al (1981) give an outstanding summary of their own work and of other sophisticated climate model calculations (Manabe and Wetherald 1967; Manabe and Stouffer 1979, 1980; NAS 1979) which, while they portray the earth geographically much simplified, include many of the convective and radiative transport phenomena just described, plus some other phenomena.

The models predict that the average global temperature should rise logarithmically with increasing CO_2 and other trace gas concentrations, and we can write for the average increase on account of all these gases

$$\Delta T = \rho \Delta T_d [\ln(C/C_o)]/\ln 2$$

Here, ΔT_d is the increase arising from doubling the CO_2 concentration, C, from its pre-industrial base, C_o, i.e., an increase to about 580 ppmv. ρ is a time-dependent multiplier which depends principally on the relative emission rates of trace gases, and for which a value of about 1.3 was suggested (Bach et al 1980). Hansen et al and most of the other workers assign a value of ΔT_d = 2.8°C, with an estimated uncertainty not larger than a factor of 2.

Before discussing the likely timing and consequences of the predicted warming, let us again with Hansen et al ask whether any present evidence exists to confirm these calculations. Figure 3.8 shows their best estimate of the average global temperature since 1880, obtained from various measurements in both hemispheres. This "observed" temperature, itself somewhat uncertain (especially in the earlier years), is shown by the dotted line, plotted identically six times and compared with six specific calculations.

First, consider only the three curves on the left. The top curve shows the effect of the known CO_2 increase and a thermal capacity represented by a 100 m deep mixed-layer ocean, and no thermal transport downward into the thermocline at 1000 m. Dust from volcanoes changes the atmospheric absorption as mentioned above, and its effect can be roughly estimated. The largest eruptions were Krakatoa a century ago, and Mt. Agung in 1963. Adding their effects gives the middle curve. The solar variations, fairly well known, should also be included; thus we have the bottom curve of the left side of Figure 3.8.

These models predict too large a variation, and thermal diffusion toward the deeper ocean has been added to these same calculations, to give the results on the right. Hansen et al choose a diffusion coefficient $D = 10^{-4}\ m^2/s$, which minimizes the data/model misfit, and finally obtain the curve at bottom right. This value of D corresponds roughly to the observed downward diffusion rate of trace materials. It suggests a characteristic time of about 250 years for diffusion from 100 m to 1000 m down, but only some 13 years for 100-300 m diffusion. Thus the curves on the right are flattened, especially with respect to shorter-term phenomena.

Although uncertainties persist in both data and calculations, it seems unlikely that the global greenhouse effect is not real, or has been seriously misjudged. Additional facts--for example that Antarctic pack ice receded 100-200 km further south during 1973-1980 than it did during 1929-1938--may be explainable by natural variability, but they are about what would be expected from the effects of CO_2 increase (Kukla and Garvin 1981).

How serious would a global average temperature rise of 2.8°C be, perhaps ranging from +2°C at the equator to +8°C at the poles? The preponderance of land in the northern hemisphere and of ocean in the southern one places the Earth's climatological equator at about 5°N latitude; the CO_2-stimulated effects seem likely to move it several degrees farther north (Flohn 1982). The changes would then most likely be least in the southern hemisphere, and accentuated in the north. The total range in Europe during the past 1000 years was 1.5°C, most notably the "little ice age" of the 1600s, a time of much distress. The earth was about 1.5°C warmer than now during the Altithermal, or Holocene, warm period, 6000-8000 years before the present (BP); pollen counts, river deposit analyses, etc., indicate that frequent summer droughts occurred in the mid-latitudes and with drought in the northern winter rain belt, accompanied by (inter alia) wetter tropical monsoons. At the depth of the last ice age, 20,000 BP, the earth was about 7°C colder. A +2.8°C global change would probably cause the Arctic summer ice to disappear, which it has not done in the past million years.

From these calculations, and historical and present data, one can easily conclude that the effect of doubling atmospheric CO_2, probably augmented by the effects of anthropogenic trace gases, would cause large climate changes, upset global agriculture and forests, and lead to environmental and ecological changes which would dwarf anything else in recorded history. Furthermore, some groups would see themselves as relative winners, some as sure losers. If the changes happened slowly enough, the global civilization could, given reasonable will and consensus, adapt to it. Thus arises not only the total eventual magnitude ΔT, but the rate of change dT/dt, and rates of technological, political and social adaptation.

The next section summarizes some analyses made along these lines.

3.7 GETTING OFF FOSSIL FUELS: IMPLICATIONS OF GLOBAL CLIMATE AND ENERGY SCENARIOS, CONSIDERED TOGETHER

Assume, as will be done in this and subsequent sections, that the climate models are approximately correct. Then we can transfer attention to a series of much more specific questions: (a) Is it possible to keep the global CO_2 level from building past 500, 600, 700, etc., ppmv, and what steps would be required to realize such asymptotic limits? (b) What do the present scenarios of future global energy use imply? The answer to (a) is: 500 ppmv with great difficulty and a prompt start on large-scale implementation of non-fossil energy sources, 600 ppmv with less difficulty, and so on. The answer to (b) is that most scenarios take little or no account of CO_2 limits, and imply trouble ahead.

Araj and co-workers at M.I.T., Perry and Fulkerson at the Oak Ridge National Laboratory, and Rotty at the Institute for Energy Analysis have together and separately considered these matters (Perry et al 1982). What follows comes mainly from Araj's work, but the ORNL-IEA calculations are similar and lead to the same conclusions.

Figures 3.9a, 3.9b and 3.10 catch the spirit of the calculations, and the difficulties. Most naively, one might admit that a maximum allowable CO_2 level exists, above which climate changes will not be acceptable, and below which they will be. Will society ignore it until the CO_2 limit appears near enough in time for near-term market and other forces to evoke effective action? Figure 3.9a is an extreme caricature of such an attitude. Figure 3.9b illustrated a more thoughtful but still dangerously naive view: that the minimum realistic global energy demand leads to a CO_2 level labeled "Minimum Realistic," and that CO_2 level gives acceptably small climate changes; the maximum allowable level lies well above. Thus a prudent world can plan global energy scenarios that satisfy both realistic energy requirements and climate stability, such as curve E.

If neither the mix of energy technologies (e.g., coal fraction, oil fraction, etc.) nor the climatological parameters (e.g., retained air fraction of CO_2) change, then the slope of the curves of Figure 3.9 describe the annual energy uses, and Figure 3.10 shows the results. Technological, economic, political and other constraints make a sudden stop impossible; large technological changes take many decades. Thus, serious consideration focuses on the option space of Figure 3.9b, and its Figure 3.10 implication. Exploring that option space is the main task of this section.

But suppose, when the numbers are put in, the two limits of Figure 3.9b lie not as shown, but interchanged, so that only painful and disputatious options exist. The problem becomes more complex.

One more parameter needs defining in these calculations: the Action Initiation Time (AIT). In this over-simple approximation, the world is assumed to have followed a CO_2-uncaring strategy of energy use up to some prescribed year, the AIT.* At that time, a new global strategy already decided upon starts to take effect: consciously reducing the startup rate of new fossil fuel systems, and increasing strongly and purposefully the startup rate of non-fossil energy systems, in order to keep the asymptotic CO_2 concentration below some agreed-upon level. This AIT is not the time when serious discussion begins, nor yet when a global consensus comes, nor even when new industrial plants start to be built to produce those energy systems; all these things happened before the AIT. At the AIT, the CO_2 production rate starts to change because of the new technology. Thus it might correspond to the startup of the first new solar or nuclear systems installed with the object of limiting the CO_2 buildup.

Of course, no such exact fiducial time exists, especially for the world as a whole; but it serves well to calibrate early and late actions, and the consequences.

The stage is now prepared for showing sample results of the principal calculations: what the development of fossil and non-fossil energy must be if various global energy scenarios represent reality, and prescribed CO_2 limits are not to be exceeded. A multitude of cases could be, and have been, examined, viz:

Different CO_2 asymptotic limits: 500, 600, 700 ... ppmv;

Global energy scenarios: IIASA high, IIASA Low, World Coal Study ... (see Chapter 1);

Different atmospheric retained CO_2 fractions, e.g., 0.42, 0.52, 0.6;

Several AITs: 1980, 1990, 2000, 2010.

There are 108 different combinations of just the parameters listed here, still without mention of the transition scenarios in detail.

Nevertheless, a few sample results will show the principal trends. Consider now Figure 3.11, the lower curves of which are like Figure 3.10, but quantified. The curve labeled "World Total" follows the IIASA high energy scenario up to the year 2035, when that calculation stops. It is a version in which fossil fuels have been somewhat de-emphasized compared to present median expectation (Low Coal, or "LC"); higher non-coal (NC) use makes up the difference. It has been extrapolated to the year 2100, preserving value and slope at 2035, with a tapered growth rate. Although the curve looks steep, its annual fractional increase is 1.5%/yr between 1980 and 2100, much less than the 4-5%/yr of recent history. Thus, this curve, the higher of two to be displayed in this section, already assumes either substantial decoupling of energy and economic growth, or substantially reduced economic growth per capita, or substantially slower population growth in the future, or some combination of these.

Next, fossil fuel scenarios must be chosen so as to lead to specified asymptotic CO_2 limits. In these calculations, the functional dependence is chosen for the atmospheric CO_2 concentration C(t) itself, as a logistic function

$$C(t) = \frac{\beta}{1 + \gamma \exp[-\alpha(t - t_o)]} + C_o - \frac{\beta}{1 + \gamma} \quad (1)$$

Here, t_o is the Action Initiation Time, up to which the global fossil energy use has followed the IIASA scenario, and after which the fossil fuel use starts to become constrained. At time t_o, the CO_2 concentration is C_o, and the remaining constants, α, β, γ, are determined to:

(a) set an asymptotic CO_2 limit:

$$C(\alpha) = C_o + \beta\gamma/(1 + \gamma) \quad (2)$$

(b) match the fossil fuel energy rate at t_o:

$$E_f(t_o) = \frac{1}{(\text{const})(\text{AF})} \left.\frac{dC}{dt}\right|_{t = t_o} \quad (3)$$

where AF is the atmospheric retained fraction,

(c) match energy slope at $t = t_o$:

$$\left.\frac{dE_f}{dt}\right|_{t = t_o-} = \left.\frac{dE_f}{dt}\right|_{t = t_o+} \quad (4)$$

These criteria account for industrial inertia; changes come gradually. Figure 3.12 shows four such curves of C(t), calculated from Equations 1-4.

Surely, no one can predict what will happen so far in the future, and these curves do not pretend to do so. These are "if ... then" calculations; if the fossil energy, total energy and CO_2 profiles follow certain paths, then the consequences are as shown. Some paths would require global effort hitherto uncontemplated; others would not. Some have CO_2 levels rising to 600 ppmv or more, with climatic consequences also hitherto uncontemplated. No carefree path emerges. Furthermore, the numbers beyond about the year 2040 will not matter much, it will turn out. Even the choice of mathematical functions does not seem to matter much. The limits and matching criteria constrain the choices so much that the curves of Figures 3.11 and 3.12 cannot be made to look very different. Thus these scenarios, seemingly arbitrary, give credible insight.

Return now to Figure 3.11. The fossil curves are the time derivatives of the four curves of Figure 3.12. The area under each is a measure of total CO_2 produced. The remainder of the total must be produced by non-fossil means, and therein lies the difficulty: the rate of its introduction is very high.

Several comments can be made about Figure 3.11:

(a) The action initiation time for these curves is 1980, representing an opportunity already missed. The real transition must come later, and be correspondingly more sudden and difficult.

(b) For all the CO_2 limits, the non-fossil energy consumption must equal the present global total of 10 TW sometime between 2010 and 2020--a very difficult task--and overtake the total (increased) fossil rate by 2015, if a CO_2 level of 600 ppmv is not to be exceeded.

(c) The non-fossil rate increases between 6 and 9 percent per year in the period before 2010, a very high global rate; these startup rates of new systems will be discussed a little later.

Bear in mind that these non-fossil systems are not biomass, hydropower, or geothermal energy; those resources are too small. Only two real choices exist: solar collectors on a large scale, or nuclear power on a large scale. No adequate technology now exists for either option. Photovoltaic collectors are still being developed, with still uncertain prospects. Present-day nuclear reactors would use too much uranium, unless it could be supplied in very large amounts at acceptable cost; breeder reactors and their associated fuel cycle are also not yet ready for deployment, and bring political and social problems. Later chapters describe some of the options.

Figure 3.13 shows an IIASA low-energy scenario, giving 24 TW in year 2035 (instead of 36 as in Figure 3.11); this is the high coal/low non-fossil version, but others would not differ much for this early AIT of 1980. The fossil curves closely resemble the corresponding ones of Figure 3.11; but now the non-fossil energy increases much more gradually. The principal difficulties of shifting the global energy base will relate to developing, installing, paying for, and accommodating to the non-fossil part, so the importance of rational and effective energy use becomes emphasized again.

How do different AITs affect the scenarios? Figure 3.14 shows how one of the curves (500 ppmv CO_2) of the low scenario in Figure 3.13 changes, as the AIT recedes from 1980 to a more likely 2010. The transition becomes qualitatively and quantitatively much different, with frenetic growth of non-fossil systems and probable forced decline of fossil ones.

The time derivatives of these curves gives the startup (or shutdown) rates of the specified technolgies. Thus, consider Figure 3.15, which shows the time derivatives of two non-fossil curves like those of Figures 3.11 and 3.13, but for an AIT of 2000. The different energy scenarios require dramatically different investment rates. A startup rate of 1200 GW/yr of advanced technological systems on a global basis would be very difficult, and one can conclude that global scenarios like IIASA-high and a 500 ppmv CO_2 limit are incompatible.

On the other hand, 600 ppmv and the IIASA low scenario seem much more compatible, especially if a low coal (hence higher non-fossil) path has been followed up to the AIT, as Figure 3.15 shows. The importance of using energy rationally, effectively, frugally becomes dramatically evident.

Of course, the curves of startup rate of new systems do not really drop at later times, as Figure 3.15 implies; the derivative of Figures 3.11, 3.13 and their analogues for other parameters do not account for the replacement rate of old systems. Figure 3.16 shows the total startup rate, including replacement of all equipment after 30 years in service, for some cases like Figure 3.15.

The annual increment of new power plants described in Figure 3.15 must have come from factories that produced them. Those manufacturing facilities were presumably built to respond to the need. Thus, in the same sense as before, the derivative of Figure 3.15 has physical significance at times before the maximum, admittedly with less precision. Suppose that the plants starting up all took ten years to build. Then the time derivatives of Figure 3.15, shifted ten years earlier, should be a measure of the rate of change of dedicated manufacturing capacity. Figure 3.17 shows those time derivatives. Surely only the rising parts are significant, because after the peak, the manufacturing plants provide replacements, components and so forth.

Although the exact shape and size of the curves in Figure 3.17 are questionable, the general trends and conclusions are not; the combination of AIT of 2000 or later, a high-energy scenario, and 500 ppmv are incompatible. Figure 3.17 shows a peak requirement of almost 50 GW/yr of new manufacturing output capacity to be put in place, each year. Fifty GW/yr is perhaps half the total capacity of the U.S. electric plant manufacturing capacity, if it were all to be fully employed; to replicate it each year, even if spread over the whole world, seems very ambitious.

Figure 3.18 shows the effect of different AITs, and the importance of early decisions. Here, we see results for 600 ppmv, an asymptotic CO_2 level that the world may have to settle for, and even that only after some effort. The additions to new capacity come at rates that fall within the range of present estimates of what can be done. Note that the areas under the earlier AIT curves are less than under the late AIT ones, as follows. For earlier AITs, the manufacturing plant remains in use longer; for late AITs, manufacturing plants must be built to provide large output for a short time of relative emergency, after which they are not needed, and have been inefficiently used.

Finally, Figure 3.19 shows what would happen if the world started on a path leading to high CO_2 concentrations, then, after analyzing the consequences, decided later to shift to a lower CO_2 asymptote. Here, the IIASA high-energy scenario is followed out to the year 2000, with the idea that 700 ppm is acceptable; that gives the bottom curve, marked "700 ppm." Now suppose that at the year 2000, ten years late, a decision is made to go for a 500 ppmv asymptote. Because manufacturing capacity has not been installed to anticipate this switch, the new AIT becomes 2010, and the shift must be made from a then-burgeoning fossil fuel technology. Then we find the "700-500 10-yr delay" curve of new manufacturing capacity, starting at 2000 and peaked much more than the "pure" 500 ppmv curve had been. Similarly, suppose this 700 ppmv scenario had been followed to 2010, at which time there is a sudden decision to limit CO_2 to 500 ppmv. Now, ten years more have passed, and we see the impossibly high and peaked curve which comes from the 20-year delay.

The startup rates reported here can be compared to estimates of manufacturing capability, based on present data plus extrapolations. Araj, adding up all he can find for accelerated nuclear manufacturing capabilities worldwide, finds that a maximum completion rate between 350 and 440 GW (electric) could be established by about the year 2020, or 750-900 GW (thermal), somewhat above the IIASA estimate of 332 GW electric. These thermal numbers seem not far below the upper curve of Figure 3.15, but consequent insouciance would be a mistake; those installed capabilities to manufacture quite new systems would not exist then, if not pressed for now, but the later AITs deny such present concern, and present experience suggests that just those scenarios will come to pass.

In summary, the analysis just given strongly suggests that the IIASA high scenarios, with a present high coal/low non-fossil path, are incompatible with CO_2 limits below 600 ppmv, and maybe even higher. However, prospects are not so dismal for the lower scenarios, especially for AITs not later than 2000, even perhaps to keep below an asymptote of 500 ppmv; but realizing those prospects would require not only very efficient development, installation and utilization of new non-fossil technologies, coupled with increased emphasis on rational and efficient use, but also social consensus surpassing either prior experience or present expectations.

3.8 CHANGES IN THE BIOSPHERE

Sea level would rise 5-6 m if the West Antarctic ice sheet were to melt. The climate changes and the resulting effect on the world's biomass, both managed (i.e., agriculture) and unmanaged (chiefly forests) are just as important, perhaps even more so. The tropics are expected to warm by about 2°C, mid-latitudes by 3°C, and polar regions by 8°C, more or less, for a CO_2-doubling, with the biggest changes in the northern hemisphere, as stated earlier. Those changes, modified by particular circulations in the oceans and the atmosphere, affect not only regional temperatures, but also precipitation.

Figure 3.20 is a wetter/drier map for a warmer world, made by Kellogg and Schware (1981), partly on the basis of evidence from the Altithermal period. Much uncertainty still exists, but dominant opinion holds that the U.S. mid-latitudes will become drier; Mexico, East Africa, part of the Sahara, India and part of Australia will become wetter. Other regions will surely become drier or wetter, and Kellogg and Schware's figure agrees in general with the others, for example Butzer (1980).

The effects of more or less rainfall, and of modest temperature changes on particular crops and ecosystems can be fairly well described, chiefly on the basis of observing existing agricultural systems that function under various conditions, and the viability of forests and other biomasses under known conditions of stress. It is much harder to predict the behavior of all these systems with increased CO_2, and particularly of complex and/or slow-growing ones. For example, in the unmanaged biosphere, the order of species dominance will surely change.

Regarding individual species, increasing CO_2 alone with no other changes seems probably to be more beneficial than harmful. The world's vegetation is divided into two major categories depending on how CO_2 is utilized in photosynthesis. The first category consists of the so-called C_3 plants, for which it is generally thought that growth is limited by the availability of CO_2; for the concentration of interest here, growth is more or less proportional to CO_2 concentration. To this C_3 category belong almost all trees. The other category, the C_4 plants, with a dicarboxylic pathway which serves as an internal CO_2 concentration mechanism, is relatively insensitive to moderate increases in external CO_2 concentration. To this C_4 category belong many important crop species, grasses and shrubs.

The responses just described might lead one to be at least cautiously optimistic about the agricultural consequences of increasing CO_2. But the data in hand generally come from relatively short-term experiments, with very little at all done on the unmanaged biosphere. The CO_2 has other effects--for example, tending to close the stomata on leaves, which reduces the water transpiration; this might improve the plant's ability to survive under more arid conditions, but still more changes will surely occur.

Despite these seemingly neutral or even beneficial indications, the outlook may not be so favorable, especially in the short term. Consider present managed agricultural systems, most of which have been optimized to prevailing climate, soil, rainfall and so forth. Changes will generally lead to reduced output, until a new agricultural pattern develops, attuned to the new conditions. Regarding the short-term loss, Araj summarizes some recent findings on the effect of climate change. Four major world food crops are maize (394 million metric tons production in 1979), wheat (425 million tons), rice (380 million tons), and soybeans (94 million tons). Benci et al (1975) conclude that a 3°C temperature rise, coupled with 10% decrease in rainfall, would reduce the yield from the U.S. corn belt by 35%. For wheat, the global yield might decrease by about 10%, taking into account decreases in the U.S., probable increases in Australia and India, etc. The climate change might actually increase rice production, for instance, via multiple-cropping outside the present tropical regions (Stancel and Huke 1975). The soybean crop, now grown principally in the U.S. Midwest, would decrease by about 10% (Curry 1975).

On the average, this is bad news. Agronomists concerned with the managed biosphere, especially those that have developed maize, tend to opine that plant breeding or locational shifts will be able to keep up with the climate changes, and cite success with hybrid corn, short-stem high-yeild rice, etc. But things are not so simple:

o Corn, having separate male and female flower parts, is much easier to modify than wheat, rice, soybeans or barley.

o The hybrid species tend to require very specific conditions, if their maximum yield is to be realized. For example, the new rice species yield more if well-watered and fertilized; but their shorter growing period makes them more susceptible to short droughts.

o How long it takes to optimize to new conditions depends on many things. If the U.S. Midwest becomes unproductive, but the Canadian lands 1000-1500 km north warm up, still the Midwest productivity could not soon be reproduced there; the soils are poor, and the time to build new ones must take many centuries, perhaps millenia. Given good land, farmers can settle in new regions and develop them well in one or two generations, but that also means making new cities, transportation systems, and so forth, all at great cost.

Rising above all thsoe issues is another, far larger--the perception of winners and losers, of some major regions being unable to adapt in time, of global redistribution of wealth and power, etc. It matters not that Figure 3.20 is imprecise; other maps will come, better than now, and the surer the predictions, the more will be the polarization. More on that in the next section.

Effects on the unmanaged biosphere--chiefly forests--must be based on flimsier data, and perhaps their C_3 photosynthetic cycle will help individual species. But present forests are for the most part well matched to their climate and soil conditions; adjusting to a new mix takes several full growth cycles to achieve--that is, several hundred years in the temperate zone, and probably a somewhat shorter time in some tropical regions. Those times are comparable to or longer than the time for significant climate change, if the greenhouse phenomenon develops as rapidly as many of the scenarios described earlier imply. Thus, even though individual trees for which the conditions remain constant might grow somewhat faster because of increased available CO_2, the total effect on the world's forests would be very hard to predict. Sharing this view, silviculturalists tend at present to be more worried about CO_2 buildup than are agronomists. This difference in attitudes is strikingly evident in the reports of the two groups at a 1979 workshop (AAAS 1979).

3.9 CO_2: COMPLICATIONS AND REFLECTIONS

The problem will be harder to resolve than the analysis so far implies because several complicating features were omitted.

A chief weakness was the adoption of a single AIT, as if the whole world would, at one time, decide to travel a new path, and march in lock-step that way thereafter. Neither history nor common sense supports such a vision. First, with few exceptions, all the parts of even one major country never change their attitudes at one time. Second, even the OECD countries, among which one might expect a relatively good measure of technological, economic and cultural agreement, will have very different opinions, technological and economic patterns, and resources, ~~and~~ consequently a range of AITs which will extend at least one or two decades.

Recall the debates about acid deposition.

By far the largest spread of AITs arises from different stages of industrialization throughout the world. Many of the most populous countries of the world, now relatively non-industrialized, follow a path leading rapidly toward much increased use of fossil fuel, rather than the inverse. For China, India, Africa and elsewhere, AITs might be 50 years later than in some OECD countries, unless extraordinarily large incentives arise to switch earlier. Complicating the situation even more, some of those countries will not perceive themselves as losers if the CO_2 level rises. All this suggests that the transitions so neatly shown in Figures 3.11, 3.13, etc., will be much slower; but slower means more CO_2, and an asymptotic limit of 500 ppmv looks even more illusory than before.

Suggestions have been made about what to do. Among the least helpful is the idea of capturing the CO_2 from fossil fuel burning, then sinking it directly in the deep ocean. One suggestion, to burn all fossil fuels at the straits of Gibraltar, where the outflowing undercurrent descends directly to the deep ocean, fails on the basis of simple geographic inequity.

A second suggestion is to capture the CO_2 from power plants, convert it to dry ice, then push it below 1000 m in the oceans (where the pressure keeps it from vaporizing), whereupon it continues sinking, being denser than seawater. That idea, admittedly better than the Gibraltar one, fails on two counts. First, it is estimated that 30%--maybe more--of the fossil fuel energy would be needed for the capture and disposal, making fossil fuels even more expensive and unattractive. Second, more than half the fossil fuels are burned in facilities too small to be fitted with devices to capture CO_2: stoves, automobiles, airplanes, small industries, water heaters, etc. It might be argued that most of these can be technologically altered to run on direct solar or electric power, but that is part of the panoply of shifts being discussed here, and such a shift is not necessarily in the direction of continued fossil fuel use.

Yet another suggestion is to plant vast regions of the earth with fast-growing trees, say sycamores. Elementary calculations of available land and biomass production rates show that the fossil fuel consumption implicit in Figure 3.13 (let alone in Figure 3.11) could not be counterbalanced this way, by an order of magnitude. Disposing of the mature trees would imply a global biomass energy technology, a prospect dealt with and declined in Chapter 8.

Summaries of these and other scemes are given by Baes et al (1980) and Albanese and Steinberg (1980), who show that they are impractical in various ways.

Attempts have been made and continue to be made to assess the economic costs of applying control strategies, or of switching to non-fossil energy sources now or later. The analyses of Nordhaus are better known than most. In a recent paper (Nordhaus 1981), he uses control theory to find optimal emission strategies. This involves maximizing the discounted expected utility of consumption, and thus depends critically on the discount rate. For different assumptions about the latter, he obtains current shadow prices of CO_2 ranging from $10/ton for high discount rates to about $100/ton for low rates, between 1 and 5% per annum. The low discount rates would imply that it would be in the world's best economic interest to switch to non-fossil sources rapidly.

Some feeling for how people and nations might respond to an increasing CO_2 challenge comes from studying current events and history. Acid rain, already amply discussed, gives a dismal prognosis. Araj recounts several other applicable cases.

Consider pollution on the Rhine River. France, West Germany, Luxemburg, Switzerland and the Netherlands took steps to abate pollution there (Rhine Convention 1976). The states agreed to reduce or eliminate the discharge of certain environmental pollutants, in particular chlorides, which are primarily caused by nearby regional potassium mining. However, the French, facing internal opposition to the convention, failed to ratify the agreement, much to the distress of the Dutch downstream. In general, most international river and river basin agreements have shown that upstream users put downstream users at their mercy.

The Trail (British Columbia, Canada) smelter case is small but revealing. That large plant, owned by Consolidated Mining and Smelting, Ltd., located on the Columbia River at Trail, regularly polluted the air in the downstream valley and damaged fruit crops miles away in the State of Washington. The damage occurred mainly in the 1920s and 1930s and was actually settled, with monetary compensation, by an international arbitration tribunal. In its final decision, in 1941, we find this (Trail Smelter 1949):

> The Tribunal therefore finds ... under the principles of

international law, as well as of the law of the United States, no state has the right to use or permit use of its territory in such a manner as to cause injury by fumes in or to the territory of another or the properties or persons therein, when the case is of serious consequence and the injury is established by clear and convincing evidence.

The Tribunal's decision incorporated two principles of inernational law which are of value to the CO_2 problem, mainly the principles of equitable use and state responsibility for environmental harm. We find here a response lag of one to two decades, where the source, dispersion, change, technical responsibility and ability to pay were all well known.

Here is an example from astronomy. The tale of Galileo, his telescope and the Roman Curia's reluctance to consider its evidence is well known; we imagine that it could not happen now. Not in just that way, to be sure, but Rubin (1980), in an excellent overview of the present state of astronomy, tells us this:

Only during the past decade have astronomers acknowledged that much of the mass of the universe must be invisible, although the controversial evidence has been accumulating for a long time. Almost 50 years ago, Smith and Zwicky made an amazing observation--individual motions of galaxies in a (galactic) cluster are so large that the gravitational attraction of all the cluster galaxies is not sufficient to bind the cluster. Galaxy clusters should thus be dissolving, although they apparently are not.

This strong evidence for a large, invisible mass to provide adequate gravitational pull was generally known, and its significance was great. Why was scant attention paid to it for 40 years? Apparently the need had not become acute enough, the intellectual pain had not become high enough, to require astronomers to change their views. They still had plenty to do using their old paradigms. This interpretation would be in general accord with Thomas Kuhn's views as contained in his Structure of Scientific Revolutions.

It is not so much the "existence" of knowledge which seemed to count here; more important was the delay until the affected group became sufficiently pained that they could no longer ignore it, plus the eventual passing from the scene of those with older views. But if the 40-50 year delay is interpreted as a response lag, the outlook for resolving the CO_2 problem, which is far more complex, in a timely way looks bleak.

Looking much farther back in history, Butzer studied the ancient Egyptian and other civilizations to discover how they adapted to environmental vicissitudes. He points out that they tend to buffer themselves by multiple layers of technology, social organization and exchange networks. This produces a metastable equilibrium; the layers become too heavy to support, so the system breaks down as a result of chance concatenation of several mutually reinforcing processes, such as poor leadership, external political stress, internal socio-economic pathologies or environmental stress.

Thus we come to catastrophe theory, in which at some level of stress further inputs produce large rapid changes. Faced with breakdown, political, economic and social structures may be abandoned in part or in whole as the system seeks to adapt and survive at a more rudimentary level.

Kates (1979) presents a partly alternative view, pointing out that in recent years losses to rich nations from floods, droughts, storms, etc., have been fractionally very small, but in the poorer nations they have been much larger. He concludes that climatic hazards are about 25 times more severe in developing countries than in industrialized ones. That is true, but perhaps irrelevant for changes as large as the CO_2 analyses portend. Butzer's descriptions seem more applicable.

These examples, plus others that could have been cited, stimulate pessimism about whether the response to CO_2 buildup will be timely, or even well thought out. To repeat some earlier phrases, it has all the features that lead to selective inattention and present inaction: ~~it is~~ not easily describable, ~~has~~ no closely affected group (now), no strong institutional groups to care (now), disputed models, a long time before bad consequences, many uncertainties, winners and losers. Indeed, the future may be dismal. But it need not necessarily be; the proof is not absolute. Increasingly audible calls for global distributive justice and for a sustainable and equitable society do not fit the mold of economic analysis or short-term political accommodation. Therein lies the hope, and at the end of this chapter I associate myself with it, because the alternative gives no hope. Some substance can be given to support such an attitude. A strategy of limiting the growth of fossil fuel use and more efficient and rational energy use is valuable for more reasons than avoiding CO_2 buildup. Araj puts the case well:

> Such reasons include more immediate environmental and health effects of fossil fuel use; the needs of the less-industrialized countries (LICs); desire to accelerate the transition to renewable and inexhaustible energy sources; and other more narrow reasons such as national security considerations.

Most of the above arguments are frequently articulated elsewhere and we shall simply highlight certain points. LIC energy requirements occupy central priority in any discussion of a New International Economic Order, and certainly in any international energy conferences or forums. Over the next decade, the LICs are projected to be the fastest-growing sector in world energy economy. But given the fast depletion of fossil fuel supplies and fuelwood combined with rising prices, the LICs with their ever-widening balance of payments deficits <u>cannot possibly</u> under the <u>status quo</u> pursue such an energy development path. Thus, barring any reduction of fossil fuel use in the industrialized world, the <u>entire</u> geopolitical system will be at stake. International instabilities will be the outcome as most of the LICs will approach that "inner" or "outer" limit of tolerance. By then, everybody, North and South, West or East, will lose. In summary, as Scroggin et al (1981) and many others correctly point out:

If control of CO_2 is considered an insurance balance, the "premium" (net cost of de-emphasizing fossil fuel) is low, or even negative (a bonus) ~~(dividend)~~ because the activities it comprises are economically attractive, pose little environmental hazard, and reduce dependence on imported oil.

FOOTNOTES - CHAPTER 3

3.9 Besides the references in the coal chapter, see CONAES 1980.

3.11 In 1974 a senior official of the Federal Energy Administration, in charge of such matters at the time, when told the acid rain story, affected to be hearing it for the first time, and responded that he was sorry to receive such information, because the decision was for tall stacks, and would stand.

3.14 Twenty-three of the 24 required ratifications achieved by July 1982 (Amasa Bishop, UNECE, private communication).

3.16 Greenhouse glass has similar properties--transparent to visible but not to infrared radiation; but greenhouses warm up mainly by eliminating convection to the outside cooler air. The global phenomenon analyzed here could better be called a one-way blanket effect.

3.20 The fractional biomass contribution to global energy probably lies between 8% (WEC 1978) and 12% (Häfele et al 1981, p. 532), but it comes largely (though not entirely) from biomass that is soon replaced, e.g., straw or dung, so its net effect on global CO_2 is small.

3.28 This is not the response lag introduced at the beginning of the chapter; the response lag is a period of time preceding the AIT.

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SO$_2$

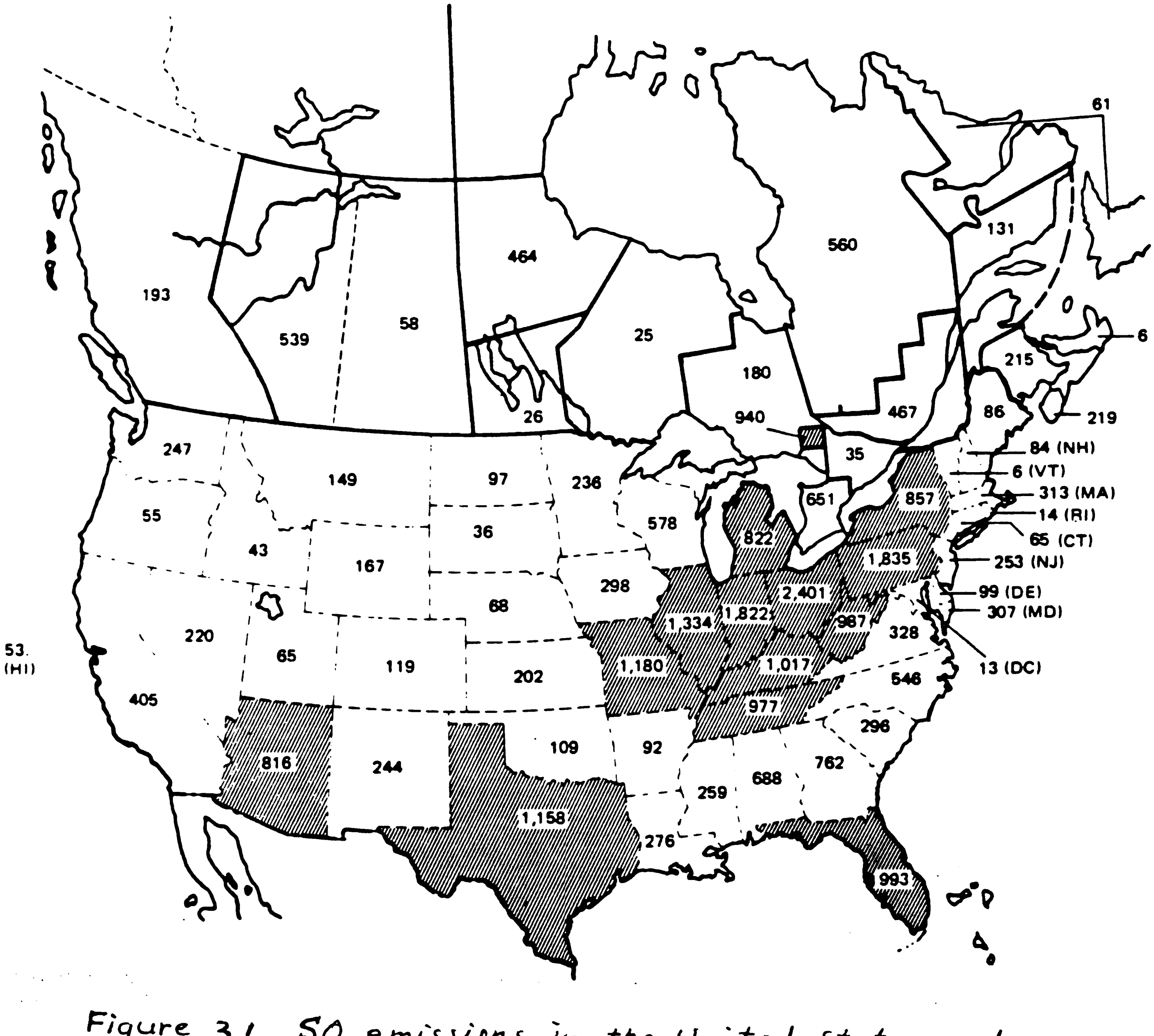


Figure 3.1 SO$_2$ emissions in the United States and Canada in 1980 (thousands of metric tonnes/year) ~~From Acid Deposition: Atmospheric Processes in Eastern North America, National Academy Press, Washington DC, (1983) (Their Fig. 1.2) (N~~ From (National Research Council 1983) Their Fig 1.2

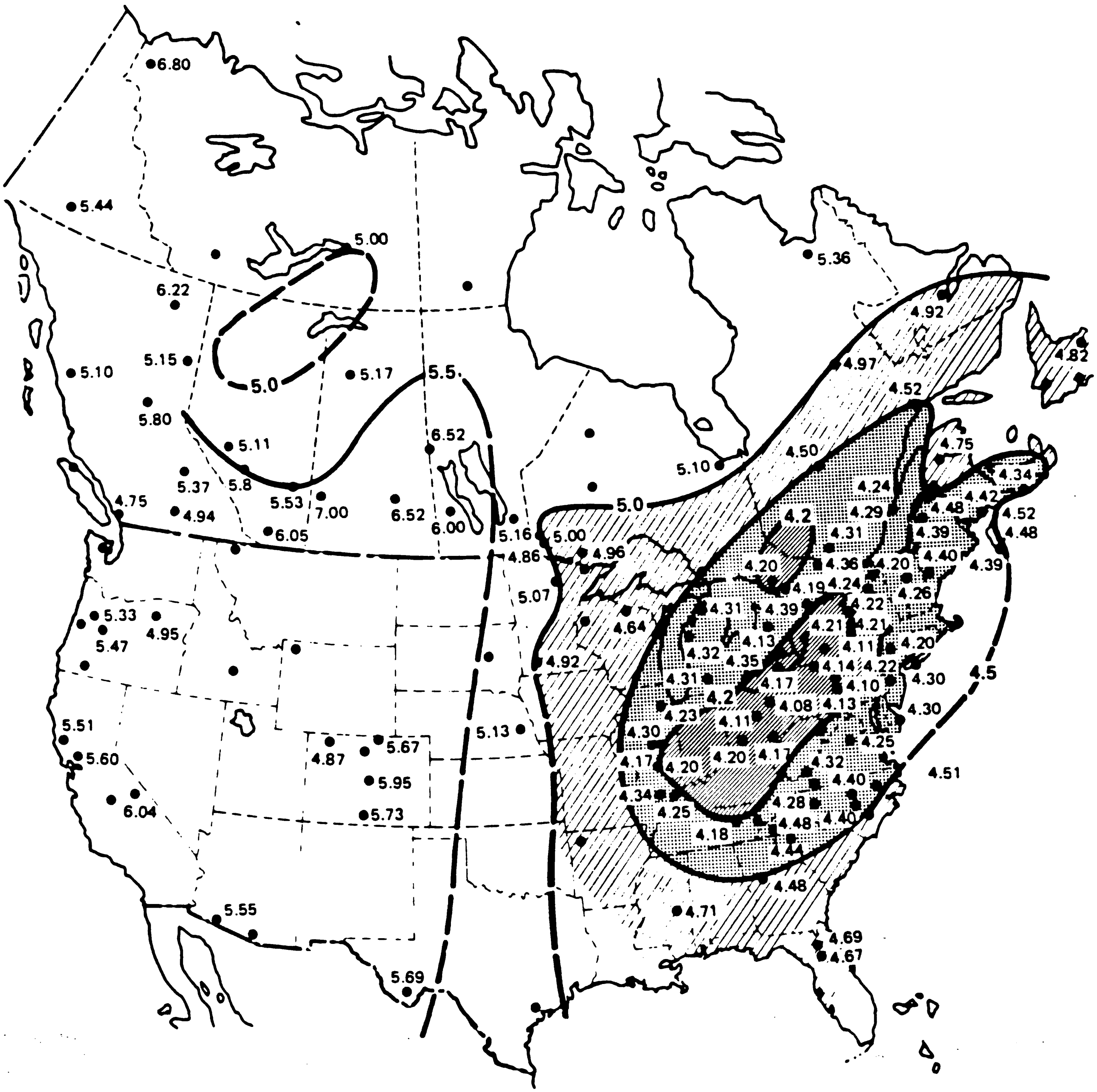


Figure 3.2 Annual mean value of pH in precipitation weighted by the amount of precipitation in the United States and Canada for 1980. From Acid Deposition: Atmospheric Processes in Eastern North America, National Academy Press, Washington DC, (1983) (their Fig. 1.1)

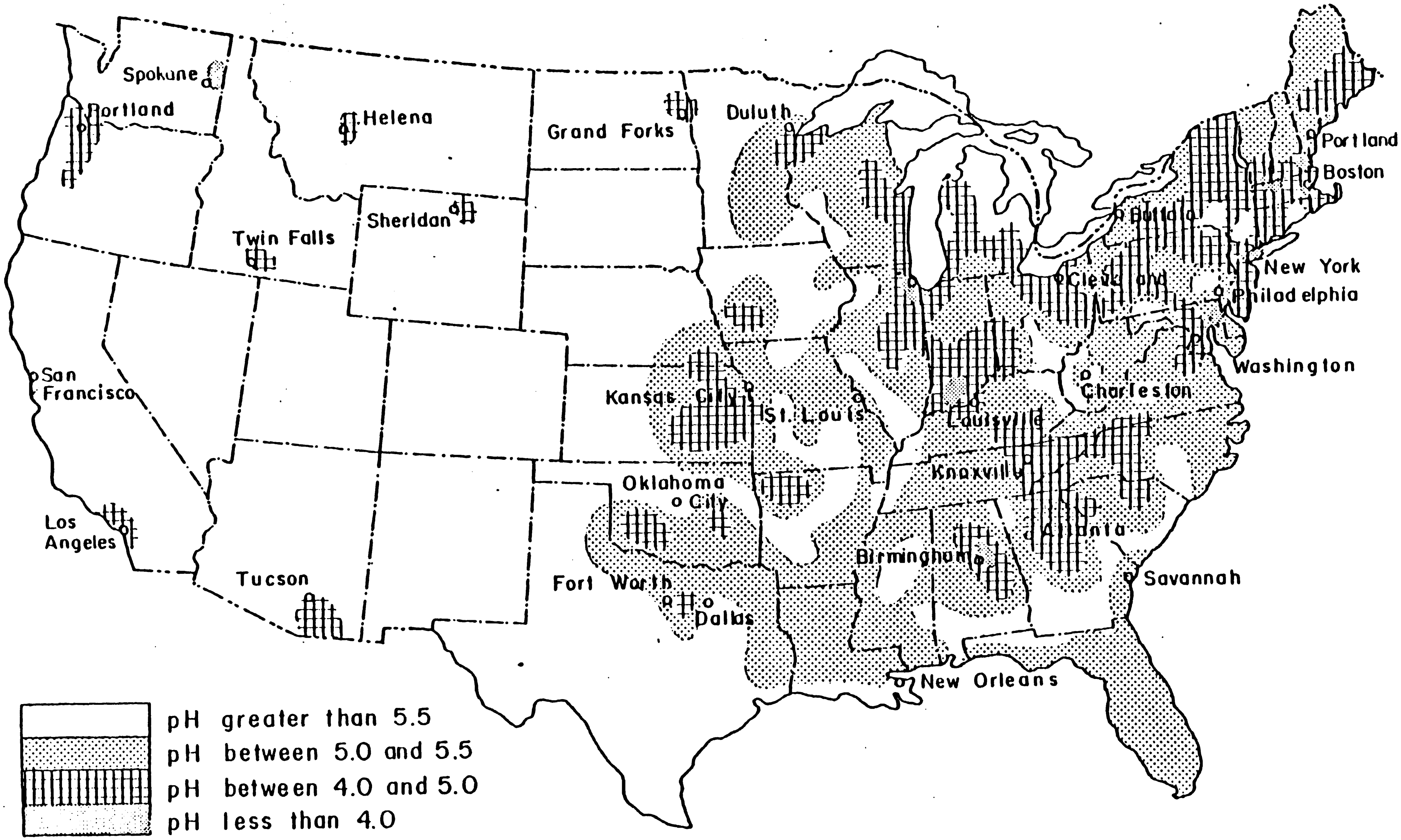


Figure 3.3 Acidity of rainfall in the U.S., 1974.
From C.L. Strong, (1974.) ~~"The Amateur Scientist," Scientific American, Vol. 230, No. 6, June 1974, pp. 126-127.~~

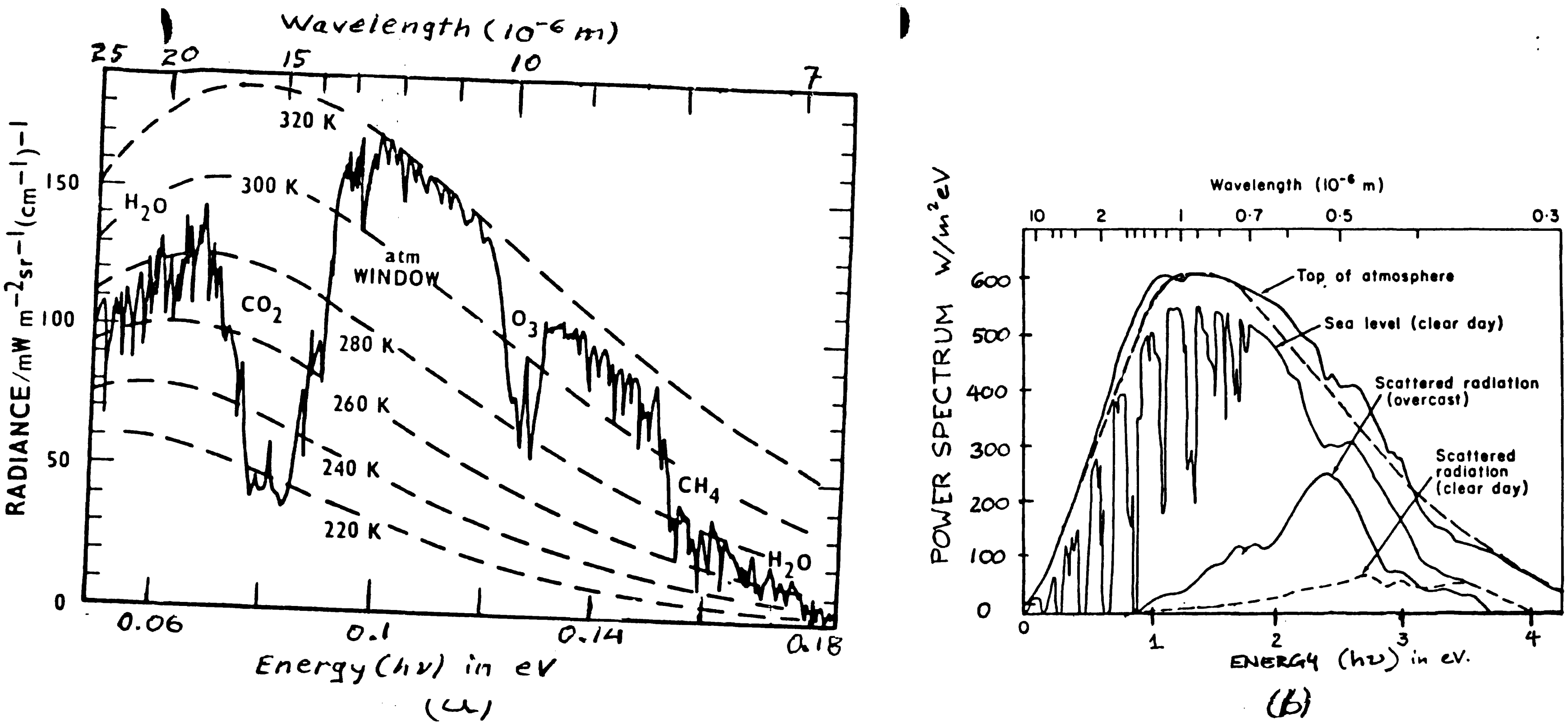


Figure 3.4 (a) (left) and (b) (right). Solar and terrestrial spectra relevant to our needs.

(a) Emission spectrum of infrared radiation from the earth, as measured by a satellite above the Sahara. The smooth curves indicate emissivity spectra of black-body radiators at the indicated temperatures. (Hanel et al 1971; Roach and Slingo 1979; Lacis et al 1981)

(b) The solar power spectrum. The upper dotted line represents a 5760°K black-body spectrum, normalized by the measured incident curve.

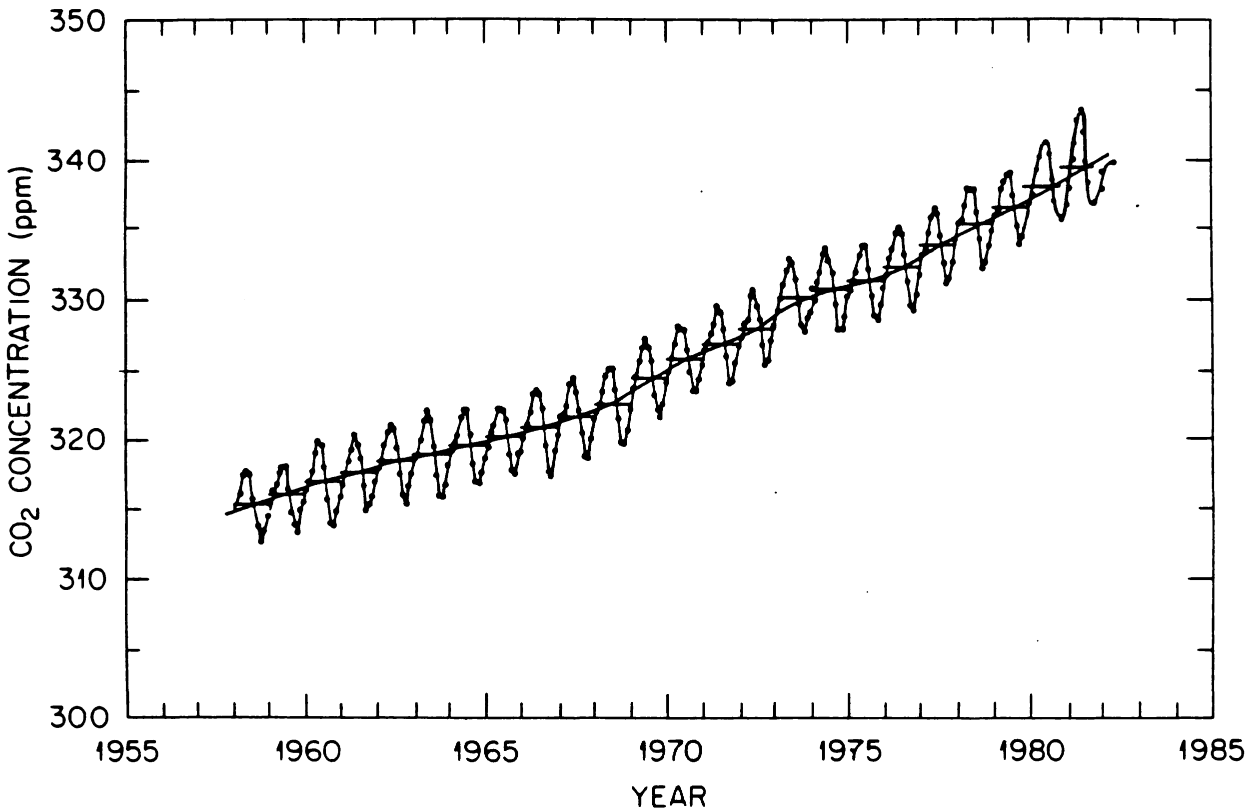


Figure 3.5 CO_2 concentration at Mauna Loa, Hawaii between 1958 and 1980. Data from C.D. Keeling et al, Scripps Institution of Oceanography. The average annual increase 1960-'69 was 0.89 ppmv, and during 1970-79 was 1.28 ppmv.

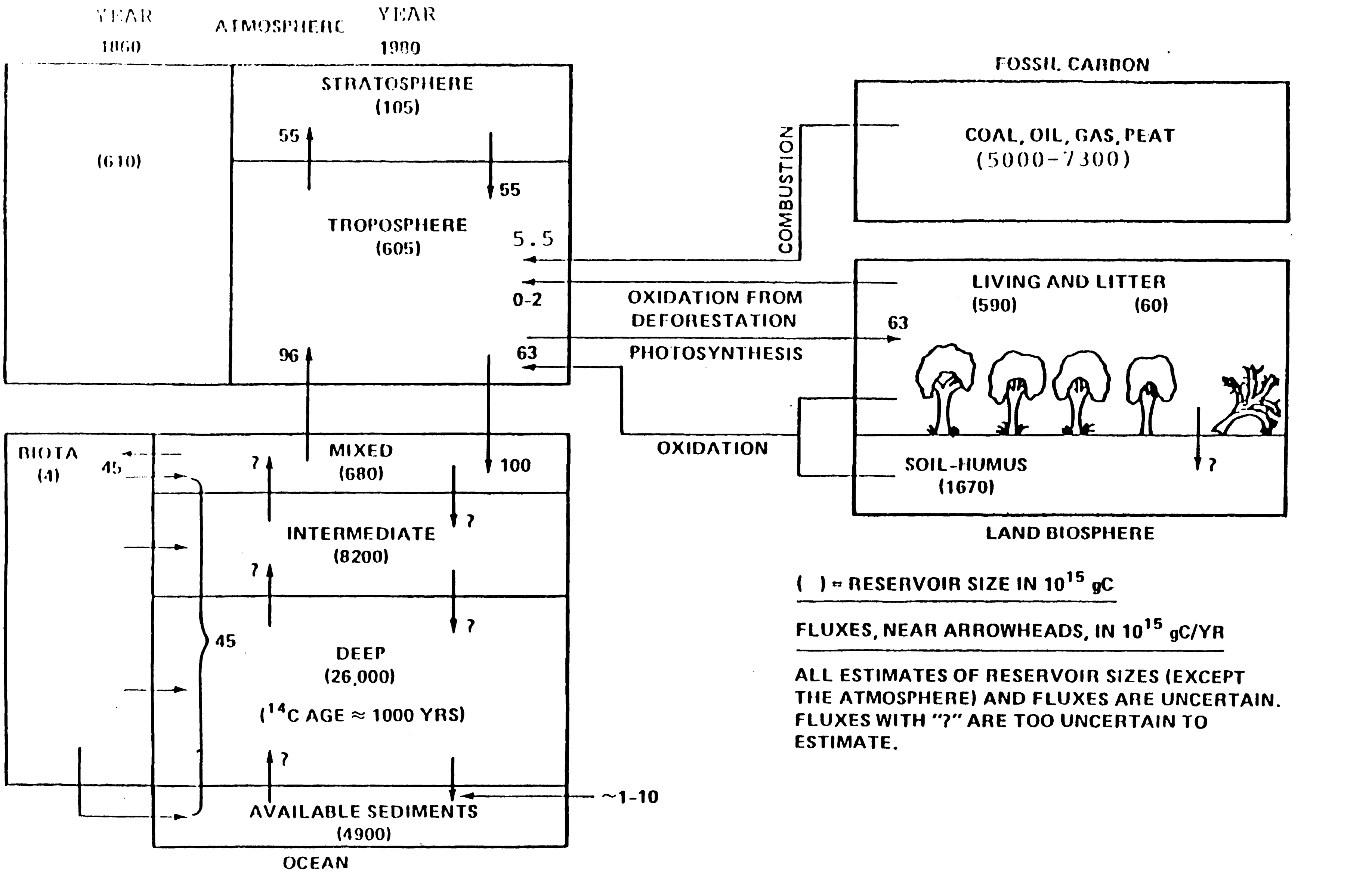


Figure 3.6 Exchangeable Components of the Global Carbon Cycle

[Adapted from (B. Bolin et al, 1979) ~~eds. The Global Carbon Cycle (Scope Report 13)~~.
~~J. Wiley & Sons, New York, 1979, which is an~~ extensive review of ~~this topic~~].

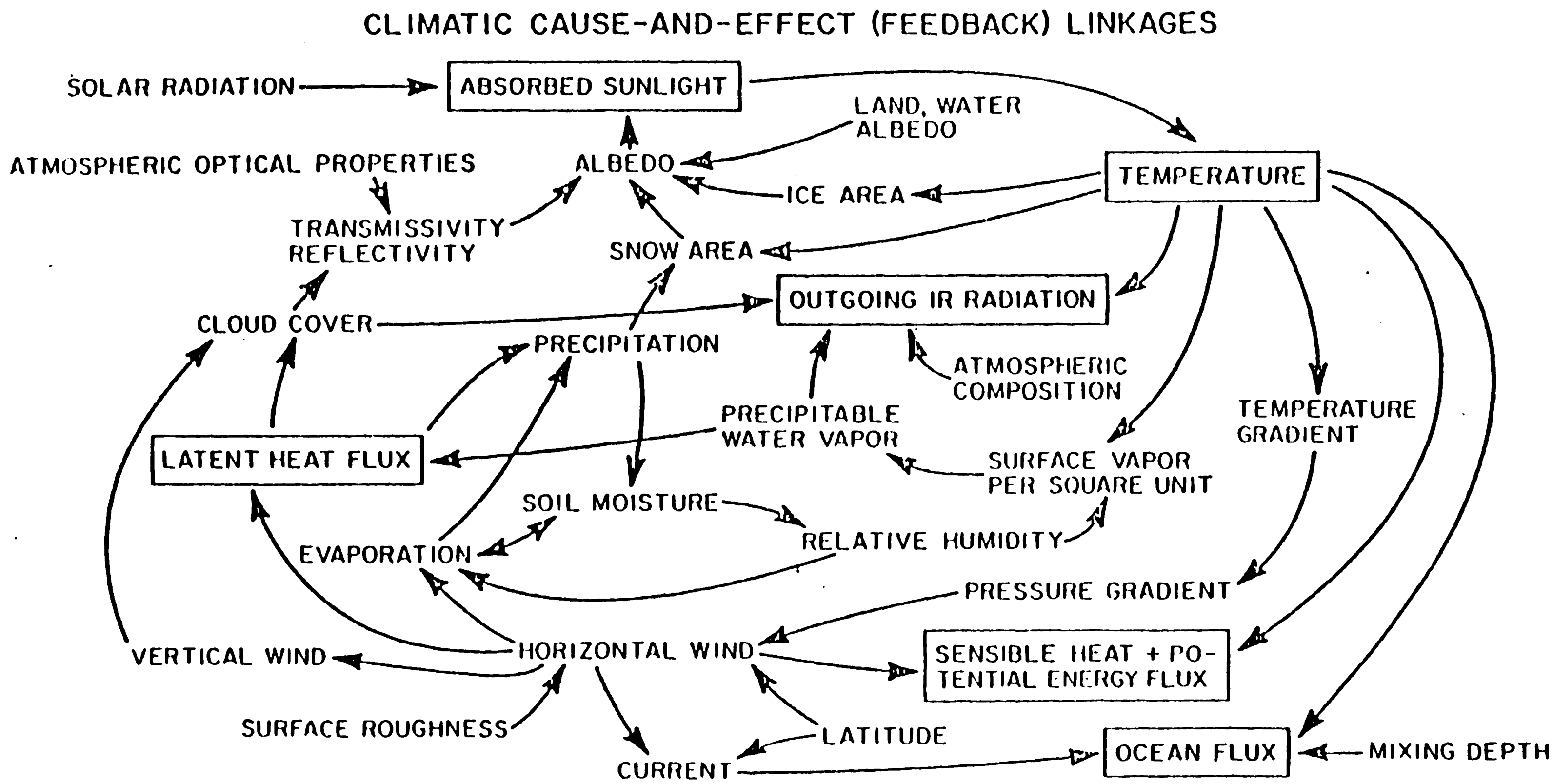
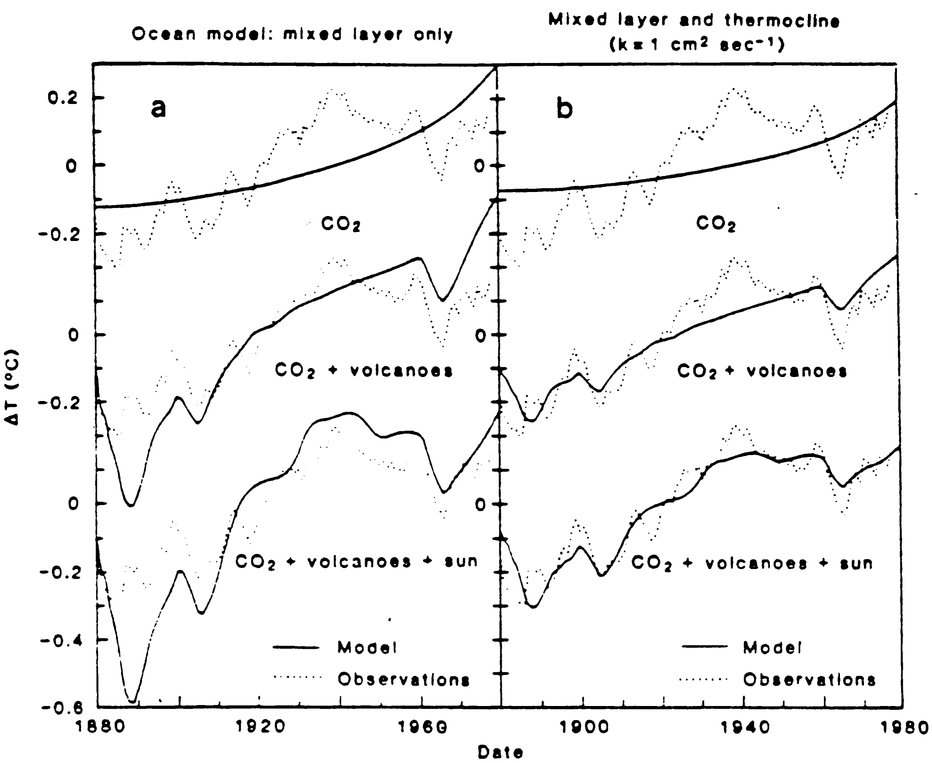


Figure 3.7 Interactions, linkages and feedback loops in the climate system [from W.W. Kellogg and S.H. Schneider Science 186 1163, (1974)]



. Global temperature trend obtained from climate model with sensitivity 2.8°C for doubled CO_2. The results in (a) are based on a 100-m mixed-layer ocean for heat capacity; those in (b) include diffusion of heat into the thermocline to 1000 m. The forcings by CO_2, volcanoes, and the sun are based on Broecker Lamb and Hoyt . Mean ΔT is zero for observations and model.

Figure 3.8 Filtering the "signal" out from the "noise" (From (41))

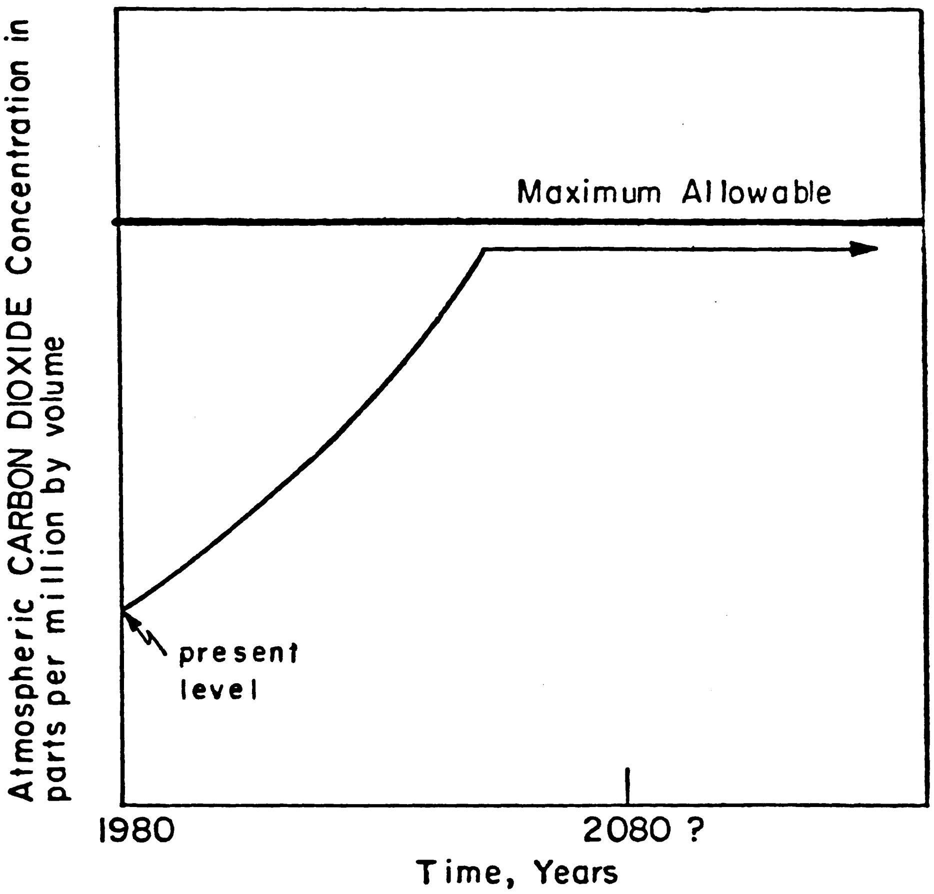


Figure 3.9a Can we go up almost to maximum allowable CO_2 level, then control it like this ?

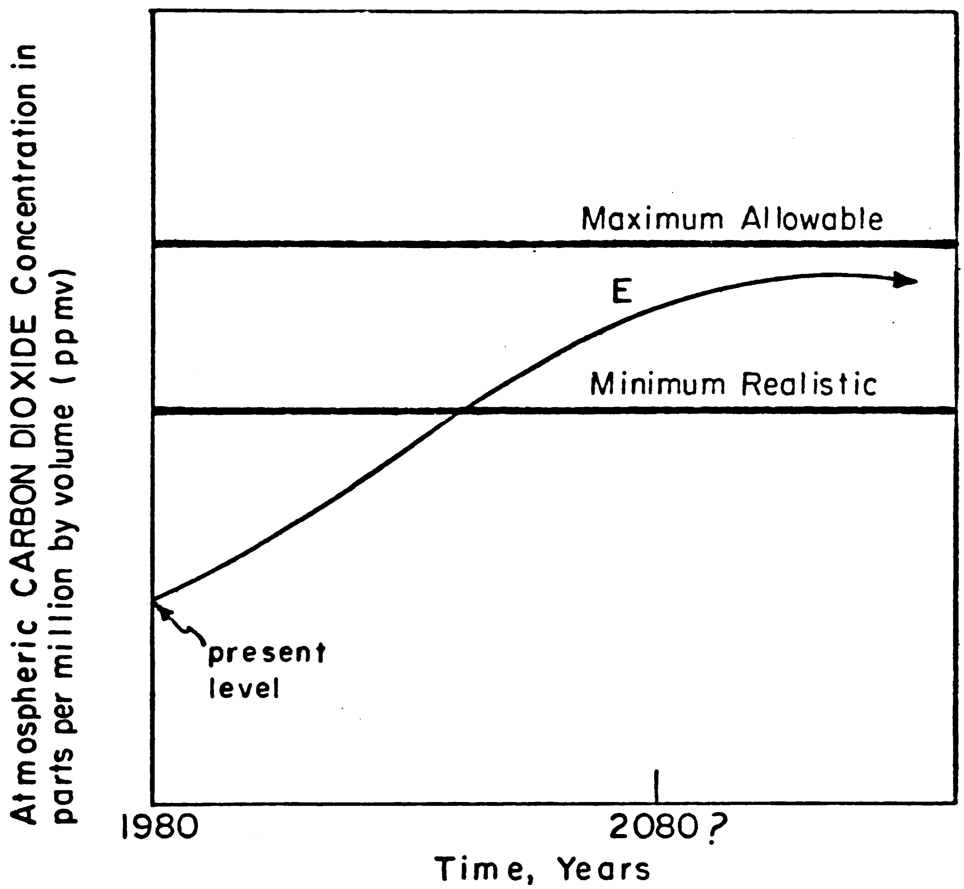


Figure 3.96 Things as some imagine and many wish.

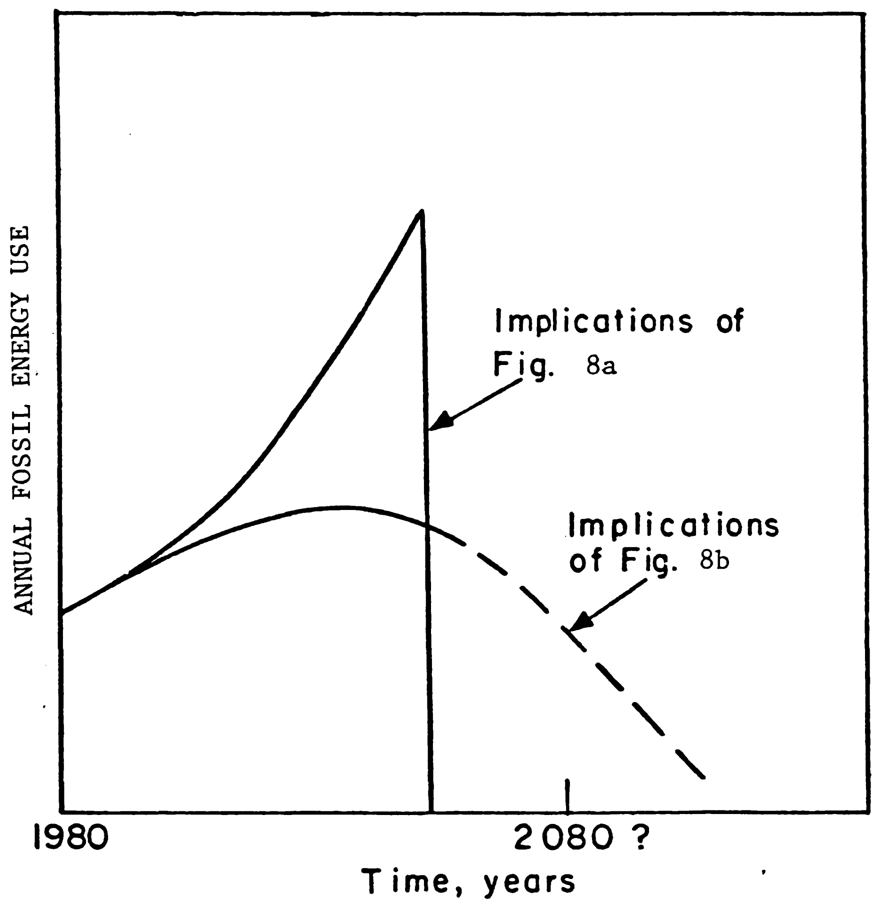


Figure 3.10 Implications of the two scenarios in Figs. 8a and 8b A sudden stop is impossible.

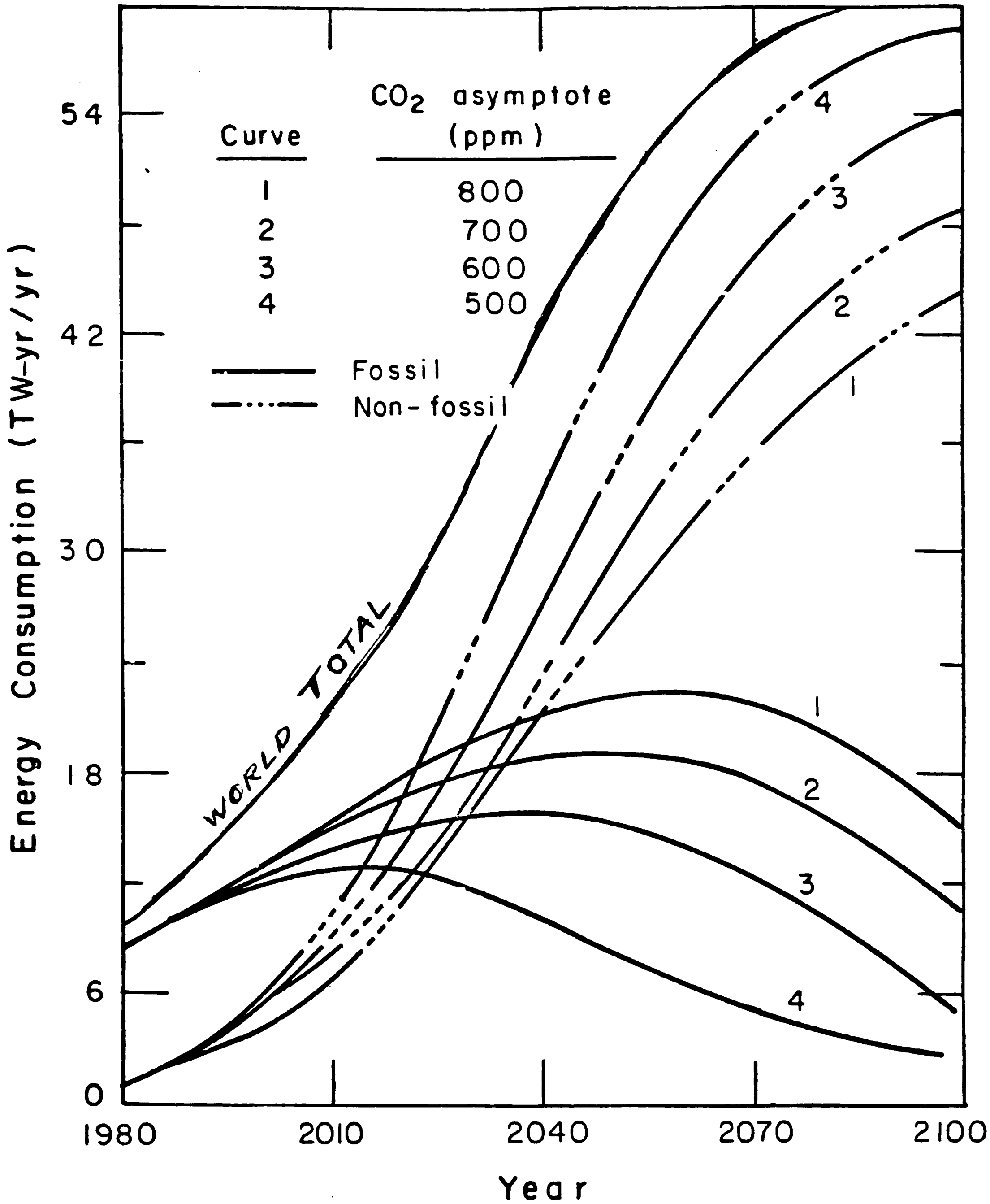


Figure 3.11 Effect of Asymptotic CO_2 limit on the Fossil and Non-fossil Components of World Energy Supply (High Scenario; LC/HN, AIT = 1980)

1.52/r

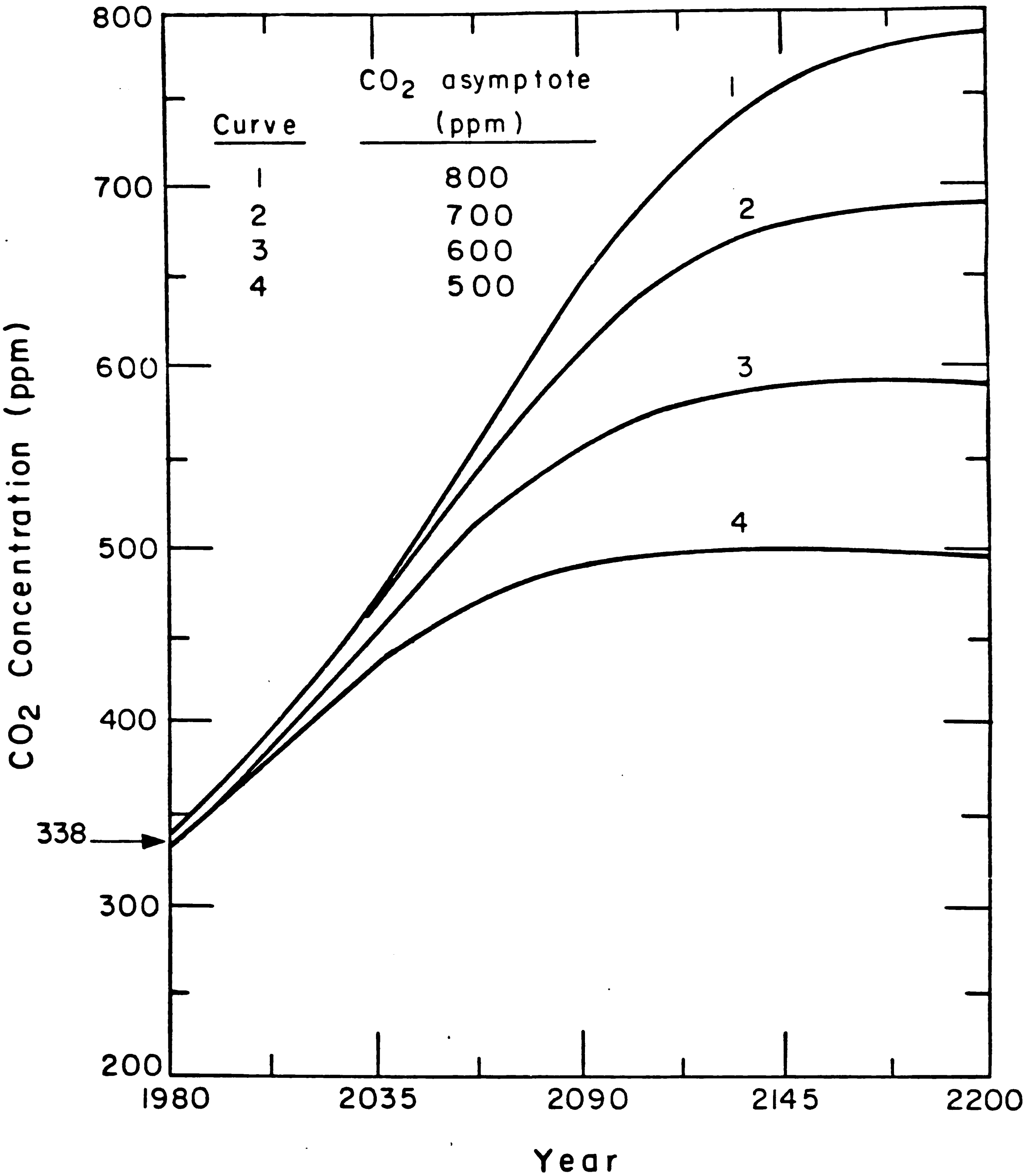


Figure 3.12 Projected Atmospheric CO_2 Concentration for the Scenarios Shown in Fig. 5.10.

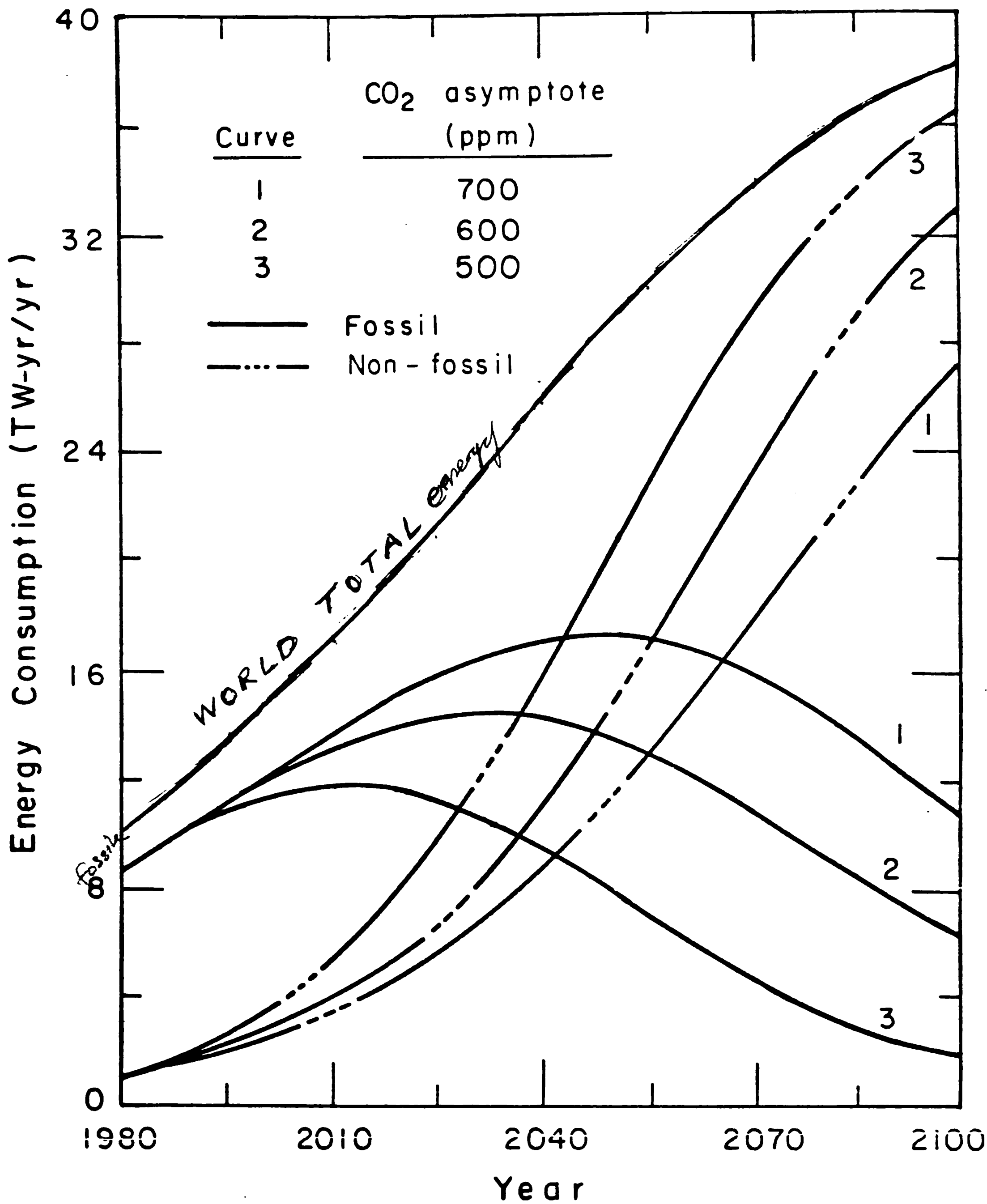


Figure 3.13 Effect of Asymptotic CO_2 limit on the Fossil and Non-fossil Components of World Energy Supply (Low Scenario; HC/LN, AIT=1980)

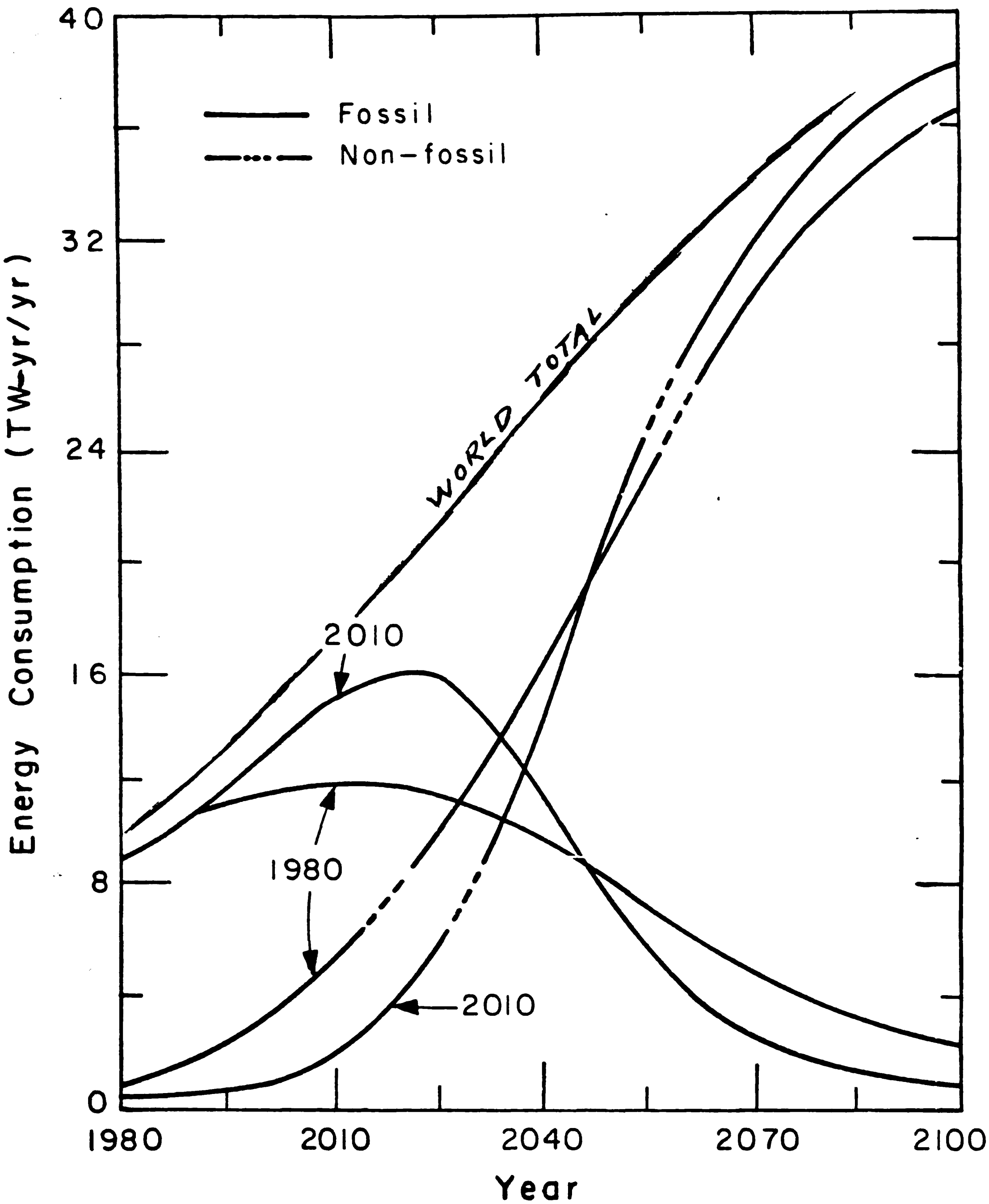


Figure 3.14 Effect of Action Initiation Time on the Fossil and Non-fossil Components of World Energy Supply for Asymptotic CO_2 of 500 (Low Scenario; HC/LN)

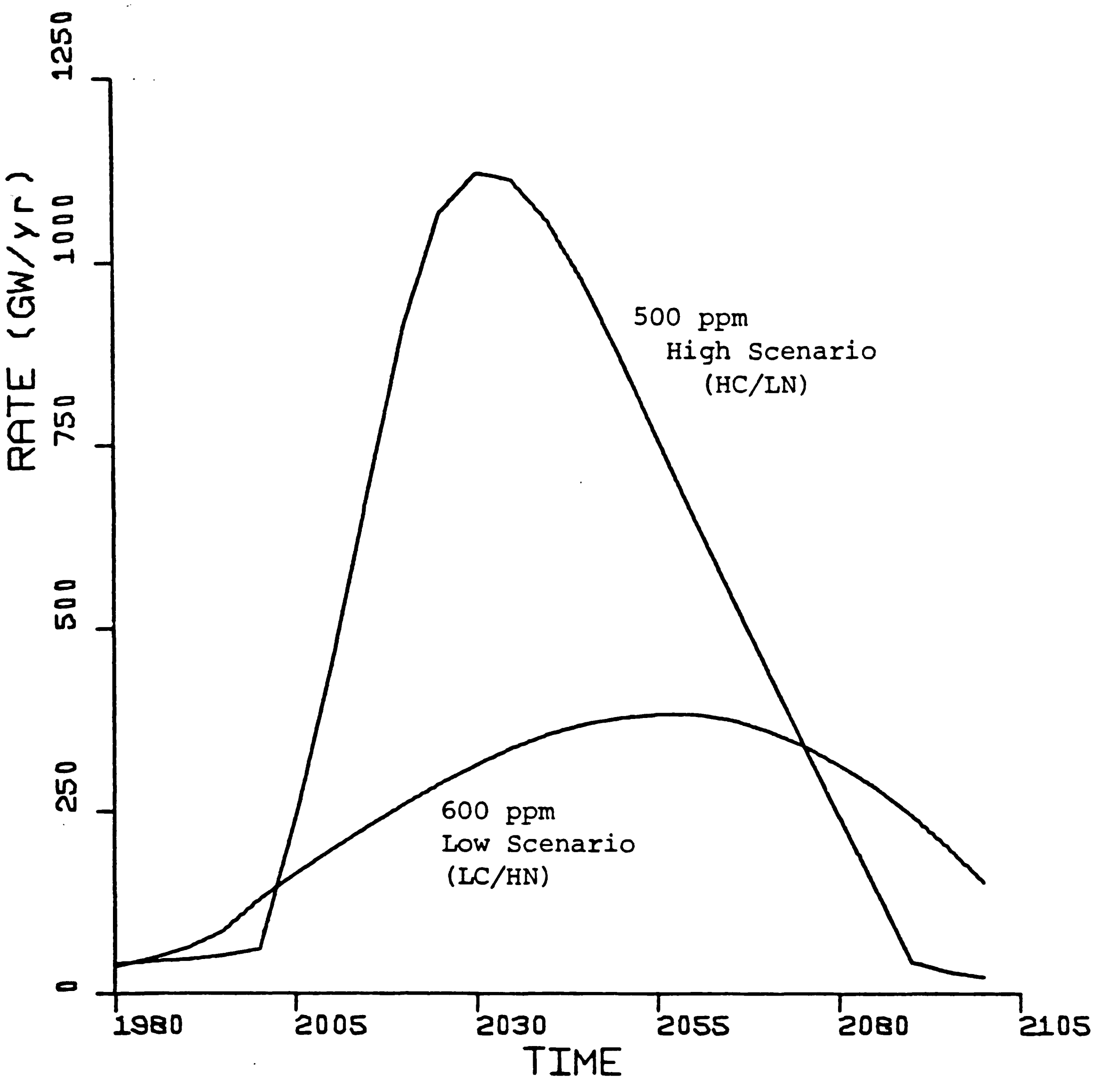


Figure 3.15 Required rate of startup of new non-fossil energy technologies for Action Initiation Time of year 2000, for two semi-extreme cases.

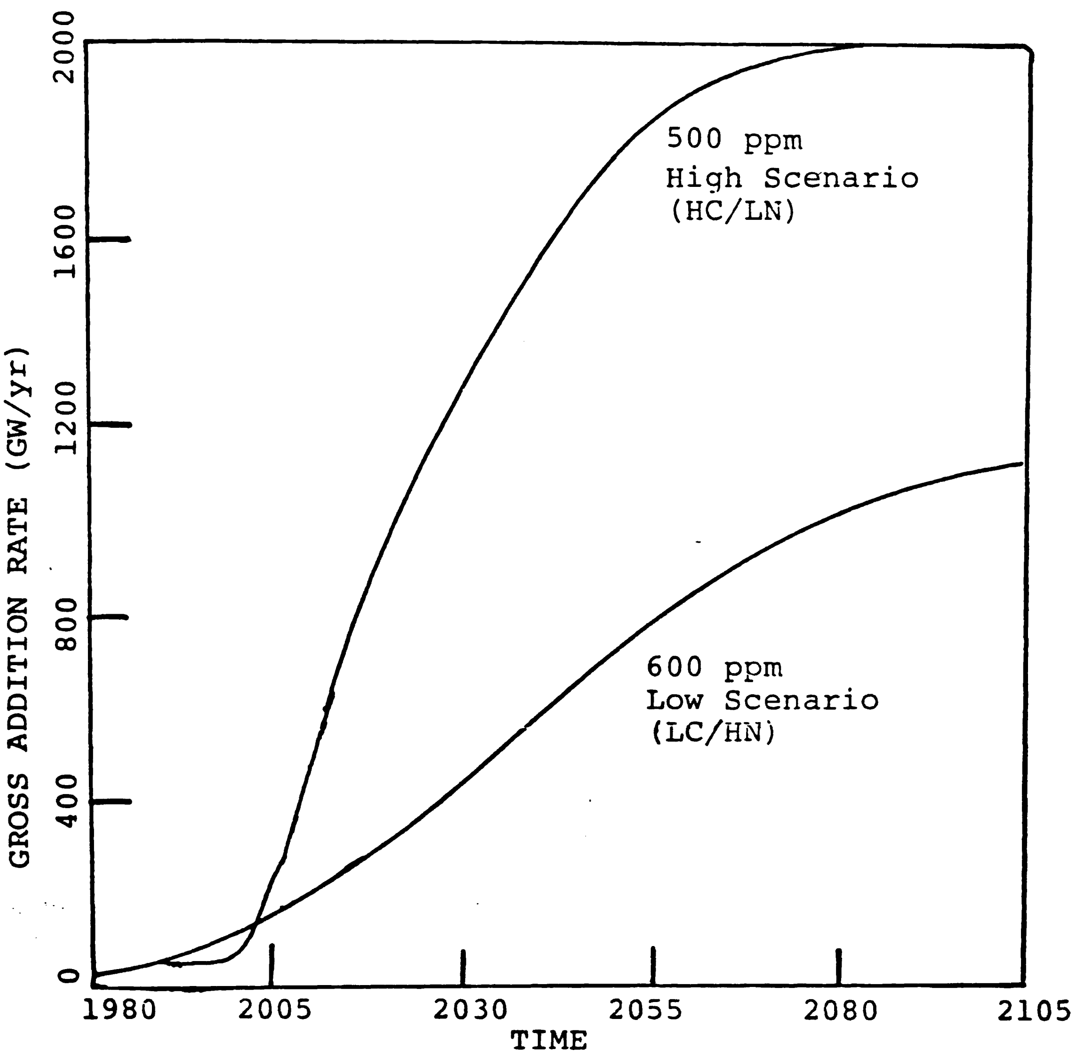


Fig. 3.16 Gross annual additions of non-fossil energy facilities (AIT = 2000)

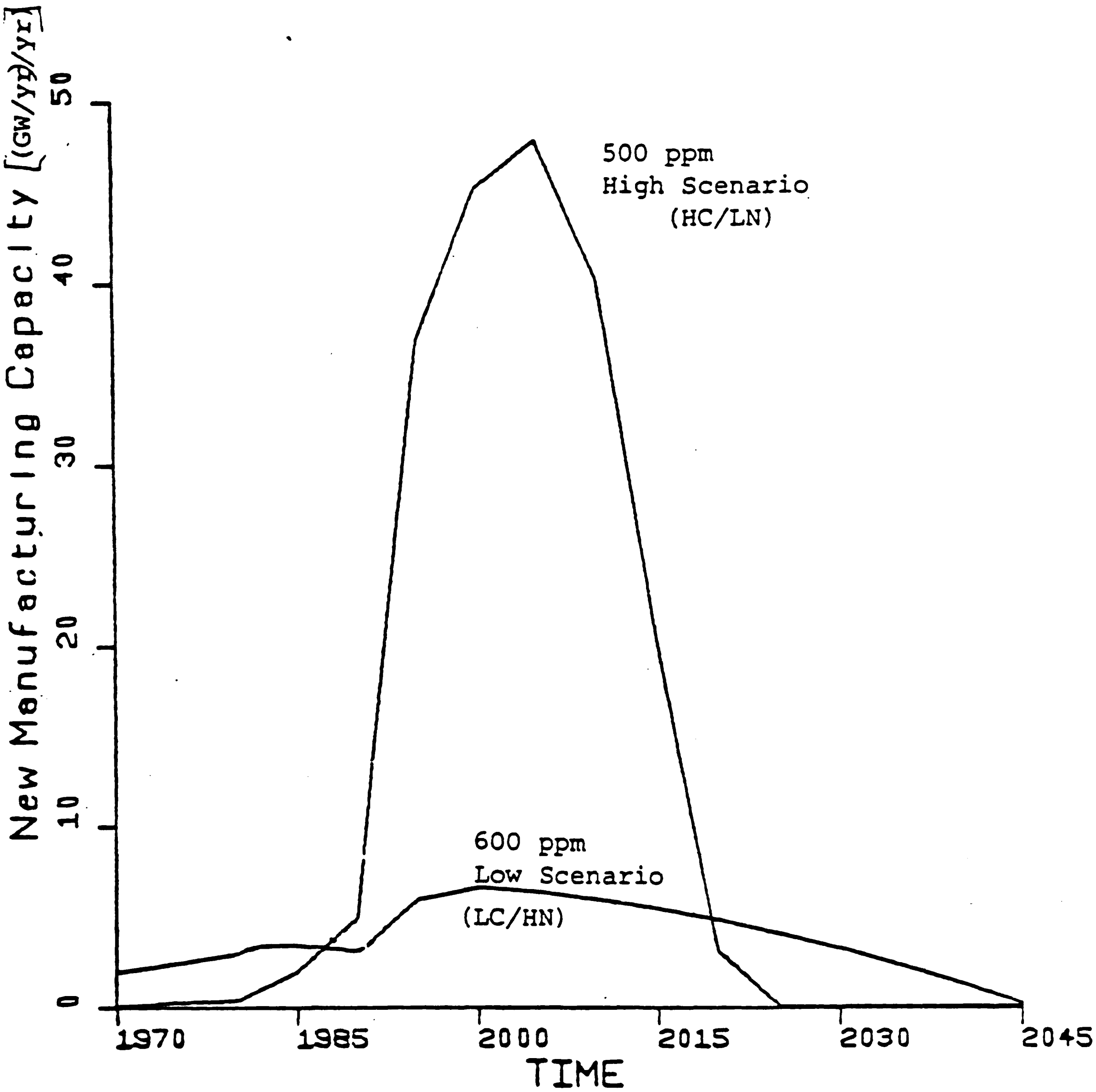


Fig. 3,17 Required Rate of Buildup of new manufacturing capability of the curves in Fig.5.14.

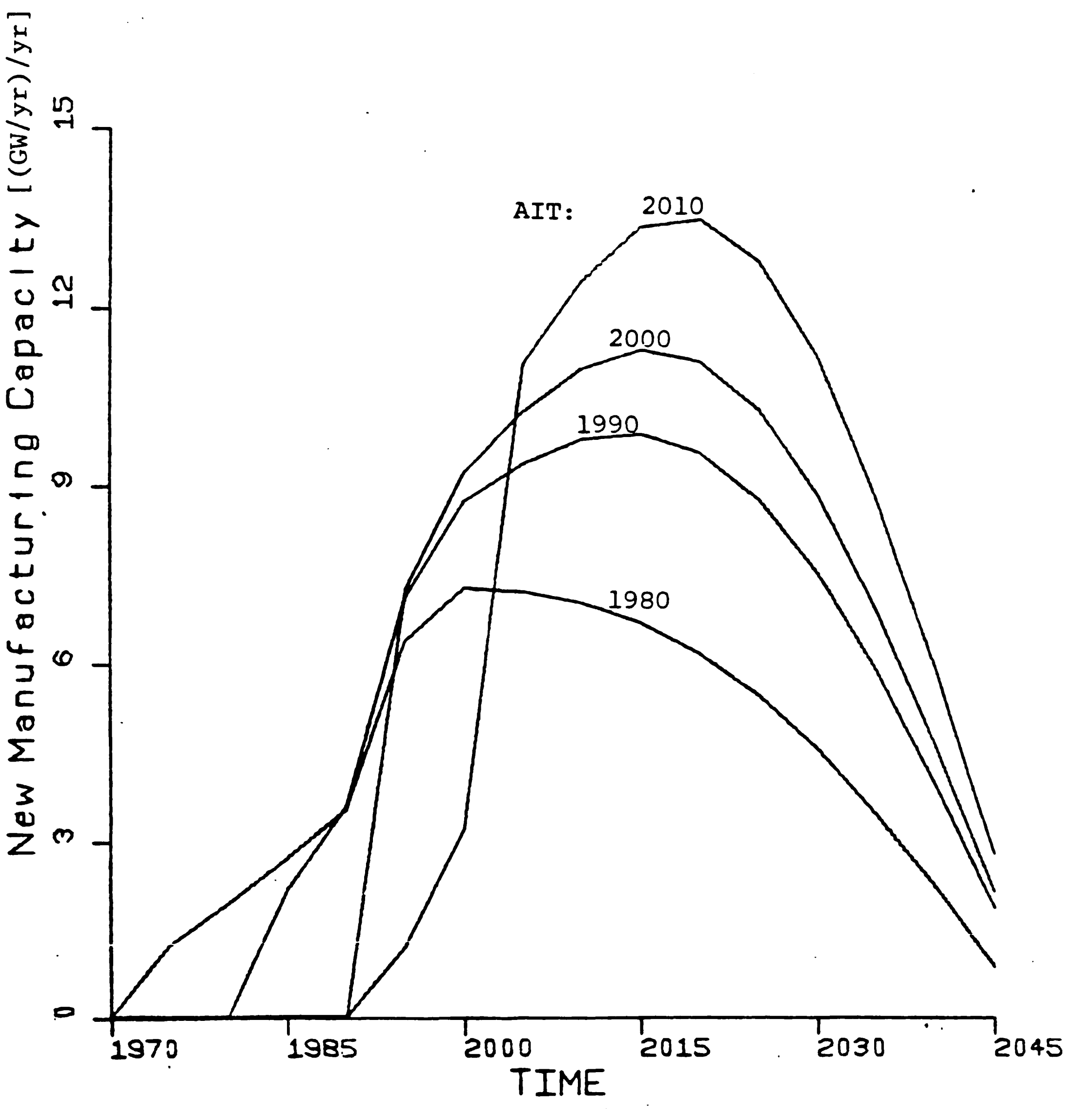


Fig. 3.18 Effect of Action Initiation Time on the required rate of buildup of new manufacturing capability for Asymptotic CO_2 of 600 ppm and Low Energy Scenario (HC/LN)

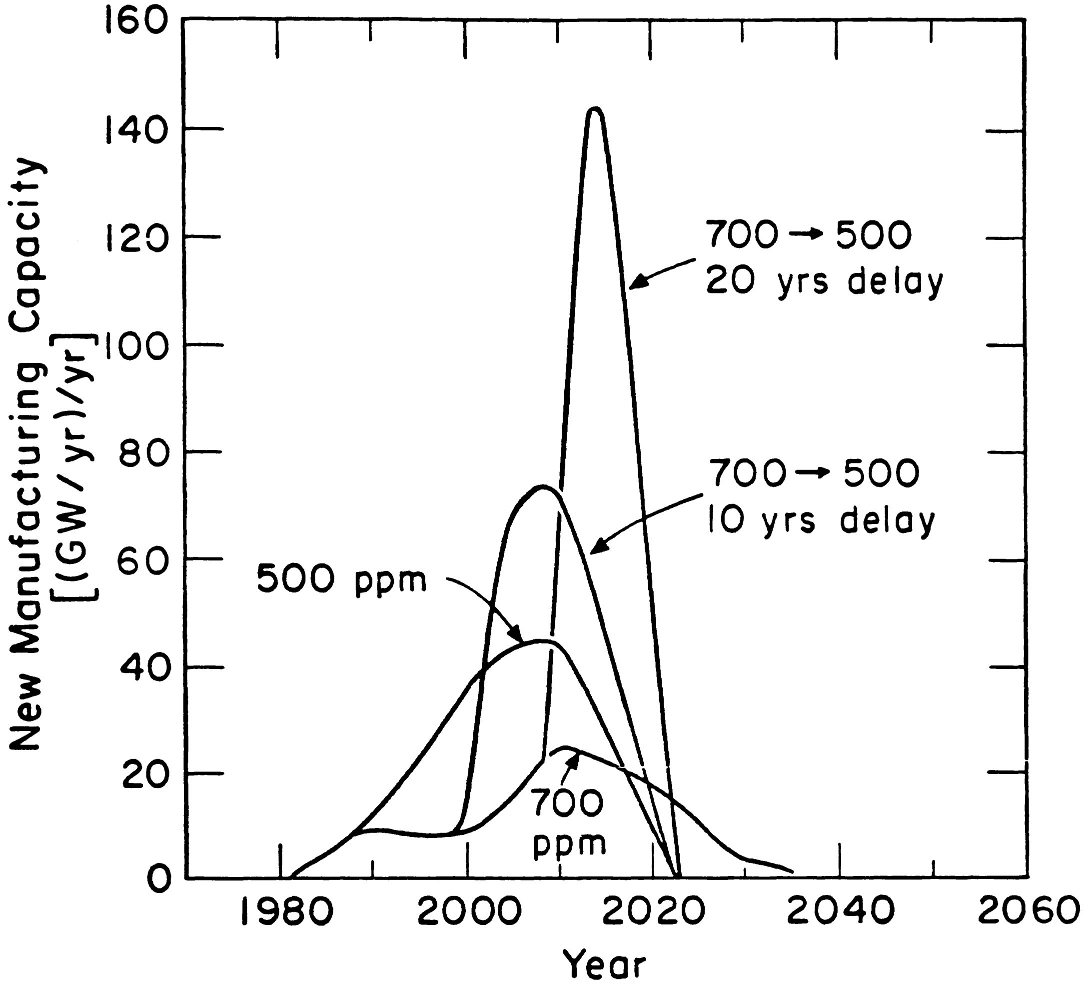


Fig. 3.19 Effect of the "change of mind" Policy on the manufacturing capacity required. (High Scenario, AIT = 2000, HC/LN)
Shift from 700 ppm asymptote to 500 ppm asymptote.

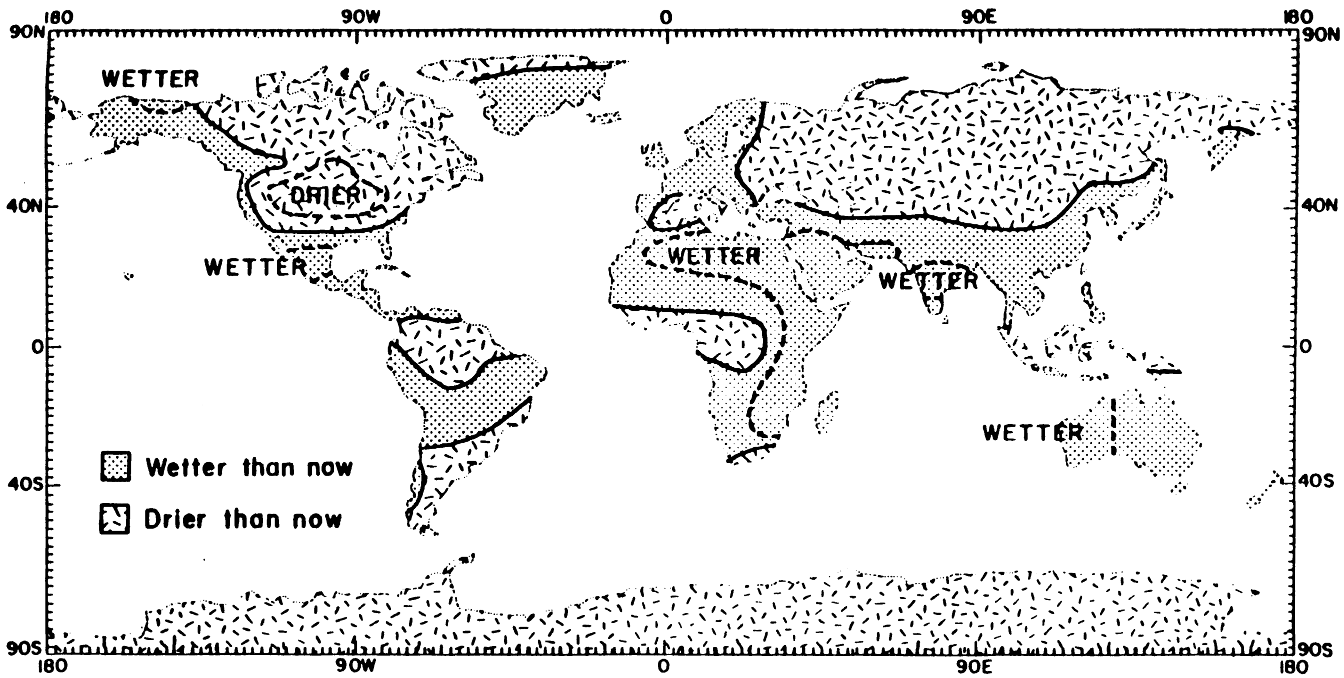


Fig. 3.20 Kellogg (1981) updated scenario for possible precipitation changes in a warmer earth. Labelled areas (defined by dashed lines) are those in which more agreement between various researchers is reached.

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CHAPTER 4

RATIONAL AND EFFECTIVE ENERGY USE: CONSERVATION

4.1 INTRODUCTION

The environmental consequences just described, other consequences to be described later, rising costs and long-term depletion of resources establish the importance of using energy efficiently and productively, of not squandering its thermodynamic potential. The ubiquitous and casual use of energy creates an attitude of false familiarity which leads to undervaluing both the importance and complexity of rational and effective use. Other impediments also exist, to be described later. Knowing the substantial possibilities for better use of energy also influences our ideas of how much needs to be provided, and often of what kind. Therefore, this chapter precedes those that deal with supply options.

No sharp distinction exists between rational suppy and rational use, or even between whether some particular facility should be viewed as supply or use. Should a solar-heated house be described under energy provision or energy conservation? Some topics in this chapter could with equal logic have appeared elsewhere, and vice versa, mutatis mutandis.

The history of energy provision, use and accounting is fascinating. H. G. Wells (1914) proposed an energy utopia.* In the early 1930s, Scott (1933), the founder of the Technocracy, Inc. movement, proposed an energy theory of value, based on the second law of thermodynamics. Corresponding roughly to modern concepts of energy availability, all society would be organized to conform to a social system built on these values. The mood of those Depression years in the United States stimulated many to seek salvation in simplistic systems--the logo of the 1932 Chicago World's Fair was: "Science discovers, technology provides, man conforms."

The simplistic ideas persist, albeit sustained by different stimuli, most recently by high fuel costs. Odum and Odum (1976) proposed much the same thing in 1974; Rifkin and Howard (1980) tried to exalt the concept of entropy to a universal religion, abhorring any capricious increase of entropy as if it were equivalent to the loss of precious bodily fluids.

All these single-item theories of value--Marx's labor theory, or pure capital theories, for example--suffer from the disease of selective inattention to the interconnectedness of things and to the complexity of civilizations.

Nevertheless, energy has value, and therefore value lies in its rational and effective use. This is especially true as energy is realized more and more as being a public good, tied to public welfare, environmental quality, food, international trade, international security, and development. Rational and effective use of energy, commonly and often inappropriately called energy conservation, then stands almost self-evident, demythologized, along with rational and effective use of capital, of labor, of food, of everything, all of which can be summed up in the phrase "Waste not, want not."

Speaking of "rational and effective use" in preference to "conservation" is more than mere semantic detail; to many financially constrained groups, "conservation" can sound like curtailment imposed by the rich upon the poor, whereas the more correct phrase makes clear that the activity is applicable to rich and poor societies alike. Extracting the maximum utility from each unit of available energy is a task of global importance. Nevertheless, the word "conservation" has become so embedded in literature and bureaucracy that it will be used here, with its broader implication.

Allied to these ideas about energy conservation are the changing attitutdes toward it during the past decade. The first coherent program supported by the U.S. Federal Government started in 1970 at the Oak Ridge National Laboratory, in Tennessee. But the idea of rational and effective energy use got little serious suport at first. Present Nixon's first energy message in 1971 had in its first draft a strong plea for conservation, which was struck from the final version. In 1974, then-Secretary of Transportation, Claude Brinegar, in response to a query about why his department was taking no action to stimulate fuel economy in automobiles, replied that the Federal Government had no intention to intrude on the free choice and rights of the people. Also in 1974, the first submitted budget of the newly formed Energy Research and Development Administration (ERDA), for the fiscal year 1976 had \$33 million for "conservation," of which \$30 million related to items such as reducing losses in electric transmission systems, and only \$3 million was for all end-use of energy.

However, a combination of economic, technical and political arguments brought about rapid increases in the conservation budgets, federal and state grant programs, and tax credits. Four years later, in FY 1980, the U.S. Federal energy conservation budget reached \$780 million, and the tax credits totalled \$650 million, as shown in Table 4.1

In early 1981 the Federal attitude changed drastically, with attempts by the Reagan Administration to curtail as many of these programs as possible, in the belief that they were more appropriately placed and efficiently carried out by the private sector in the market-place. This chapter deals with some pros and cons of that matter.

4.2 PUBLIC SECTOR INTERVENTION

Business time perspectives that govern heavy investment decisions, in particular to produce oil, gas and coal, are typically five years, and usually not more than ten years, determined by the expected return on investment, cost of borrowed money, etc., as described in Chapter 2. Also, both technical literature and practical experience offer many examples where the return on energy "conservation" investments is higher; or what is the same thing, the payback time is shorter. Thus, superficially at least, it seems that energy conservation ~~will~~ would come about by rational market mechanisms, and government would have little role to play.

That may be true in a perfect steady-state economy, but in fact energy conservation is liable to lag behind supply, despite the apparent investment advantages just mentioned. The same literature and the same data that show the potential also show that the the activity lags. There are several reasons.

Energy provision brings fairly prompt rewards to well-developed commercial groups ready to receive them, for doing tasks (mining, drilling, pumping, etc.) which may be technologically complicated, but are fairly simple to organize. The petroleum industry, albeit complex compared with a grocery store, is much less complex than the totality of stores, farms, residences, transportation systems and industries (including the petroleum industry) which make up the fabric of civilization. That larger sector, more massive, diffuse and poorly organized, does not usually respond rapidly. Social costs (pollution, for example) generated by industry or any other sector generally fall upon this less-well-organized public later in time.

In contrast to the more-simply-organized supply sector, rational and effective energy use above the personal and local level involves the less-well-organized public majority, and hence tends to lag. Investment now for later benefits may be possible for an industry concerned with and expert in its own business, but may not be understood by, or be available to, many energy consumers. This non-parallelism between the two sectors works to the disadvantage of conservation, which then loses out unless public law and/or public spirit intervene.

Examples abound. The well-discussed case of whether the landlord or the tenant insulates the rental apartment is typical. If the landlord pays for the heat and can add it to the rent, his motive to insulate ~~evaporates~~ disappears. But the tenant will not be anxious to pay for a long-term benefit which accrues principally to the landlord, unless the tenancy is very long-term. Thus a rational conservation opportunity evaporates. Until the late 1970s, the automobile industry found little incentive to downsize its cars and improve engine efficiency; the automobile industry would have had to pay the costs, and the public would capture the benefits. Consequences of neglect are well known. In the late 1970s, market pressure finally took over, but in a different way. Manufacturers of small cars, principally in Japan but also in Europe, who had been used to matching their products to high petroleum costs, in general had taken a longer time perspective of the problem, and had collaborated more effectively with their governments in developing small energy-efficient cars. Then, when the combination of public awareness and rapidly rising petroleum prices stimulated a search for public alleviation, the imports were prepared, and Detroit was not. A somewhat colorful but generally accurate account of the subsequent distress of much of the U.S. auto industry is contained in an article, "The Wreck of the Auto Industry," by William Tucker, in Harper's, November 1980, pp. 45-60.

In addition, consider an industry dedicated to making some particular item. Suppose it is suggested that, by redesigning the plant so as to capture waste heat, perhaps cogenerate electricity, etc., a significant energy and dollar saving could be realized. But the engineering effort to accomplish these tasks lies outside the normal activity of the company; therefore, valuable time of its best engineers must be diverted from a known profit-making activity to something else that seems less certain, despite predictions (by others) of substantial benefit. The company then usually wants to see an even shorter return on investment for engaging in this (to them) extraneous activity, if it is to divert its effort. Thus again the system is out of balance.

These and other imbalances stimulate knowledgeable entrepreneurs to offer these services for fees, and also suggest the appropriateness of activity by the public sector in the form of technological R&D, grant programs, tax incentives, information and education, or some other activity depending on particular circumstances. A rational government would normally use a combination of them.

4.3 SUPPLY-DEMAND, AND THE DECOUPLING OF ENERGY AND GNP

The idea of rational and effective energy use is often expressed as saving barrels of oil (or coal, etc.) more cheaply than providingly them. Figures 4.1 and 4.2 present the idea graphically.

Consider first the upper part of Figure 4.1, concentrating first on only the curve marked "supply" passing through points A and B_o. In the simplification adopted here, different fuels are not distinguished by type or suitability, but only by price. Some is available at low cost, near point A on the price axis. More can be supplied, but at higher cost, so the price per unit increases with the demand; most supply curves have the generally concave shape shown in the figure.

Next, observe the curve marked "demand"; in general, if the price per unit is low, demand is high, and vice versa. Thus the demand curve declines with increasing price, as shown.

The two curves cross at point B_o where, in a perfect economic system, supply equals demand, at a price P_o and quantitity q_0. This corresponding price P_o is called the marginal cost, the cost to provide the next unit of energy. If supply were to become more expensive, for example because of the need to replace depleted cheap resources with more expensive new ones at the margin, the supply curve shifts toward the right, the equilibrium point B_o moves correspondingly, the equilibrium price increases, and the equilibrium quantity q_o decreases.

The slope of the demand curve at the equilibrium point determines the so-called price-elasticity of demand, ε_D, which is in this case

$$\varepsilon_D = \left(\frac{P_o}{q_o}\frac{\partial q}{\partial p}\right)\Bigg|_{B_o} \qquad (1)$$

and usually $-1 < \varepsilon_D < 0$.

How much did all this energy cost to provide, up to the point B_o in Figure 4.1? How much was paid for it? The two questions are not necessarily identical, and involve complicated questions of pricing policy and government regulation. The presumably cheap energy near point A is not more costly to produce because the most expensive unit sells at P_o. Thus the annual cost to produce all the energy is approximately given by the area bounded by curve O-A-B_o-q_o-O (quad/yr x \$/quad = \$/yr). Is that what the customers pay? The fortunate producer with source cost A is likely to charge the full marginal cost P_o if he can get it, reaping what is sometimes called a windfall profit. Thus the total payment to the energy sector may be as large as the rectangle O-P_o-B_o-q_o-O.

Cost and price are not necessarily the same. OPEC oil at \$3/bbl to extract and ship sells for \$30 in Amsterdam. This elementary discussion cannot include more than mere mention of the complexity, and must settle upon a simpler picture. Here and in what follows, the profits will be treated as internal transfers or re-arrangements; so, when a choice must be made, the actual cost of the service will dominate the discussion. That approach and its limitations will tend to underestimate the benefits obtainable via conservation strategies, because that approach conserves average-cost fuel, whereas conservation generally saves marginal-cost fuel. But the basic concepts embodied in the figures remain valid in any case.

Now consider the effect of energy conservation. The same energy service is to be required, but some of it will be obtained by strategies of increasing efficiency and so forth. This conservation comes at a cost, shown in the lower part of Figure 4.1. Unlike the supply curve, this one starts vertically upward from the origin, implying that some conservation comes at zero cost (closing windows, turning out unneeded lights) and an appreciable amount comes at low cost. Real experience bears this out; compare this schematic curve with Figure 4.7, which shows (with the ordinate inverted) the cost of various energy conservation actions in the residential sector.

Energy conservation erodes the energy demand, starting at the no-conservation equilibrium point, where the total demand was q_o. Thus the conservation curve of the lower part of Figure 4.1 can be inverted and applied to the upper part, with the conservation origin at q_o, as shown. The same total benefits are being received, but now at a lower cost because energy is saved at the margin. The conservation and supply curves cross at point E in the figure, and define the optimal startegy, at least up to here in this simple debate. With that much effort put into conservation, providing the next barrel of oil costs the same as saving a barrel. The total shaded area is a minimum, reperesenting the minimum total cost to provide the energy service.

no ¶ (Whether the supply price will in reality be a rectangle with vertex at point E, rather than the shaded figure with sloping side A-E depends on the circumstances discussed a few paragraphs earlier, under windfall profits.)

Figure 4.1 shows more. A sub-optimal conservation program will lead to operation at some higher point on the supply curve, for example point F, at higher total cost. Also, an energy conservation program will itself free up economic wealth, and some part will be used for new energy services. Therefore, the system tends to move toward q_o', with a new equilibrium at E', sub-optimal conservation at F', etc. Many other games can be played with figures like this.

As energy costs and prices increase with time, rational and effective use become increasingly important. Figure 4.2 shows how the curves of Figure 4.1 might be affected, if the real cost of energy supply were to double in (say) 20 years, but the demand for energy services remained the same. The entire volume to the left of the surface $A-B_o-B^*_o-A^*-A$ represents what would have been the total energy cost during the two decades, with no conservation. Optimal conservation leads to supply-demand following the curve E-E*, which slopes downward as time increases. Now the much smaller volume between the two shaded areas represents the total cost. If the demand itself, q^*_o, had also increased with time, as will in fact be the case globally, the importance of and reward from conservation strategies would have been even more pronounced. In times of rising demand and costs, good conservation strategies have large future payoffs.

Consider now the second major topic of this section; whether and to what extent energy and national or global welfare can be decoupled. The usual surrogate for national welfare is gross national product (GNP), sometimes gross domestic product (GDP), imperfect surrogates but adequate for this discussion.

Energy projections for developing countries show the ratio Energy/GDP rising during early stages, then passing through a broad maximum before declining, as sophisticated, highly technological service enterprises replace more energy-intensive production-oriented ones. For this, an energy-GDP elasticity can be defined as

$$\varepsilon_G = \left[\frac{GDP}{E}\,\frac{\partial(E)}{\partial(GDP)}\right] \tag{2}$$

or what is the same thing

$$\frac{E(t_2)}{E(t_1)} = \left[\frac{GDP(t_2)}{GDP(t_1)}\right]^{\varepsilon_G} \tag{3}$$

where t_1 and t_2 are two given times, E is measured in physical units, and GDP is measured in non-inflated money. The IIASA scenarios referred to in Chapter 1 and a lower energy case (16 TW in 2030) proposed by Colombo and Bernardini are characterized by primary energy-GDP coefficients ε_G for three of their world regions listed in Table 4.2.

Elasticities $\varepsilon_G > 1.0$ imply energy use is rising faster than GDP; the 16 TW case assumes such sharply rising energy prices that energy use is severely constrained everywhere, and that developed countries decreased per capita energy consumption due mainly to higher efficiency of end use.

The energy being discussed in these cases is energy that reaches the commercial sector; in fact, the ratio E/GDP may not be rising at all, when non-commercial energy, which is largest at early development stages, is included. See Figure 1.7 for typical ratios of non-commercial/commercial energy. Thus, the rising-falling curve may give the wrong impression, that energy efficiency techniques are more-or-less irrelevant at early development stages. The case of the U.S. shows these effects very well. Figure 4.3 shows the E/GNP in the U.S. from 1880 (when the U.S. was in a sense like some LDCs today) up to 1980. The data before about 1910 are misleading because wood, a major fuel then, was not included in the accounts, just as many traditional fuels like sticks, dung, grass, etc., are inadequately counted today in LDCs. ~~The three single-year points include the effect of fuel wood~~, ~~according to the authors of the quoted report~~. Overall, the ratio E/GNP fell or at worst stayed approximately constant during the entire 100-year span, and it seems reasonable that most presently developing countries will have a similar experience, especially as energy prices are expected to rise more rapidly in real terms than they did decades or a century ago. The present LDCs will become increasingly important energy users in coming decades, so the likelihood of successful fuel efficiency strategies will be important, as in the developed countries.

Figure 4.4 shows the growth and occasional decline in both constant-dollar GNP and energy use in the U.S., between 1950 and 1978. Some advocates of rapidly increasing energy supply have used this correlation to support the egregious misconception that energy conservation is inherently undesirable because it leads to lowered

GNP and other miseries. In that view, energy drives both society and the GNP.

The system does not work so simply. That is fortunate, because Figure 4.4 taken literally predicts that as energy costs rise and its use inevitably declines, the GNP would truly drop. The figure shows that the short-run correlation is strong, and that GNP and energy consumption tend to correlate (hence grow in parallel as actually illustrated) in a society that develops in an unchanged direction. It is like driving a car: the faster it goes, the faster it uses gasoline. Contrary to the prior simple view, Figure 4.4 predicts a dismal future in the absence of improved efficiency.

Further study confirms this interpretation and gives additional insights. See Figure 4.3 again. The ratio E/GNP was indeed approximately constant from 1950 to 1974, but during that time energy prices declined in constant dollars, implying that if real energy prices had remained stable, E/GNP would have declined with time. The period 1920-1945 was such a time, and Figure 4.3 shows a decline of about 1%/yr. The 1979 oil-price rises and the gradual maturation of energy conservation technologies (coupled with an economic recession) brought the U.S. energy use in 1982 back to its 1972 level--72 quads.

Supporting evidence for this trend comes from elsewhere: e.g., in Japan, the GDP per unit of energy increased by about 30% between 1973 and 1980, after correcting for inflation (EWC 1983). Total energy use stayed about the same, but (significantly) the electric fraction grew substantially, just as it has done in the U.S. and almost everywhere else.

All this becomes much clearer as we realize that the short-term elasticities are small, but the long-term elasticities are higher. That is to say, if a factory must use less energy tomorrow than it does today, it can usually do so only by shutting something down. But given time, the factory workers and management can tune up the machinery, eliminate needless heat losses, etc. Given yet more time, they can invent or buy more efficient machinery, and so gradually improve the energy productivity. How long does this latter activity take? This it the technological and capital equipment change-time discussed in Chapter 2, perhaps 30 years. If the changes were to result in zero energy use, that would imply a rate of 3%/yr. But the energy use does not vanish, it only decreases, so the real attainable ~~rate of flexible~~ long-term change is less, say 1-1.5%/yr, a rate alluded to in early chapters.

These ideas find confirmation in the sophisticated energy modeling of the CONAES study. Figure 4.5 shows the results of several modeling attempts to answer the question: if the E/GNP ratio were forced to decline from its 1975 value to a fraction of that value by the year 2010, by what fraction would the GNP decline from the value it would have had if E/GNP had remained constant?

That question, awkward to state, asks in effect about the medium- and long-term elasticities being discussed, and at what rate energy and GNP can be decoupled. The curve shows, for example, that E/GNP can decline to 0.6 of its 1975 value in 35 years with GNP being adversely affected by only about 1.3%, a number surely within the uncertainty of the calculations. Also, if E/GNP is forced below 0.4 of its 1975 value in 35 years, GNP suffers appreciably. The slower adjustment corresponds to about 1.4%/yr, and the rapid adjustment to about 2.6%/yr, numbers that support the previous physically and technologically oriented explanation.

The economy behaves like silly putty: deformed slowly, it stretches; deformed rapidly, it is brittle and may break.

4.4 THE CONCEPT OF AVAILABILITY

Consider a journey from one point to another, both points at sea level. At the start and at the end, both the kinetic and gravitational energies are the same. Yet energy was required for the trip. Two important questions arise: (1) What minimum energy was actually required? (2) What was the energy used for? These questions lead us to consider where energy is wasted and how less energy can be used, to concepts of efficiency based on the second law of thermodynamics, and to concepts of reversibility, irreversibility and entropy. Figure 1.10 showed two criteria of useful and wasted energy in the end-use sector. We will find that these are very judgmental, and depend on the systems being analyzed, on demands of material and time to accomplish the task and other factors. Here are two more concrete but still simple examples.

1. Electric versus diesel trains.

The electrical system is penalized by an average (approximate) two-thirds loss at the generating plant, but except for that the system is quite efficient. Many simplistic analyses credit the energy in the diesel system as properly used: all the fuel went into the engine. But the diesel engine as at best 40% efficient, and drives an on-board electric generator, which powers electric motors at the wheels. In actual fact, the diesel-electric system is generally less energy-efficient overall than the all-electric one, because of engine idling, inefficient operation under light load, and so forth.

A proper analysis would show the approximate equivalence of the two systems, allowing the real differences in primary fuel use to appear. Attention could then focus where it properly should--on comparative capital costs, system usage (the heavily traveled routes being prime candidates for electrification), pollution control, system control and general societal desirability.

2. Heating a specified house.

The heat lost by conduction and infiltration are specified; therefore a specified amount of hot air, at 40°C, say, must be provided. The fuel could be burned in a 70%-efficient furnace to do this. Alternatively, it could be burned at 33% efficiency to provide electricity, which might run a high-efficiency electric heat pump operating at 60% of thermodynamic theoretical efficiency to pump heat from the outside air at 0°C. The total heat delivered to the interior of the house by this route per unit of primary energy consumed is over twice that provided by the home furnace, and about 50% more than the heat in the fuel used in the power plant.

A principal difference between the two systems is capital cost. The home furnace is cheap, and the electric utility-heat pump system is expensive. Such trade-offs pervade the energy-use sector.

Beyond simple curtailment (which is not the topic of this section), decreased energy use sometimes means increased capital cost. New analyses spring up to incorporate these ideas in seeking new economically optimal arrangements.

The availability of a system is the maximum amount of work that can be obtained from it, in combination with an assumed uniform background environment with which it interacts. One method of deriving the availability is by combining the energy and entropy balances of the process.

Many processes of interest work by flow of masses across the system boundary; these materials may mix and react inside, but for present pruposes we need consider only conditions at the boundary, as in Figure 4.6. For the i^{th} stream, the rate of change of energy in the reactor for a mass flow dm_i is

$$dE_i = (e_i + P_iV_i)dm_i \tag{4}$$

where e_i and V_i are the total energy and volume per unit mass of stream i, and P_i is the pressure. For simplicity, consider e_i to consist entirely of internal energy u_i (e.g., chemical, thus neglecting gravitational, kinetic, etc.). Then,

$$dE_i = (u_i + P_iV_i)dm_i = h_idm_i \tag{5}$$

where h is the familiar enthalpy per unit mass.

The system exchanges heat at a rate $\dot{Q}_o$ with a surrounding environment at temperature T_o, and provides work at the rate $\dot{W}$.

Counting inflowing mass rates $\dot{m}_i$ as positive and outgoing ones as negative ~~rate~~ yields for the rate of change of energy

$$\frac{dE}{dt} = \sum_i \dot{m}_i h_i + \dot{Q}_o - \dot{W}. \tag{6}$$

In a similar way, the entropy balance can be written

$$\frac{dS}{dt} = \Sigma \dot{m}_i s_i + \frac{Q_o}{T_o} + \Delta\dot{S}_{irr} \tag{7}$$

Here, s_i is entropy per unit mass of stream i, and $\Delta\dot{S}_{irr} \geq 0$ represents the net rate of entropy increase of the streams and surroundings due to the process. Now multiply Eq. 10.7 by T_o and add to Eq. 10.6 to get

$$\frac{d}{dt}(E - T_o S) = \Sigma \dot{m}_i (h_i - T_o s_i) - \dot{W} - T_o \Delta S_{irr} \tag{8}$$

We now consider steady-state processes only; thus

$$\dot{W} = \Sigma \dot{m}_i (h_i - T_o s_i) - T_o \Delta S_{irr} \tag{9}$$

If the input flows are represented by subscript 1 and the output flows by subscript 2, we can write Eq. 10.9 as

$$\dot{W}_{1\to 2} = \Delta H_{1\to 2} - T_o \Delta S_{1\to 2} - T_o \Delta S_{irr} \tag{10}$$

where ΔH and ΔS are the changes in the respective sums.

The maximum amount of work will be obtained when the irreversibility $\Delta S_{irr} = o$. If the output of the process is in a state of equilibrium with the environment at T_o, then it can be shown that

$$(\dot{W}_{1\to 0})_{max} > (\dot{W}_{1\to 2})_{max} \qquad (11)$$

in all other states 2. The rate of availability input to the process can now be defined: it is $\dot{A}_1$, equal to the maximum rate of work that is possible from the process $(W_{1\to 0})_{max}$. The availability of the equilibrium state (0) is zero (we can get no work from it), thus we can write

$$(\dot{W}_{1\to 2})_{max} = \dot{A}_1 - \dot{A}_2 \qquad (12)$$

and symbolically

$$W_{max} = \Delta A = \Delta H - T_o \Delta S \qquad (13)$$

This derivation has simple interpretations. For a work-consuming device, $\dot{W}_{max} < 0$ and $|\dot{W}_{max}|$ is actually the minimum amount of work required for the process. We can then define a second very useful quantity, the effectiveness ε:

$$\varepsilon = \frac{\text{minimum work required}}{\text{work actually consumed}} \qquad (14)$$

In its useful applications, the quantity ε is process-dependent, in both its numerator and denominator.

As an example, consider in more detail the trip mentioned at the start of this section; let it be by automobile between two cities. Considering only the beginning and end states, for which $\Delta A = 0$, we might conclude that the effectiveness of the fuel consumed is zero, a result much lower than might be derived on the basis (say) of the engine's efficiency. In fact, by traveling very slowly on windless days (to ensure laminar flow through the air), with all other friction losses assiduously reduced, we could reduce the fuel consumption drastically, but that is not practical enough. Thus, consider traveling at 90 km/hr, in an automobile of some particular shape (hence a certain drag coefficient in the air), using energy in climbing hills and dissipating it on the way down, and so forth. We can calculate for this specified system an ideal minimum energy required. The effective- is then this quantity divided by the actual amount used.

Availability analysis has been applied to many energy-intensive processes, for example the lime industry and synthetic-fuel-from-coal processes to discover where losses of available energy occur, hence where improvements can best be made either to save energy or improve the throughput. Modern lime kilns for example have remarkably high second-law efficiencies--i.e., effectiveness of using the availability of its fuel--about 50% (Bazerghi 1982).

The effectiveness ε considered this way can include unavoidable irreversibilities (the aerodynamic drag, for instance), but is always less than the usual first law thermodynamic efficiency. The house-heating example earlier in the chapter could be adapted to show the effectiveness was very low, despite the fact that 70% of the heat in the fuel actually went into the house. The large loss in availability came in burning the fuel at high temperature, then mixing the heat with much cold air to produce heat at 40°C--giving a large irreversible increase in entropy. The energy that was originally in the fuel lost most of its availability to do useful work.

How the two end-use waste calculations of Figure 1.10 differ should now be clearer. The conventional efficiency analyses took account of some gross losses, and in many cases (but not all) neglected many of the availability losses that occurred, via unnecessary irreversibilities, etc. The availability calculations took more of these into account. As stated earlier, what to include in any practical calculation is a matter of judgment and sophistication, because the major purpose of this entire exercise is to identify where major improvements can be made in any system of choice. In that sense, the concept becomes somewhat semi-qualitative, depending on the actual system definition and resulting constraints. As we will see, large opportunities exist for improvement, as "ultimate attainable" effectiveness need not usually concern us.

4.5 RECENT PROGRESS IN USING ENERGY MORE EFFECTIVELY

Much improvement in rational and effective energy use has been made since the early 1970s. Both research and documentation of progress have been good. Hirst, Marlay, Greene and Barnes (1983) have written so excellent a summary that it is included with permission as an appendix to this chapter. These next several sections provide additional material, and reference will be made to Hirst et al from time to time. See also Gibbons and Chandler (1981), who give in their very readable book an account of conservation opportunities found in the reports of the U.S. National Academy of Science Committee on Nuclear and Alternative Energy Systems ("CONAES"), especially its Demand/Conservation Panel, plus additional material.

Most publicly visible and most readily susceptible to simple technological improvement are buildings, both residential and commercial. Great opportunities exist. According to the Congressional Office of Technology Assessment (OTA 1982), by the year 2000 up to 7 quad/yr of energy savings is technically possible from investments in the energy efficiency of buildings in cities. Furthermore, 70-80% of all potential savings would come from retrofits with 2-7 year payback. Nevertheless, OTA concludes that two-thirds of the savings potential is unlikely to be realized because of lack of access to medium- or long-term financing, and difficulty in predicting the actual savings; both impediments were mentioned in earlier sections. A report prepared by the Solar Energy Research Institute for the Committee on Energy and Commerce, U.S. House of Representatives (U.S. Congress, Committee Print 97K)* estimates that the equivalent of 5.7 million barrels of oil per day (11.4 quads/yr) could be saved if present buildings were retrofitted with better insulation, storm windows, etc., all new buildings were constructed according to new achievable and cost-effective standards, and building services (hot water, lighting, etc.) were provided in more efficient ways. Figures 4.7 and 4.8 show how various theoretical and practical results compare. Figure 4.7, referred to also by Gibbons and Chandler, shows that new residential houses could be much less energy-intensive than hitherto; with $35/bbl oil, improvements to reduce heating demand to 0.4 or 0.35 of former values are easily justified. Figure 10.8 shows some results of documented retrofits on gas-heated houses, from Committee Print 97-K. Point "G-2 Twin Rivers" is particularly notable as it refers to a series of town-houses supposed to have been originally built with energy conservations in mind. Point Er-PPL corresponds to 1,896 houses in the Portland, Oregon, area. The retrofit survey naturally shows less dramatic improvement than do Hirst and Kurish for new construction, but the trends and general conclusions reinforce each other; much can be done.

Figure 4.7 shows the cost of conserved energy is a bargain, even figured at the (presently low) capital recovery rate of 6.7%, corresponding to a 3%/yr real interest, 20-year payback. Market imperfections described earlier appear to be limiting most retrofitting to the most economically attractive items; but even so, overall real progress has been significant. Hirst et al in the appendix find 1980 savings of 3 quads/yr in residential energy use, as compared to extrapolations of pre-1973 trends (19 quads, down to 16 in 1980).

One of the outstanding programs is that of the Energy Division of the Oak Ridge National Laboratory, where the conservation work is carried out by Eric Hirst and his colleagues. Over the past decade this group has published almost a hundred technical reports, principally but not exclusively related to buildings, mostly under the "ORNL/CON" series, many of which are valuable working summaries. They analyze single-family dwellings, commercial buildings, hospitals (very energy-intensive), in many ways. For example, one report outlines the energy reductions that could be achieved by the year 2010 by an energy-efficient building sector (Pine 1981). Table 4.3 from Pine shows end-use energy consumption in the residential and commercial (RC) sectors in 1977; electric generation and trasmission losses, oil refinery consumption, etc., are not included. He analyzes all these opportunities for improvement achievable with current technology, such as much more efficient refrigerators, better use of solar heat, use of heat pumps, etc. Table 4.4 shows his results; he finds that end-use energy consumption has the potential to be reduced to 7.71 EJ, 43% of the 1977 value of 18 EJ. This could be achieved "despite an approximate doubling of GNP, a 29% increase in population along with the increase in demand for residential services, and an increase in commercial sector activity that are all implied." Furthermore, all these improvements were judged to be cost-effective on a life-cycle basis.

Figure 15 of the appendix (Appendix p. 232 ~~54~~) shows the improvements in automobile fuel economy from 1975 through 1980. Many small cars in 1983 comfortably exceeded the 1985 mileage standards, a few by a factor of two. The drag coefficient of cars (that is, the ratio of energy lost in wind resistance compared to the energy lost by a flat plate with the same frontal area traveling at the same speed) has been reduced from about 0.5 (sometimes more) to about 0.3 by sloping the front hood and grill, rounding corners, smoothing the underside of the vehicle, etc. Radial-ply tired reduced rolling friction, giving an approximate 5% improvement in gasoline mileage. Lighter cars needed lighter and smaller engines. The list of improvements is impressive.

Passenger miles per gallon in jet aircraft has more than doubled since the introduction of the first jets in 1958-1960, from about 25 passenger miles/gallon to 60-70, under optimal conditions. This improvement arises in part from reduction in drag, replacement of pure jet engines by ducted-fan engines (in which the axial-flow jet engine drives large fan blades at the front, which provide most of the thrust), and lighter weight via better design. However, most post-1973 savings come from changes in operation, as shown in Figure 17 of the appendix (Appendix p. ~~59~~ 237). Builders of small unconventional airplanes have led in use of composite materials, clean aerodynamic design, and very smooth surfaces which give low-drag laminar flow (De Man 1983).*

An authoritative study of the magnitude and origin of the changes in energy productivity is Marlay's study of U.S. industry (Marlay 1983, 1984), some of the results of which appear in the appendix. By analyzing the actual material output and energy use in 472 mining and manufacturing industries between 1945 and 1980, he has separated the effects of shifts in product mix, technological improvement, and changes in economic growth, especially during the period 1972-1980. Figure 4.9 summarizes some of his findings. During the period 1950-1972, the output per unit of fossil energy input increased by about 0.9% per year, even though most fossil energy prices declined in constant dollars. This improvement was partly offset by an increase in electricity use, leaving a small net improvement overall, consistent with the findings stated earlier.

The period 1972-1980 showed a drastic improvement, a reduction in fossil fuel use per output of 2.3% per year, not compensated for by any increased electric intensity. Much of this improvement featured reduced use of natural gas, as a result of restrictions placed on it~~s use~~s, and reduced use of coal, as industry backed out of coal technologies because of environmental and other considerations. Figure 4.10 shows Marlay's summary of the 1972-1982 situation, a reduction in energy use by industry to some 62% of what had been projected in 1972 from historic trends, and all this in the presence of substantial growth ~~input~~ in output.

One must be careful in analyzing data like these. Many were supplied to U.S. Government agencies (for example, the Federal Reserve Board) only sporadically, and sometimes on a voluntary basis by selected industries (a circumstance now being corrected in part). Figure 4.11 shows Marlay's comparison of 1972 Federal Reserve Board data compared with Census index data, for 134 industries from which the FRB collected data. It is easily seen that errors of 5 to 10% can be made, and wrong implications drawn, especially when one is looking for changes on the order of 1% per year.

4.6 M.I.T. SOLAR HOUSE V AND CRYSTAL PAVILLION

An elegant, constructive application has been made of the same physical concepts found in the global CO_2 problem. Turn to Figure 3.4 of Chapter 3. If a material were available that was substantially transparent to the incoming solar spectrum, but acted as a reflector to infrared heat radiation (10-20 μ wavelength), and also had good conventional insulating properties, then thermal re-radiation out through such windows would be effectively blocked, and a very superior solar house could be built. Glass with a very thin coating of indium-tin oxide or copper-tin oxide (for example) has these transmission-reflection properties. Both of these have been used in the design and construction of Solar House V and its pavillion extension, at the Massachusetts Institute of Technology, latest in a series which began in the 1930s. An account has been given by Johnson (1982) and Johnson and Hubbell (1982). The following brief description also permits introducing some additional useful comments and ideas about low-energy houses.

In practice, a coated sheet of glass transmits about 80% of the incoming visible radiation, and reflects 85% of the room-temperature infrared radiation back into the heated space. Figure 4.12 shows how they were used: double-pane windows, metallized on the outside of the interior pane, and narrow concave-upward venetian blinds in the interspace. Overall thermal conductance of completed panels (radiation plus normal conduction) was about 1.4 $W/m^2 °C$. In British units, that is 0.3 $BTU/hr \cdot ft^2 °F$, known as the "U-value." The inverse of the U-value is the conventional "R-value" insulation rating. Thus, these panels are equivalent to R-3.3 insulation, as good as or better than triple-glazed windows. About half the thermal loss through those window panels of Solar House V is via framing material at the edges; the best combination, copper-tin oxide with argon gas in the interspace and improved edging, could be equivalent to R-8 or R-9 insulation.

Let us calculate what might be possible in a sunny winter climate. Total solar energy incident would typically be equivalent to six hours of weak normal-incidence sunlight (400 W/m^2, for example), giving à total daily input of 1800 W·hr/m^2·day, i.e., 6.5 MJ/day, figuring on 75% net transmission to the inside of the house. With 1.4 W/m^2°C loss, this gain could in principle balance an average inside-outside temperature difference of 54°C.

In real life, there are cloudy periods, and the heat gain must also compensate for infiltration losses (typically 0.5 air changes per hour), which is often the largest thermal drain; however, that loss can be reduced with simple counterflow heat-exchanging vents. Other losses are conduction through walls, ceiling and floors. Some thermal assistance can be expected from equipment and people in the building. On balance, one might expect to be able to sustain an inside-outside temperature difference of 25-30°C with good design.

Solar House V comes close to performing that way. Figure 10.11 shows several additional important features. Ceiling tiles contain a eutectic salt mixture (38% sodium sulfate, 43.3% water, 3.4% Cab-O-Sil fumed silica, 2.6% borax, 7.6% sodium chloride) which undergoes a freeze-thaw phase change at 23°C, storing 630 W·hr/m^2 (210 BTU/ft^2) over a 5.5°C temperature swing. The concave-upward mirror-finish venetian blinds reflect sunlight onto the ceiling tiles, which store the heat for night-time release. The thin plastic pouches containing the salt (two thin layers to prevent large crystal growth and selective crystallization of some ingredients) retail for \$2.10/ft^2 (\$35/kWh for the stored heat), somewhat expensive for daily cycling of thermal energy, but surely susceptible to reduction in large quantitites. The window assemblies themselves are projected to cost about the same as other high-grade double glazing.

This system has several advantages over most other solar house concepts:

- No movable insulation is required to cover the windows at night.
- The floors are not required for thermal storage, and can therefore be made of non-masonry material, and can be carpeted.
- Glare and spot-to-spot temperature differentials are much reduced.
- Day-night temperature excursions are much less.

Solar House V has been used as a class- and work-room since 1978.

Given this success, can one go further? Consider a cloudy winter climate, where the light is somewhat more uniform, but on the average less than half that on a sunny wall, say 3.0 $MJ/m^2 \cdot day$. A calculation like the previous one gives an inside-outside difference of 25°C, a number to be reduced in practice (as before) to account for infiltration and other conduction losses. Such a structure -- glass all around--could be expected to maintain 20°C inside with an outside temperature of (say) 7°C, and somewhat more with some internal heat generation from normal living. Such a cloudy cool climate is typical of winters in much of Northern Europe, the U.S. Northwest, and the Canadian Pacific Coast. Thus the M.I.T. Crystal Pavillion was built as an extension to Solar House V. Designed for diffuse light, it has no venetian blinds, but thermal storage in the floor, ledges, and elsewhere. It has performed according to the expectations described here since 1982. To prevent summer overheat, louvres and vents in the (glass) roof allow thermally driven air flows, and maintain the interior not more than 1°C above the outdoor ambient temperature, with a 5 km/hr breeze.

Such designs for cloudy-cool and cold climates are far superior to houses with only super-insulation and tiny windows, which can provide no thermal gain, but only minimize loss. Furthermore, even northern exposures can be made useful.

4.7 IS CONSERVATION WORKING?

4.7.1. Differing Perceptions

Much of the preceding discussion showed that decreased energy use comes from technological improvement, changes in product mix, and curtailment. Some of these involve self-denial, changing life-styles or lowered standard of living, but they are often called, confusingly, conservation.

Market responses of both the technological and lifestyle type can easily be seen. As Marlay remarks, in the transportation sector, consumers buy more efficient cars (improve energy efficiency), buy smaller cars (change in lifestyle) and drive less (curtailment). In the residential sector, homeowners insulate their houses and turn down thermostats. In business, some industries expand with modern and energy-efficient facilities, others shut down.

The same data can and has been used both in favor of and against government involvement in conservation programs. Against government stimulus:

o The value of the substantial decline in energy use per unit of output services in the U.S. in the period since 1972 vastly exceeds the Federal Government expenditures on such programs. Therefore, market ~~focus~~ forces must have taken over to bring about the change, and the government effort was unnecessary and perhaps even counter-productive, in stimulating shifts contrary to rational market decisions.

For government stimulus:

o The programs were mainly long range, and so larger results will appear over the long term. Also, would the market and the public have been so aware and as knowledgeable as they were with respect to energy efficiency in the absence of the much-publicized public programs?

The shifts toward a new more energy-efficient economy have created a high demand for capital, which drives prices upward. The very high cost of capital in the years 1979-1983 came only in part from high energy costs, but surely it impeded the shift.

Several conclusions emerge:

1. The importance of decreasing the cost of capital, if rational shifts are to be made from less-energy-efficient to more-energy-efficient technologies. This is especially important to industries that find themselves financially disadvantaged because of high energy costs, changing consumer preferences, etc.

2. An apparent discrepancy between, on the one hand, the performance of many sectors in decreasing energy use at several percent per year, and, on the other hand, estimates of low-total-social-cost shift rates, is at least partly explained. For example,

consider the CONAES Modeling Resource Group, which concluded in its report that the ratio (energy/~~unit~~ GNP) could decrease at about 1%/yr or perhaps a little more, averaged over all sectors, with a carefully managed program, without affecting the GNP growth appreciably. How was it then that the U.S. economy appeared to shift much more, apparently without very skillful management? Resolution lies in recognizing that many of the shifts were of the product mix and curtailment type also considered but generally less accounted for by CONAES.

3. The Federal program, while having small present effect comapred to market forces, is far from useless, and should not be lightly curtailed. First, many of the R&D programs are for the longer term, and without them many future options would not exist. Second, the DOE programs may have had a larger effect on the new investment part than on the total shift in the energy-using sector. Third, the very existence of the program tends to ensure that some attention will continue to be paid in future to these problems. Better understanding will come if the programs exist than if they do not. Certainly the <u>form</u> of the program may need changing, but that is different from abolition.

4.7.2. Outreach Programs

A holistic and effective conservation program must include mechanisms to diffuse its results effectively and understandably throughout the various social and technological sectors. How well does the system work?

Evidence tends to be anecdotal, but comes in large and significant enough chunks to indicate that the diffusion mechanisms have been far from optimal.

Hirst and Armstrong (1980) report on managing the Minnesota state energy conservation program. Hirst's attention to this and his conclusions about it are particularly important, because he played central roles in developing both technological and policy options at the Federal level, and spent a year in Minnesota specifically to see how things were working at the state level.

They conclude rightly that state governments play the major role in delivering conservation services to their citizens, and are key agents in the nation's conservation efforts. But they found that the budgets were small, the staff (despite individual enthusiasm) lacked in-depth training, was over-worked, had high turn-over rates, and found it difficult to sort out tasks according to logical priorities. Furthermore, the Federal DOE, in making up its program, generates rules that are too complex, time consuming, and often inappropriate at the state level. For example, the Federal Government will require a multiplicity of state plans to respond to a multiplicity of federal programs, not all of which were consistent.

Despite these difficulties, Hirst and Armstrong see examples of things well done, and see many opportunities for improvement at both the state and federal levels. Many of these relate to the need for better policy analysis, program planning and program evaluation at the state and local level.

Another review is the evaluation of utility home energy audit programs (Berry et al 1981). Based on contacting 46 electric utility companies, state agencies, etc., they conclude in part about these Residential Conservation Service (RCS) programs that:

1. Only four audit programs reported having reached more than 10% of their eligible customers. Most utilities reported participation rates of less than 5% for the entire program lifetime.

2. Audit participants are not a cross-section of the general population; participants have higher incomes, education and interest in conservation than nonparticipants.

3. Participants probably have more energy-efficient homes and probably have taken more pre-audit conservation actions than nonparticipants.

4. Both participants and nonparticipants are more likely to install inexpensive energy conservation measures (e.g., caulking and weatherstripping) than expensive measures (e.g., storm windows). However, decisions range from very good to very bad. See Figures 10 and 11 of the appendix (pp. ~~28~~ 212, ~~31~~ 215); the retrofitters need better information.

5. Participation rates may be increased by careful staging and coordination of advertising campaigns and by making the process of obtaining an audit as easy and convenient as possible.

The most obvious shortcoming of existing programs is a failure to reach lower-income and energy-inefficient households. Identifying and designing strategies for reaching households with the greatest need for improvements in energy efficiency is a crucial task for RCS program managers. Future evaluations should be designed to aid managers in accomplishing this task.

Here is a final, smaller, but also illuminating example. A study was made to discover why it is, with so much conservation technology, ethic and incentive around, the traffic on Massachusetts

Avenue in Cambridge, Massachusetts, in the two-mile part between M.I.T. and Harvard, often resembles the running of the bulls at Pamplona, but in both directions simultaneously and at glacial speed and low efficiency (Santos 1982).

His analysis of what could be done with even reasonable organization showed that fuel efficiency could probably be increased by at least a factor of two, with a considerable decrease in pollution levels, but the following difficulties, inter alia, intervened:

- Little or no enforcement of traffic rules or rules against single and double parking.
- No apparent rational program for stop-light operation.
- No interest by the Cambridge Traffic Department or the Police Department in the problem.
- No cooperation by other city offices.
- No good data on traffic patterns.
- No apparents collaboration with the Massachusetts State Energy Office on the problem, even when free services were offered.
- Virtually no DOE, DOT or manufacturers data on fuel consumption by automobiles in realistic but well-described urban traffic (real or simulated).
- No apparent interest in the report, even after it was completed and offered free to various groups.

4.8 SOME BRIEF CONCLUSIONS

1. Be it sometimes off the mark, sometimes ineffective, a strong U.S. program for rational and effective energy utilization has been beneficial, and will continue to be so.

2. Much room for improvement exists, particularly with respect to federal-state-local relations, and outreach in general.

3. Just as the U.S. conservation program started to find its feet and get some real competence, meaningful and constructive evaluations, etc., it was excessively curtailed. This is very unfortunate. The tasks are deceptively simple, but actually difficult, especially in the multiplicity of groups involved in many of the activities.

4. More attention needs to be paid to what the market does, and what is actually happening in the various social and economic sectors, which is quite different from what many persons seem to think is happening.

5. Lowering the cost of and increasing the availability of capital are essential to a good program.

A colleague who writes about energy uses as the basis for a homily the aphorism that if one's only tool is a hammer, everything looks like a nail. The problems of achieving more rational and effective energy use, in the face of many conflicting economic, social, political and environmental demands is more complicated than that, and requires something more basic and difficult--understanding how the system works. Otherwise we have the equivalent of something else--a clock and a hammer, where through total misunderstanding the clock is used like a rock to pound the hammer head into the ground, so its handle can serve as the gnomon of a sun-dial.

FOOTNOTES - CHAPTER 4

4.1 I am grateful to my M.I.T. colleague Ernst R. Berndt for reminding me of several of these references.

4.22 Some of the solar/biomass energy estimates are too large and/or premature, but they do not affect the discussion here.

4.25 Note particularly the one- and two-seat airplanes with forward stabilizers ("Canards") developed by B. Rutan; one of these designs gets 100 miles per gallon.

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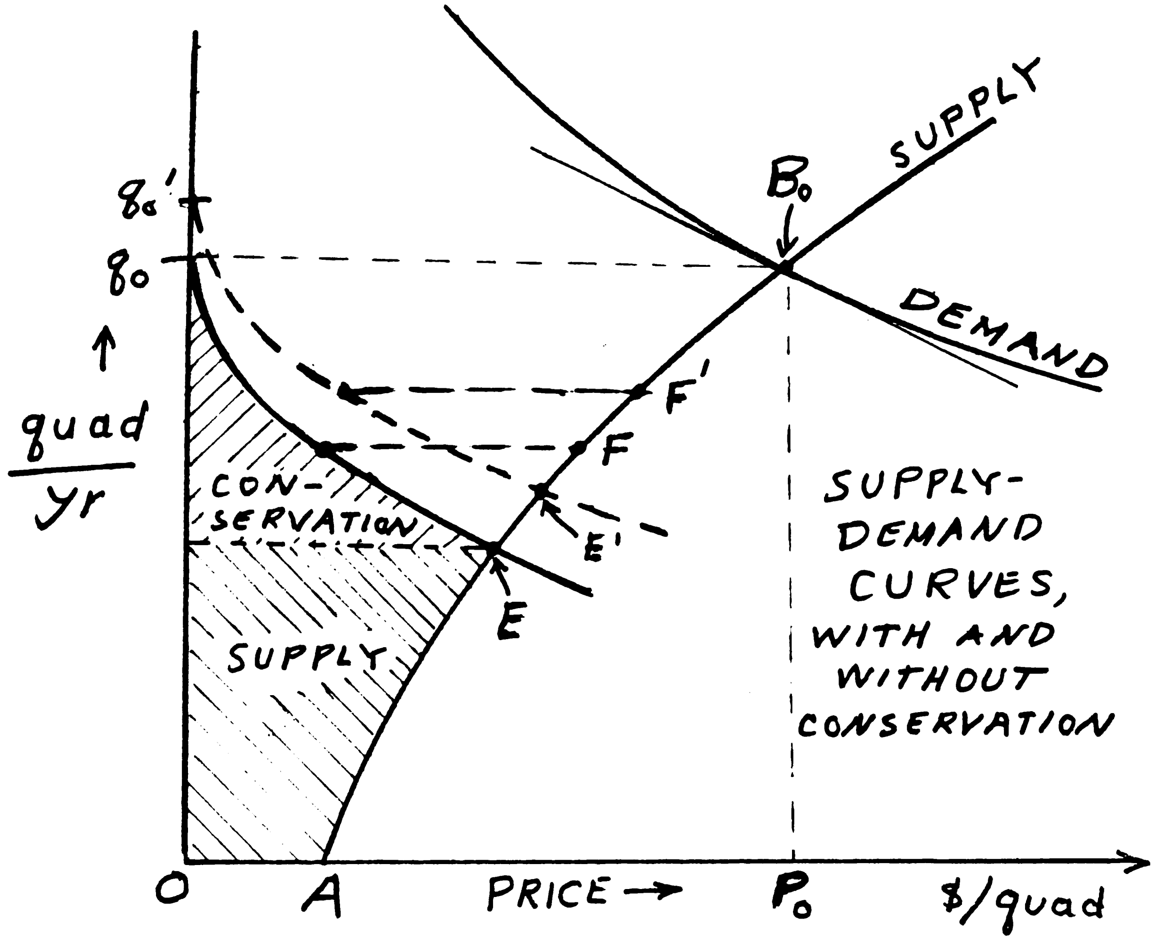
21. U.S. Congress Committee Print 97K (1981). Report on Building a Sustainable Future, Committee on Energy and Commerce, House of Representatives (April). ~~Some of the solar/biomass energy estimates are too large and/or premature, but they do not affect the discussion here.~~



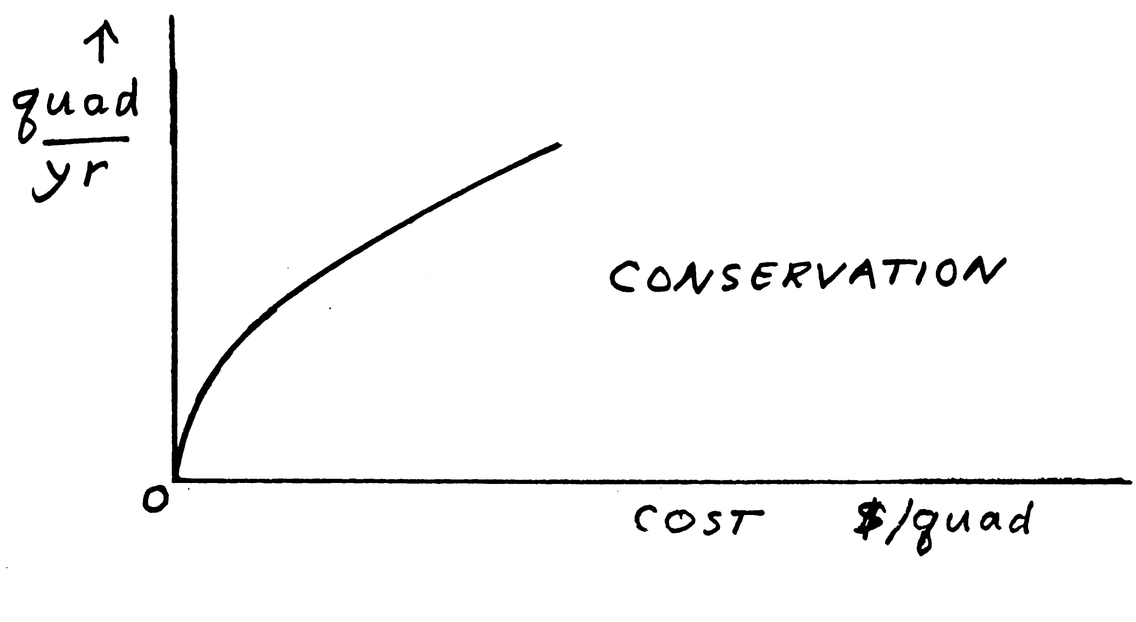


FIGURE 4.1 SUPPLY VS PRICE (UPPER DIAGRAM) AND CONSERVED ENERGY VS COST (LOWER DIAGRAM), SCHEMATICALLY

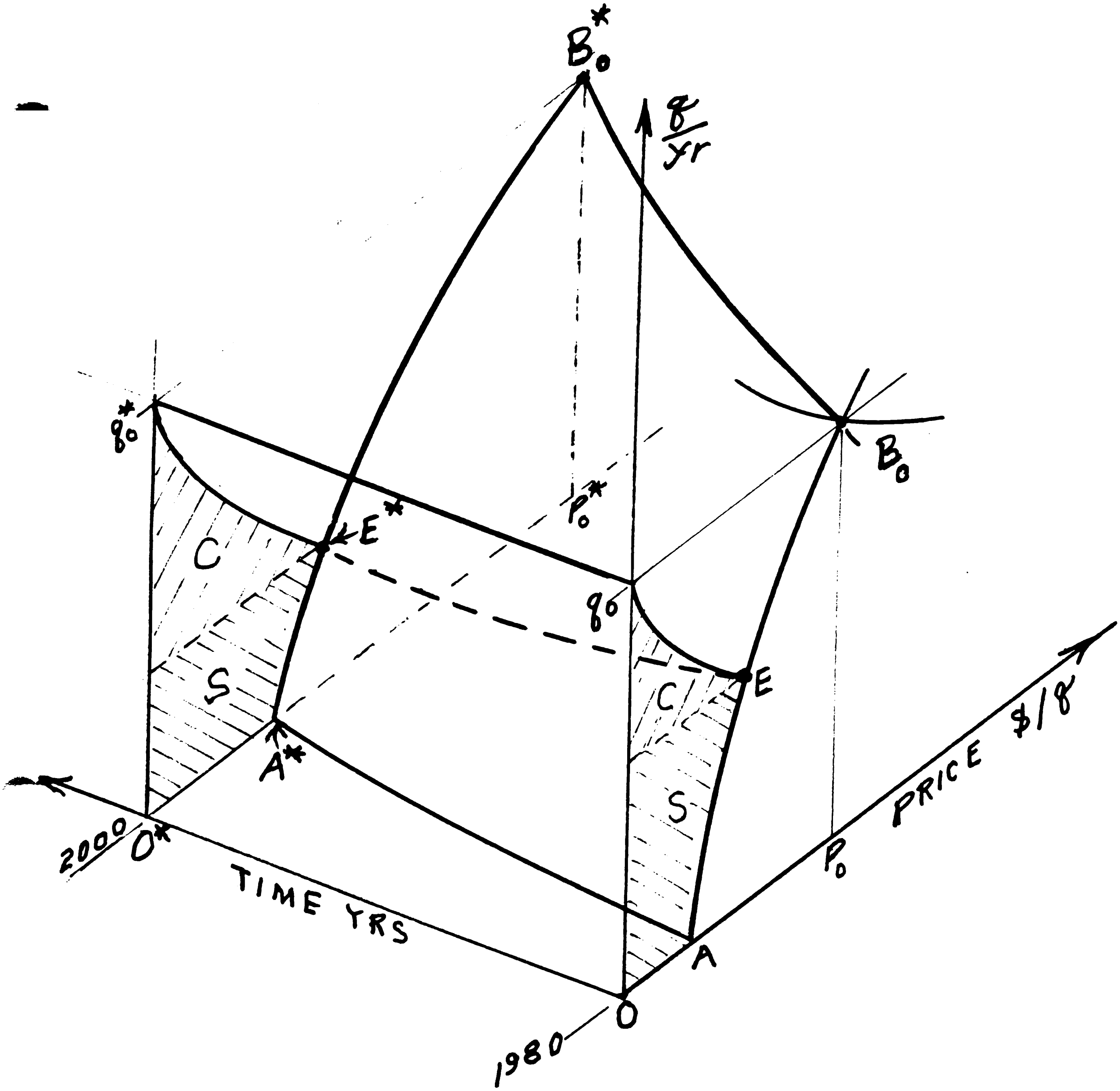


FIGURE 4.2. SUPPLY AND CONSERVATION VS PRICE CURVES OF FIG. 10.1 EXTENDED IN TIME, WITH DOUBLING OF ENERGY COST IN TWO DECADES, SCHEMATICALLY.

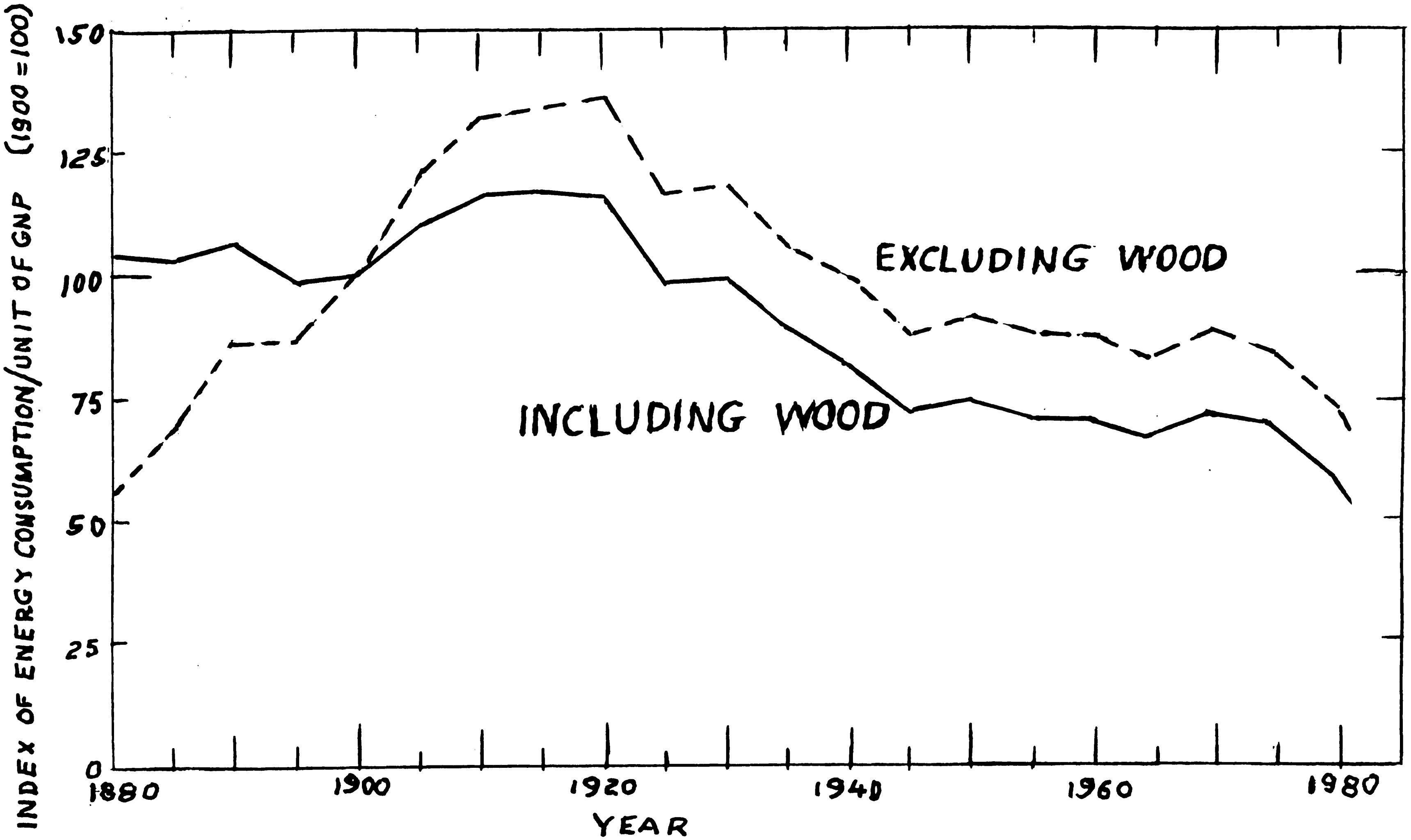


Figure 4.3 Index (1900 = 100) of energy consumed per dollar of real gross national product, 1880 to 1981. Data from Schurr, S. H., J. Darmstadter, Harry Perry, W. Ramsey and M. Russell, Energy in America's Future: The Choice before Us, Resources for the Future (Johns Hopkins Univ. Press, Baltimore, 1979), plus updates and additional data on wood, according to Schurr

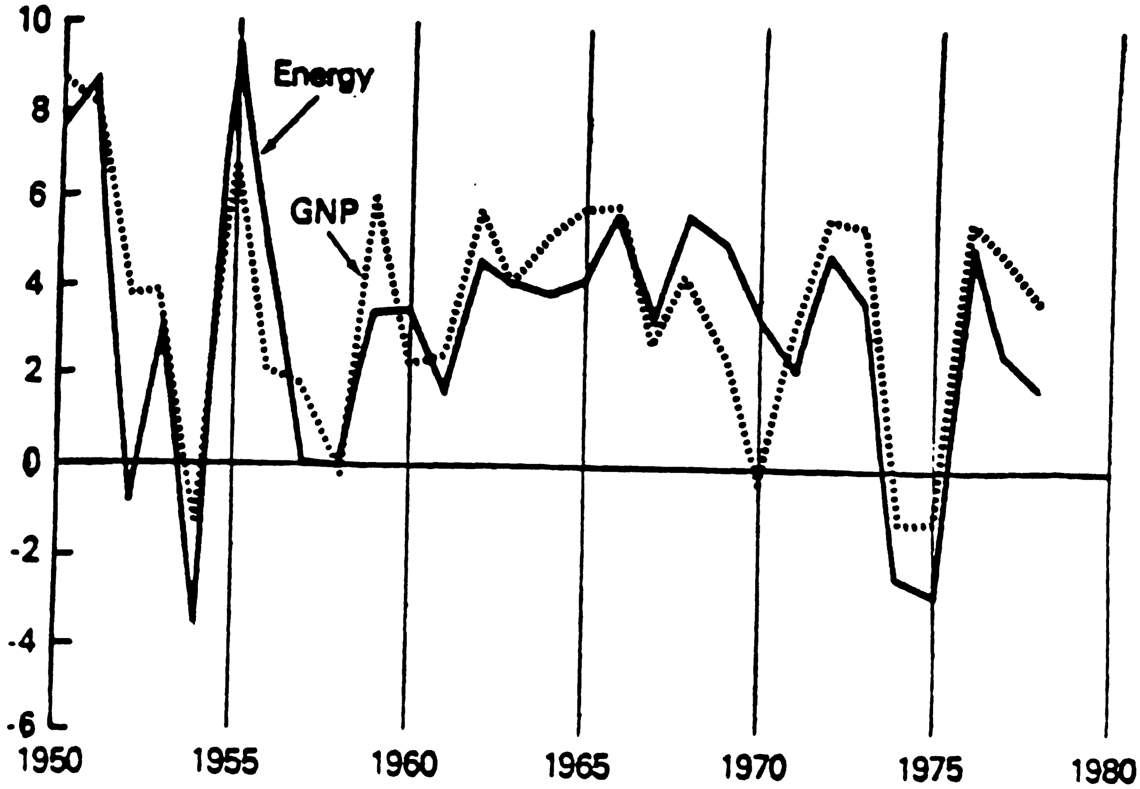


Figure 4.4 Annual percentage changes in primary energy and GNP, 1950 - 1978. Data for GNP changes are from the Economic Report of the President (Washington D.C.; Government Printing Office, January 1979). Energy data are from the Bureau of Mines for 1950 - 1974 and from the Department of Energy for 1974 - 1978,

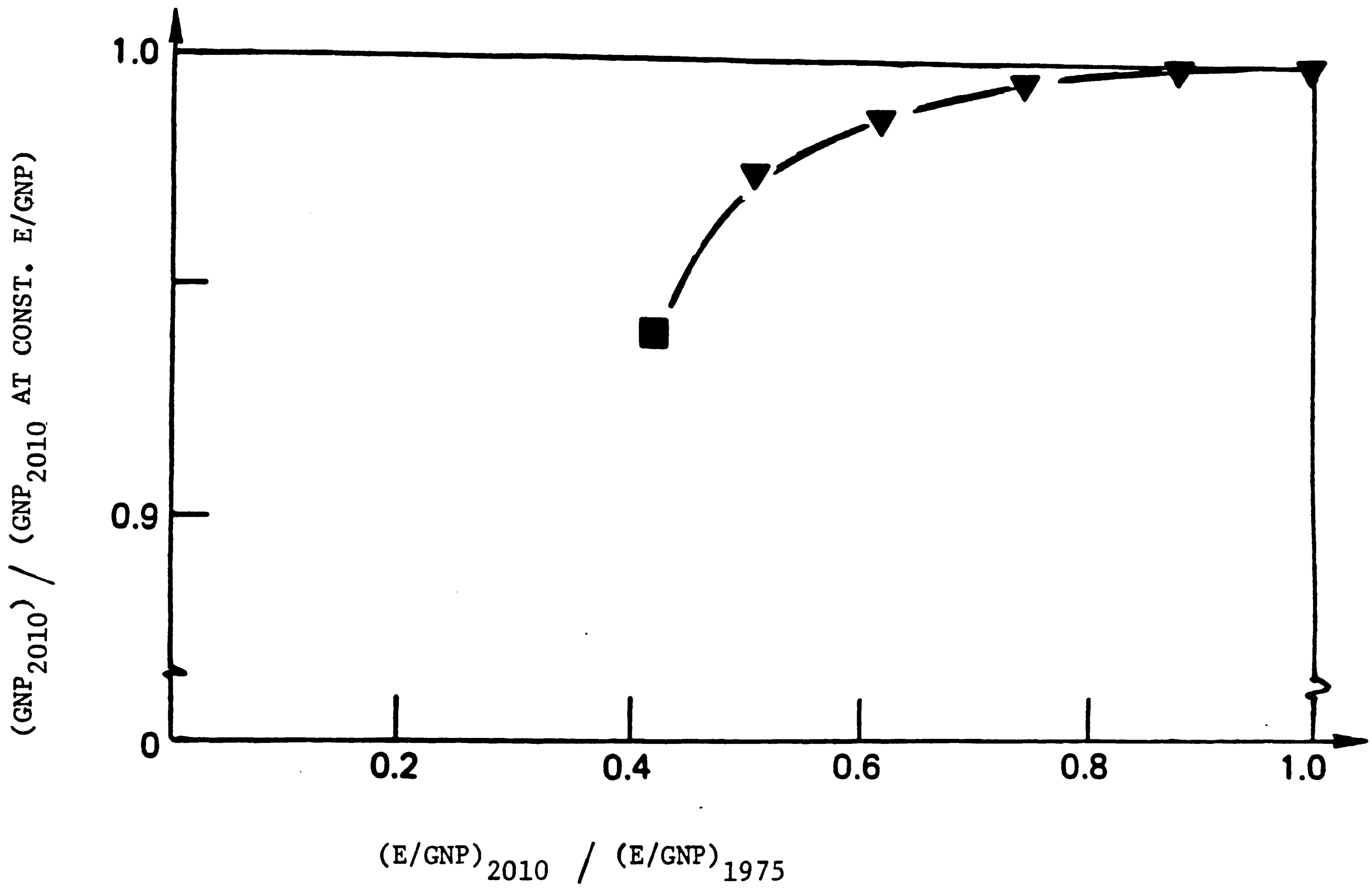


Figure 4.5 Estimates of the long-run feedback from energy conservation on undiscounted GNP for the year 2010, with 1975 as base year. See text for discussion. From CONAES supporting Report No. 2 "Energy Modeling for an uncertain Future," National Academy of Sciences - National Research Council, USA 1978, page 109.

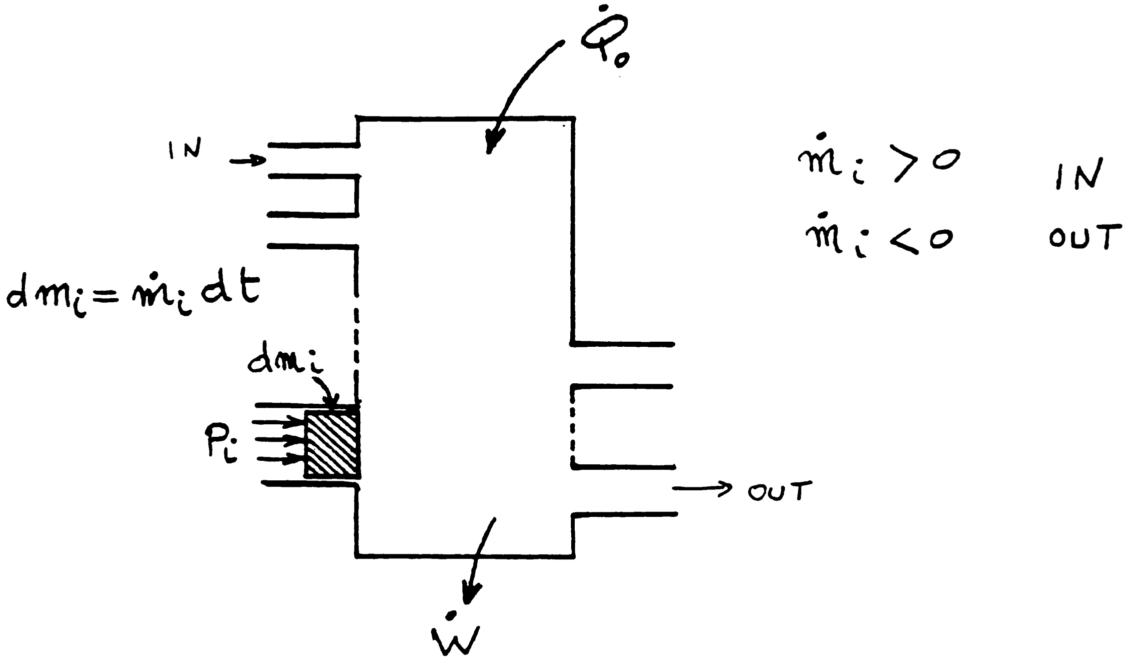


Figure 4.6 Schematic Diagram of a Bulk Flow Process

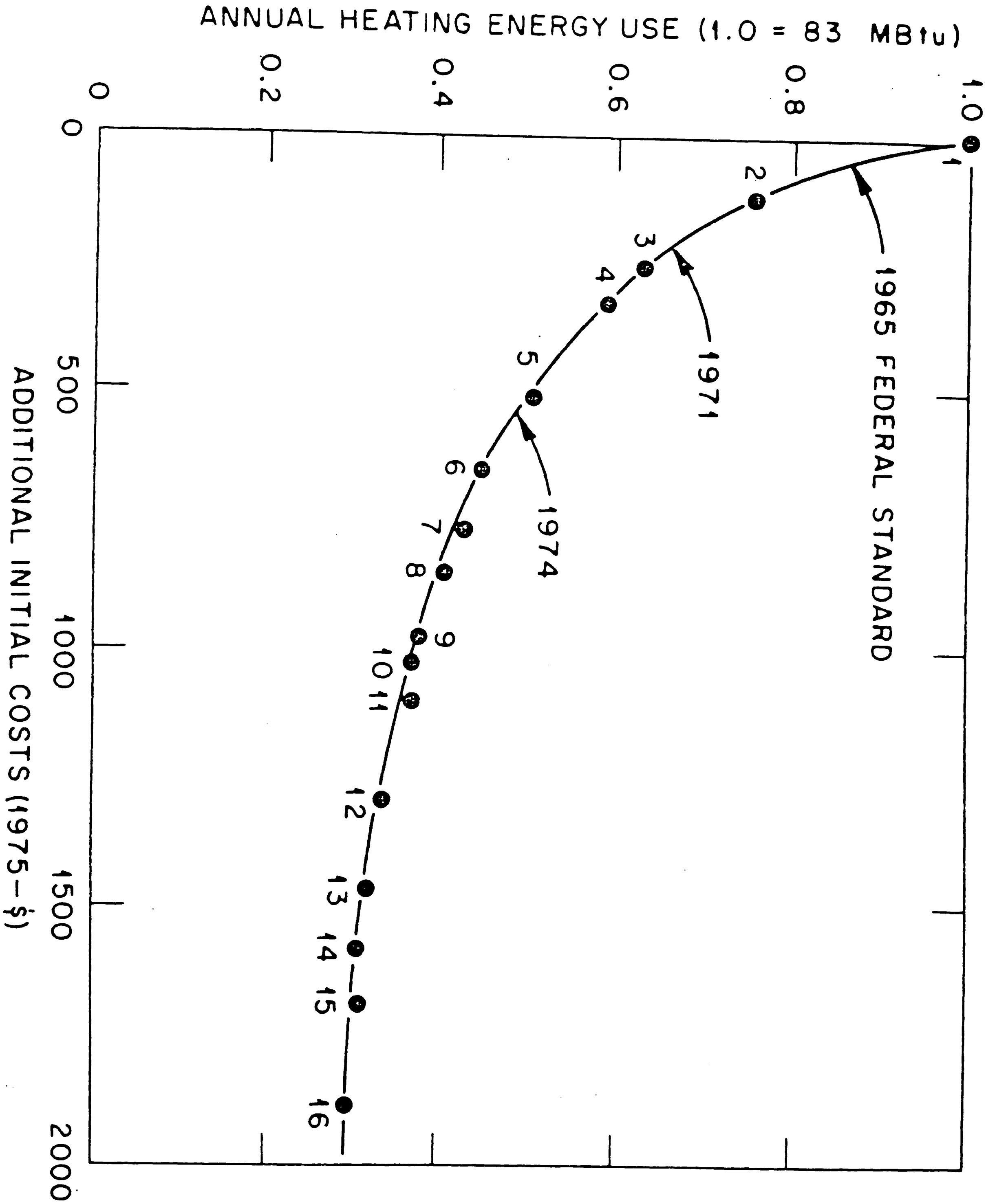


Figure 4.7. Heating load versus capital cost for a new single-family home in Kansas City, Missouri, U.S.A. Each point on the curve corresponds to additional amounts of attic, floor and wall insulation, and storm windows and doors. Adapted from E. Hirst and J.B. Kurish Residential Energy Use to the Year 2000: A Regional Analysis, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1977).

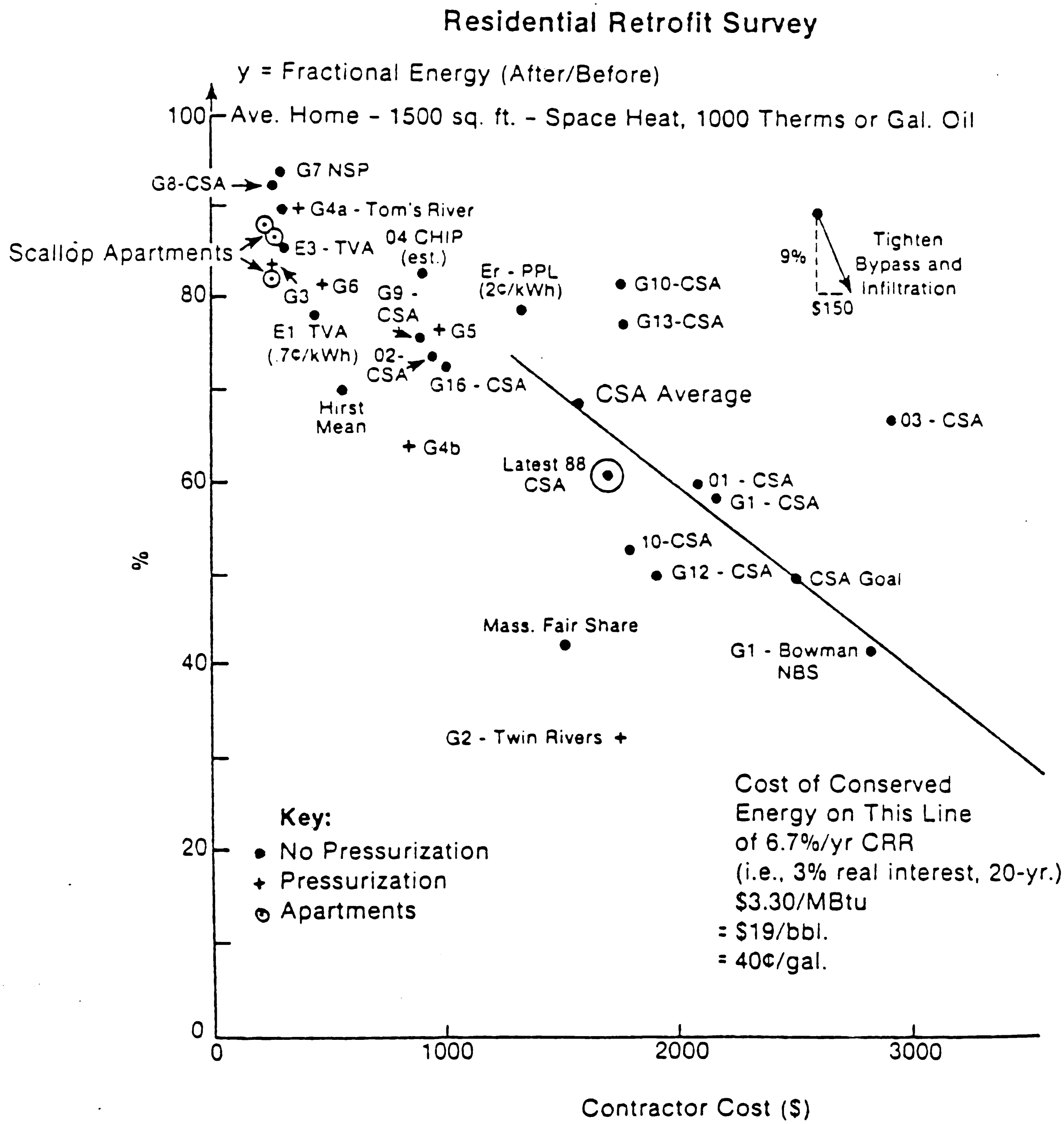
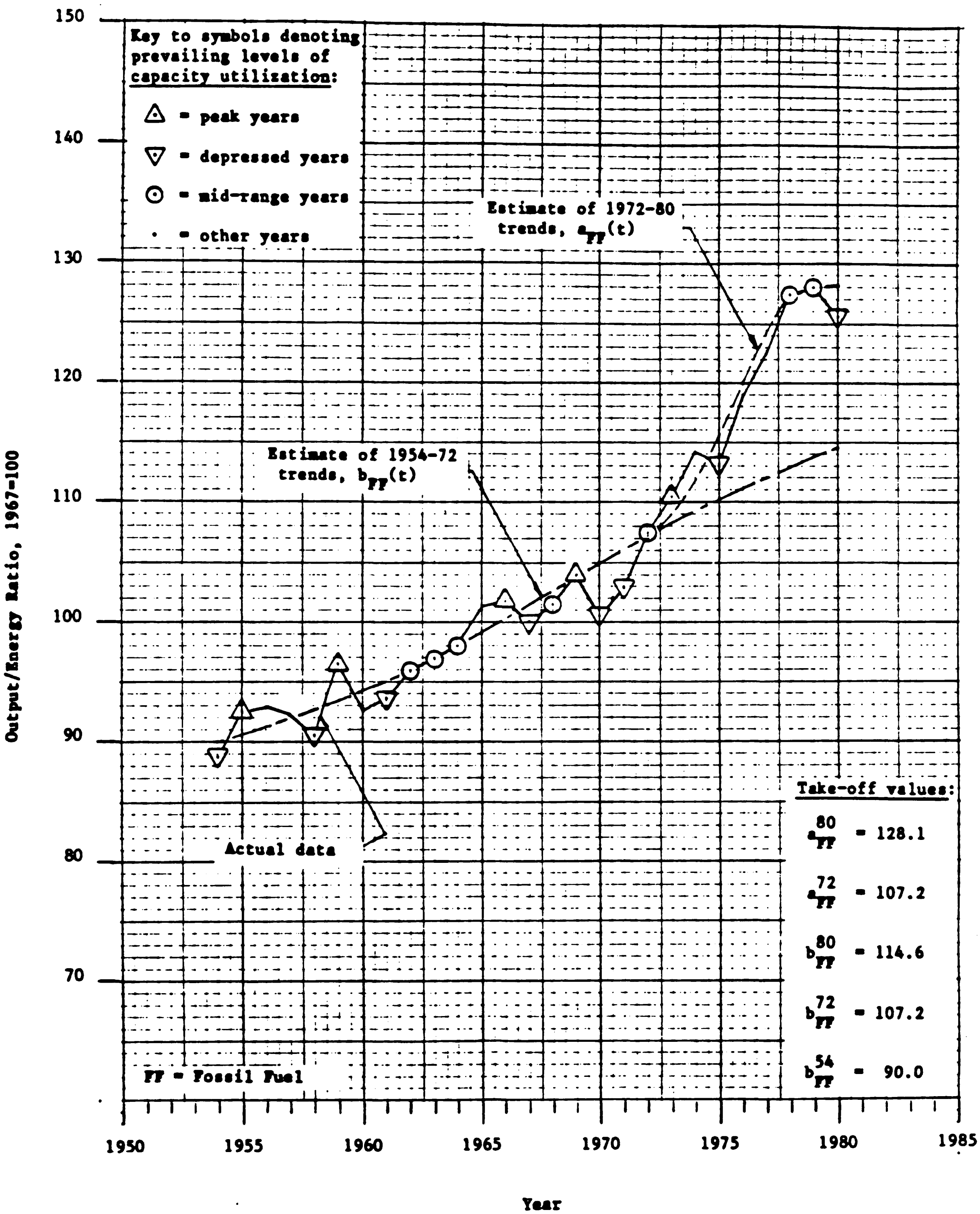


Figure 4.8. Results of a survey of retrofitted gas-heated homes in the U.S. From Fig. 2.12 of Report on Building a Sustainable Future, Committee on Energy and Commerce, House of Representatives, U.S. Congress (Committee Print 97-K) April 1981.

Figure 4.9 Fossil Fuel Weighted Measure of Output Divided by Fossil Fuel Input, 1951-1980
Mining and Manufacturing



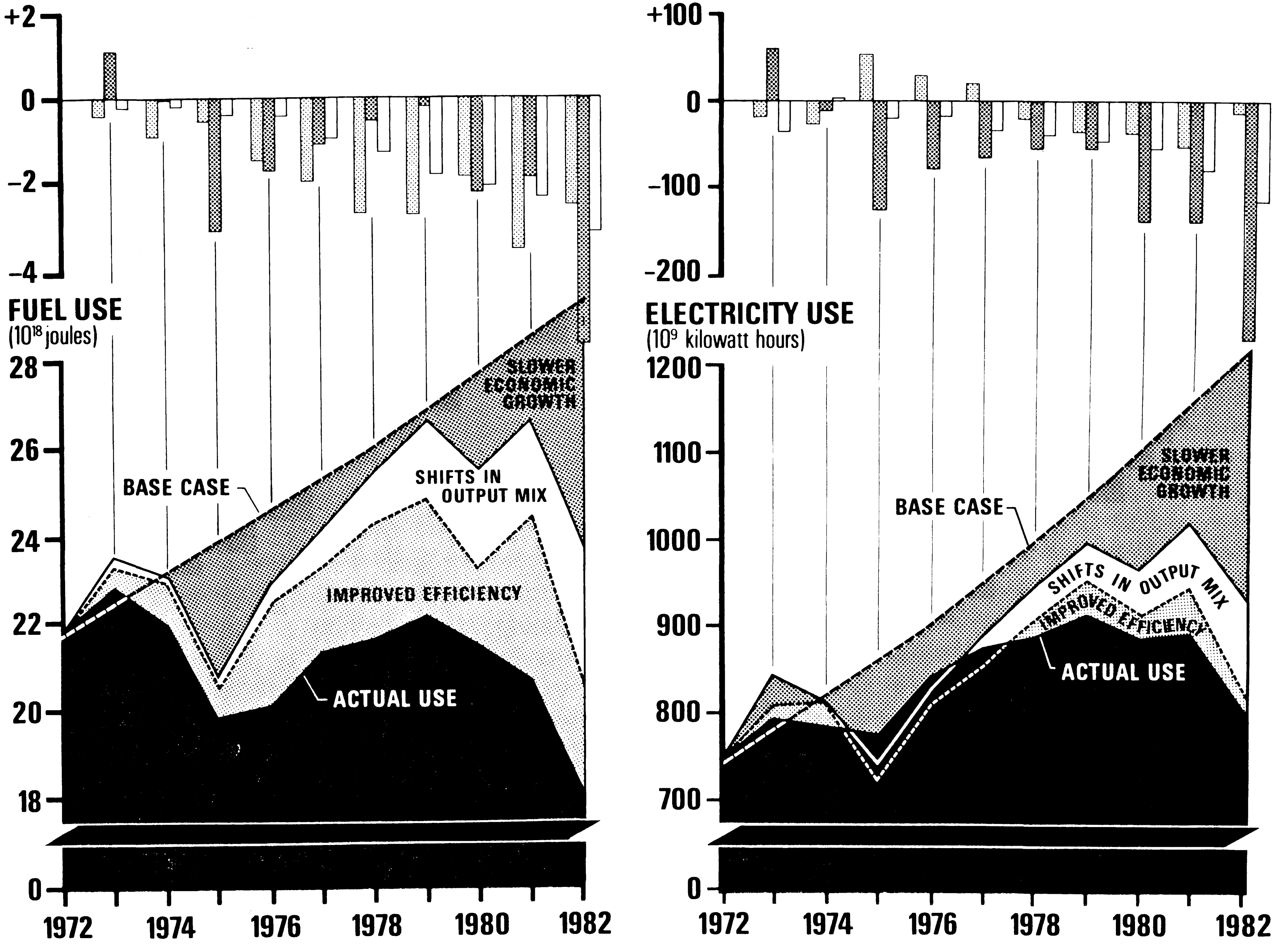


Figure 4-10 Energy use in Industry, U.S. (from Marlay)

Figure 4.11 Comparison of 1972 FRB and Census Indexes of Industrial Production for Mining and Manufacturing

For 134 FRB Industries

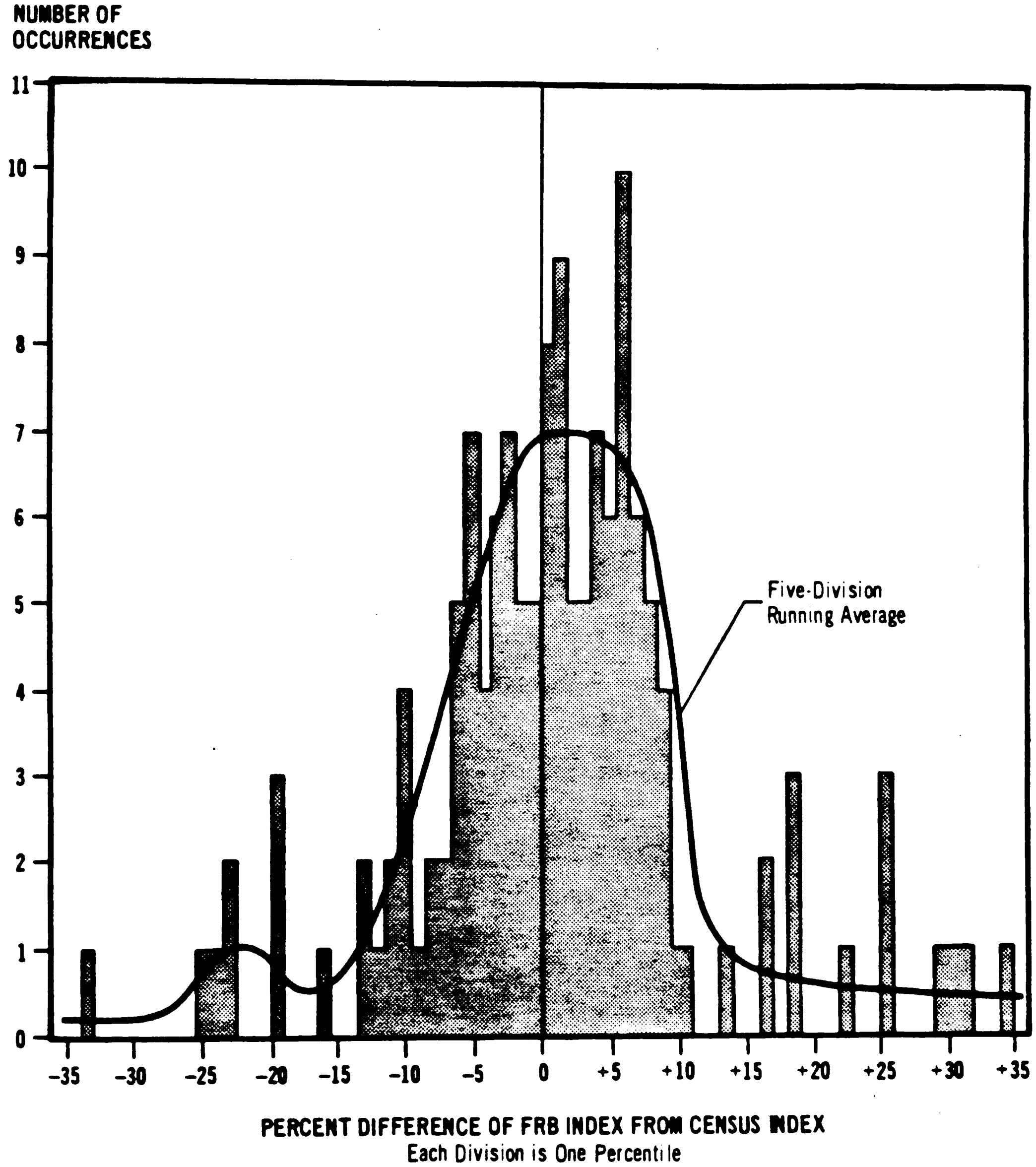


Figure ~~3-4~~ 4-11: Histogram shows percent differences between the Federal Reserve Board's Indexes of Industrial Production for 134 mining and manufacturing industries and 134 equivalently constructed Production Indexes from the <u>1972 Census of Manufacturing and Mineral Industries</u>, Bureau of the Census, U.S. Department of Commerce. The FRB indexes exceed those of Census by an average of 1.8 percent, relative to a set of common references in 1967.

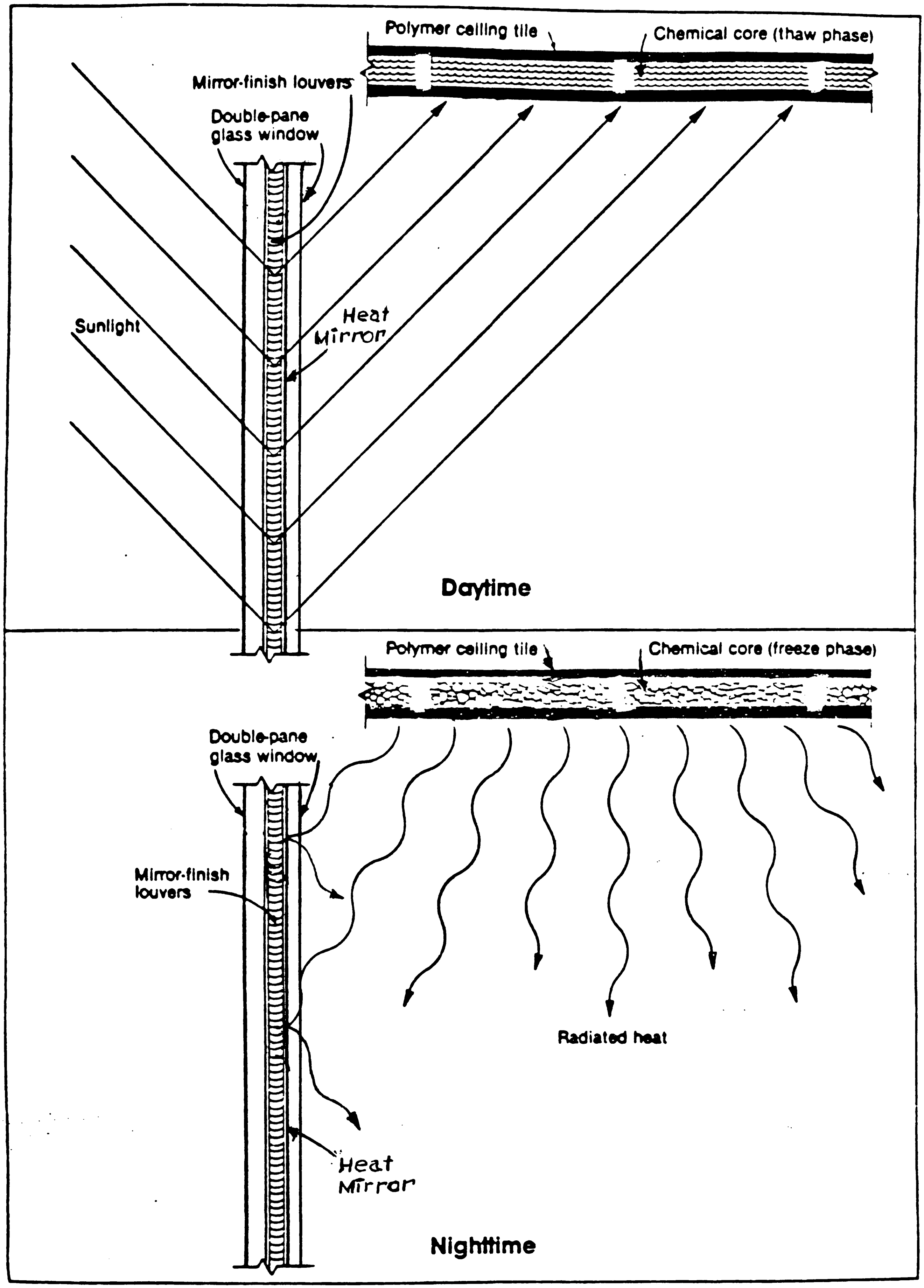


Figure 4.12 Thermal mechanism of MIT Solar House V, from (Johnson 1982)

Table 4.1 The U.S. Federal Energy Conservation Budget

	Budget Authority		
	1980	1981[1)]	1982 (as proposed in 1981
	($ in millions)		
Research and Development			
Building and Community Service	$103	$ 56	$ 31
Industrial Energy Conservation	60	43	1
Transportation	113	81	38
Residential Commercial Retrofit	--	6	--
Multi-sector	17	26	18
Grant Programs			
State and local	$443	$336	$107
Energy Impact Assistance	43	10	--
Subtotal Grant Programs	$486	$346	$107
Total	$779	$558	$195
Tax Credits			
Corporate	$190	$739	$799
Individual	$430		

1) Reflects $306 millions for recissions

Taken mostly from Energy Insider (publ. by U.S. Department of Energy) 16 March 1981.

TABLE ~~10~~4.2

Some Energy-GDP Elasticities, according to IIASA estimates*

	High Scenario 36.7 TW		Low Scenario 22.4 TW		16TW Case	
	1975-2000	2000-2030	1975-2000	2000-2030	1975-2000	2000-2030
Latin America	1.04	.98	1.06	.97	.96	.82
Africa/Southeast Asia	1.15	1.11	1.18	1.19	1.38	.90
West Europe/Japan/Australia-New Zealand	.70	.77	.65	.73	.04	.10

* W. Häfele et. al., Energy in a Finite World: Paths to a Sustainable Future, Ballinger Publishing Company, Cambridge, 1981, Table 9.1C, p. 173.

Table ~~10~~4.3. 1977 energy use for building sector (EJ)

Energy use	Electricity	Gas	Oil	Other[a]	Total
Residential					
Space heating	0.40	3.84	2.38	0.57	7.19
Water heating	0.37	0.92	0.15	0.08	1.52
Refrigeration	0.47				0.47
Freezer	0.20				0.20
Ranges/ovens	0.16	0.33			0.49
Air conditioning	0.35				0.35
Lights	0.30				0.30
Other	0.22	0.51			0.73
Total	2.47	5.60	2.53	0.65	11.25
Commercial					
Space heating	0.12	2.05	2.00	0.37	4.54
Air conditioning	0.64	0.17			0.81
Water heating	0.01	0.09	0.11		0.21
Lights	0.71				0.71
Other	0.27	0.21			0.48
Total	1.75	2.52	2.11	0.37	6.75
Total	4.22	8.12	4.64	1.02	18.00

[a]Coal, liquified petroleum gas, direct solar, and biomass.

Table 4~~10~~.4 2010 minimum practical energy use for building sector (EJ)

Energy use	Electricity	Gas	Oil	Solar and other[a]	Total
Residential sector					
Space heating	0.02	0.90	0.34	0.32	1.58
Water heating	0.11	0.46	0.07	0.14	0.78
Refrigerators	0.18				0.18
Freezer	0.10				0.10
Ranges/ovens	0.14	0.28			0.42
Air conditioning	0.33			0.08	0.41
Lights	0.30				0.30
Other[b]	0.19	0.44	___	0.13	0.76
Total	1.37	2.08	0.41	0.67	4.53
Commercial sector					
Space heating	0.00	0.47	0.37	0.19	1.03
Air conditioning	0.85			0.14	0.99
Water heating	0.01	0.09	0.10	0.01	0.21
Lights	0.35				0.35
Other[b]	0.33	0.24	___	0.03	0.60
Total	1.54	0.80	0.47	0.37	3.18
Total building sector	2.91	2.88	0.88	1.04	7.71

[a]Other fuels include direct solar, biomass, and fuels for cogeneration (coal, uranium).

[b]Other end uses include miscellaneous appliances and cogeneration plants.

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RECENT CHANGES IN U.S. ENERGY CONSUMPTION: What Happened and Why

Eric Hirst, Robert Marlay,[1] *David Greene, and Richard Barnes*

Energy Division, Oak Ridge National Laboratory,[2] Oak Ridge, Tennessee 37830

BACKGROUND

Energy-use trends during the past few years have been dramatically different from those of the 1950s and 1960s (Table 1; 1–3). Energy use in 1981 was slightly lower than it was in 1973. National energy use per unit gross national product (GNP) was 18% lower in 1981 than it was in 1973. Spurred by rapidly rising fuel prices, occasional fuel shortages, and a variety of other factors, US energy efficiency[3] increased sharply. As a result, energy efficiency is no longer a major public policy issue; energy conservation (both operational and technical improvements) is now widely accepted as a major contributor to resolution of our nation's energy problems (4–11).

However, our understanding of recent changes (by fuel-consuming sector, by region, by fuel, by end use, etc.), their causes, and their manifestations is limited. The relative importance of changes in overall economic activity (GNP), the mix of energy-intensive and nonenergy-

[1] Office of Policy Planning and Analysis, US Department of Energy, Washington, DC 20585.

[2] The Oak Ridge National Laboratory is operated for the US Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation.

[3] Energy efficiency is defined broadly to include all changes in energy consumption not caused by reduced economic output. Thus, efficiency includes the effects of capital improvements (technical efficiency) and operational changes.

Table 1 US energy use trends, 1950–1981[a]

Sector	Growth rate (%/year) 1950–1973	1973–1981	1981 Energy use[b] (quads)
Residential/commercial	4.5	0.8	25.8
Industrial	2.9	−1.2	29.0
Transportation	3.2	0.5	19.2
Total	3.5	−0.1	74.0
GNP growth (constant-$)	3.7	2.3	

[a] Sources: (1–3).
[b] Electricity is treated in terms of primary energy (11,600 Btu/kWh) rather than end-use energy (3412 Btu/kWh) in this report. British units are used, primarily because the data were collected and reported in these units.

intensive industries, weather, regional migration, fuel prices (both absolute values and rates of change), fuel shortages (and perceptions of possible future shortages), government conservation programs, and private (primarily utility) programs is difficult to determine. In addition, the breakdown of these energy-use changes in terms of operational and technical improvements is unclear.

Because of our limited understanding of the causes of recent energy-efficiency increases, the debate continues on the appropriate government (federal, state, and local) roles and budgets for energy conservation programs. If energy consumers in all sectors have adequate information about present and (likely) future energy prices and about their options regarding energy-efficiency, and if energy prices fully reflect their costs (including externalities), then the normal market response to rising prices will yield appropriate levels of energy efficiency. On the other hand, if market problems (e.g. differences between average and marginal fuel prices, lack of access to reliable information, difficulty in processing information, tenant vs. owner differences, and high interest rates) seriously inhibit operation of energy markets, then government may play an important role in encouraging greater energy efficiency.

Similar issues arise with respect to the ways in which efficiency is increased. Observed reductions in energy consumption brought about by capital investments are relatively permanent. On the other hand, reductions brought about by operational changes, while easier to implement in the short run, can be quickly undone. For example, it is important to know how much of the reduction in gasoline consumption is due to improvements in new car fuel economy (i.e., technical changes and purchase of smaller cars), how much to greater efficiency of vehicle use (i.e., slower speeds, more

frequent tuneups), and how much to reduced vehicle use (i.e., fewer trips, increased ridesharing).

There are basically two ways in which these questions can be addressed. The "bottom-up" approach would rely primarily on detailed surveys of individual energy consumers in each sector. Analysis of these data would show the changes in energy use that occurred and how they were expressed. Statistical analyses would indicate the influence of determinants such as fuel prices and economic activity. For example, we later discuss recent surveys conducted by the US Department of Energy's (DOE) Energy Information Administration (EIA) of residential and commercial buildings. However, in general, such surveys do not exist for samples representative of the United States as a whole (or even of large regions therein). Even the EIA nonresidential buildings survey is of limited use because it provides only a "snapshot" of energy-use patterns at one time, and thus provides only limited information about longer-term changes. The major impediment to this "bottom-up" approach is the insufficiency of disaggregate data obtained at different times. A related difficulty is the high cost of analyzing such data. Alternatively a "top-down" approach uses existing energy-use models to analyze recent changes by developing forecasts (literally, "backcasts") of energy use for recent years. Comparisons of different model projections, and between model projections and actual energy use, can yield insight into the effects of different factors on energy use. In addition, these projections can show how energy-use patterns changed during recent years (e.g. fuel switching, more efficient appliances, retrofit of buildings, construction of more efficient buildings, and behavioral changes).

Unfortunately, this approach is also limited. These analytical tools and the data on which they are based are of recent origin[4] and therefore not fully developed and validated. In particular, these models rely in part on the same data sources that are used for bottom-up analyses; inadequacies in the data affect these models as well as the bottom-up analyses.

This paper reviews recent work of both approaches on energy-use changes, their causes, and their manifestations. Our purpose is to examine recent energy-use changes for the economy as a whole (next section) and for each major end-use sector [residential and commercial buildings (third section), industry (fourth section), and transportation (fifth section)]. Although understanding of these issues has increased greatly during the past few years, there is still much to be learned about energy consumption and efficiency.

[4] The data are drawn from a short, perhaps atypical, time period. Therefore, our confidence in the energy-demand model coefficients is limited.

TRENDS IN AGGREGATE U.S. ENERGY CONSUMPTION

Statistics

As indicated earlier (Table 1), recent US energy-use trends were dramatically different than they were before the 1973 oil embargo (Figure 1). Between the end of World War II and 1973, energy use increased steadily;[5] however, after 1973 energy use first declined until 1976, then rose until 1978, and then fell in 1980 and again in 1981 (1). The net effect of the erratic changes between 1973 and 1981 was a total energy consumption figure in 1981 about one percent *less* than the figure for 1973.

The relationship between energy use and overall GNP is important (Figure 2), in part because conventional wisdom suggests that energy growth is a requirement for economic growth, such that the two are nearly proportional. However, the data show a different picture (1–3). During the 1950s and early 1960s, energy use per unit GNP declined steadily by about one percent per year. During the late 1960s, energy use increased more rapidly than did GNP. After 1970, the energy/GNP (E/GNP) ratio resumed its historical downward trend; however, the rate of decline during the 1970–1981 period was about double (two percent per year) the rate during the 1950s and early 1960s. These results suggest that energy use and GNP do not necessarily increase in lockstep and that the amount of energy required to produce a unit of GNP decreased during recent years more rapidly than historical trends would suggest.

Normalizing energy consumption by population (12; Figure 3) rather than by GNP shows interesting trends. Between 1950 and 1973 energy use per capita increased steadily at an average rate of almost three percent per year. Since then, per capita energy consumption has decreased, increased, and then decreased again: 1981 per capita consumption was nine percent lower than in 1973.

It is likely that the recent changes in energy-use trends were due largely to the rapid increases in real energy prices during the 1970s (Figure 4; 13–15; D. B. Reister, personal communication). Between the end of World War II and 1973, average US energy price[6] remained essentially constant. Since then, however, the average price increased by 150%.

Energy-related factors other than fuel prices have also been changing since 1973 (14–17). These include occasional fuel shortages; deregulation of

[5] Energy use declined slightly in only three years 1949, 1952, and 1954.

[6] Average price is defined as the Btu-weighted average of all fuels consumed. During the 1950s and 1960s, individual fuel prices generally declined. This was roughly offset by shifts from inexpensive to more expensive fuels.

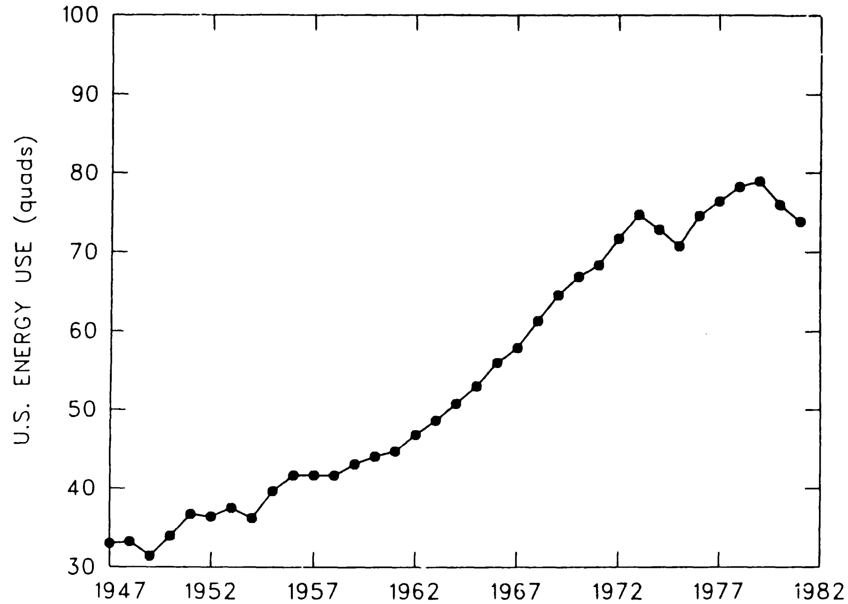

Figure 1 US energy use, 1947–1981. Source: (1).

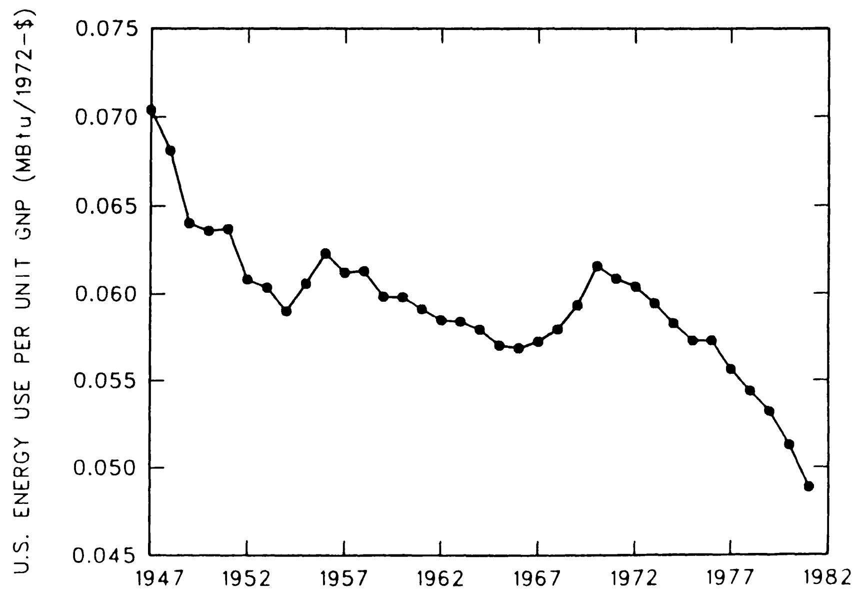

Figure 2 US energy use and GNP. Source: (1–3).

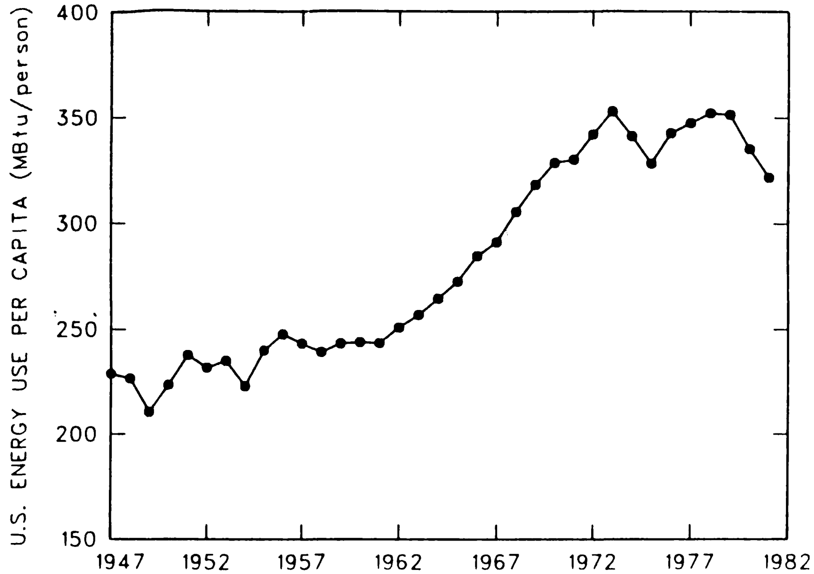

Figure 3 US energy consumption per capita. Source: (1, 2).

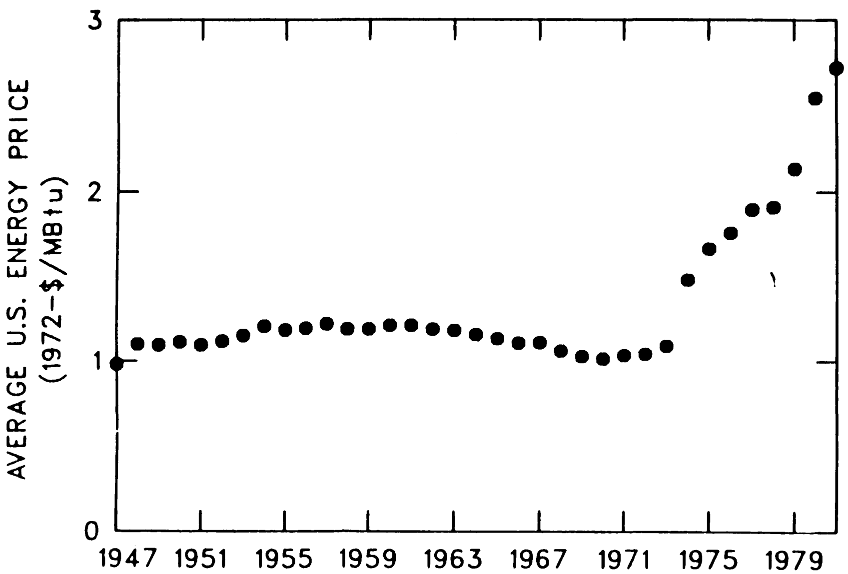

Figure 4 The average real price of energy to the US economy, 1947–1981. Source: (13, 15).

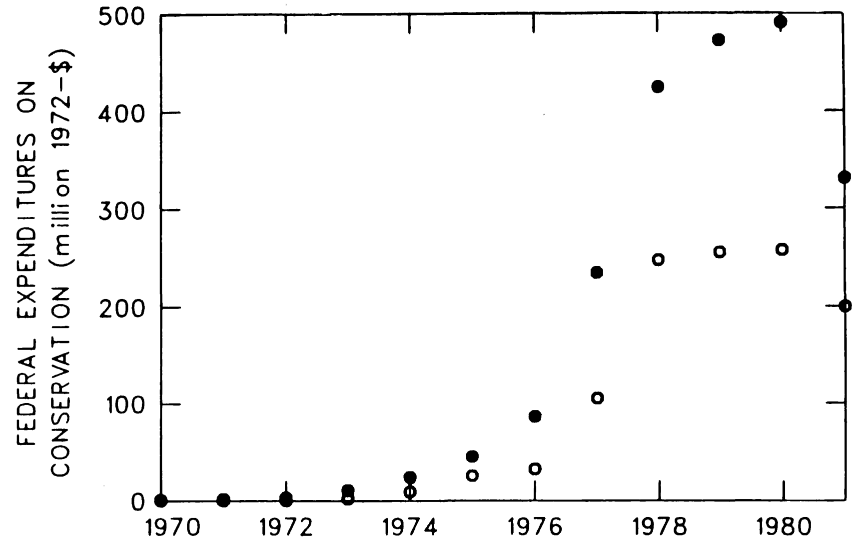

Figure 5 Energy conservation expenditures of the US Department of Energy and its predecessor agencies, 1970–1981. The open circles (lower points) are the expenditures aimed at influencing energy use in the short run [these figures do not include long-run research and development (R&D) programs]. Federal conservation expenditures are assumed to be negligible before 1970. Source: (15).

some energy-intensive industries (especially airlines and intercity trucking); accelerated shifts away from energy-intensive heavy industries toward service, information, and light manufacturing industries; and implementation of government (at all levels) and private energy conservation programs. For example, DOE energy-conservation program budgets increased from about $10 million in 1973 to a high of almost $500 million in 1980 (both in 1972 dollars) (Figure 5; M. Savitz, P. Patterson, personal communications).

Analyses

To explore the possible relations between aggregate energy use and its assumed determinants, we developed very simple regression models of US energy use as a function of GNP, average energy price, federal expenditures on energy conservation programs, and the previous year's energy use (14, 15). There are, however, limitations inherent in the projections obtained from these models. First, the experiment that history provided is seriously compromised by multicolinearity, i.e. correlation of some of the key variables. This is a particularly serious problem with respect to average energy price and federal conservation program expenditures[7] (compare

[7] The correlation coefficient (r) between energy price and federal expenditures is 0.9.

Figures 4 and 5). In addition, we were unable to capture explicitly the effects of some variables (e.g. occasional fuel shortages and changing composition of industrial output) in these simple models; therefore, the results may suffer from misspecification. Nevertheless, they are useful because, as far as we know, they represent the first effort to include nonmarket forces explicitly in energy-demand models. The models[8] were used to project energy use from 1973 to 1981 under four sets of assumptions:

1. GNP grows at its pre-embargo rate (4.2% per year real); federal expenditures on energy conservation and fuel prices remain constant at their 1973 levels.
2. GNP follows its actual path; federal expenditures and energy prices remain constant at their 1973 levels.
3. GNP and energy prices follow their actual paths; federal expenditures remain constant at their 1973 level.
4. GNP, energy prices, and federal expenditures follow their actual paths.

Figure 6 shows the projections and values of actual energy use. US energy use in 1981 was 28 quads below what a pre-embargo business-as-usual projection (#1 above) would suggest. Almost half (12 quads) of the reduction (the difference between runs 1 and 2, the top two projections in Figure 6) was due to slower economic growth.

The remaining 16 quads represent increases in overall energy efficiency. Of this 16-quad reduction, almost 11 quads was due to higher fuel prices (the difference between runs 2 and 3), and about five quads was due to nonmarket forces (the difference between runs 3 and 4).

The projections for the entire post-embargo period show an increasing divergence between actual energy use and the business-as-usual projection. The difference increases steadily from four quads in 1974 to 28 quads in 1981. Changes in GNP account for two-thirds of the energy-use reduction in early years, declining to somewhat less than half the reduction in 1981; the GNP effect increases from two quads in 1974 to 12 quads in 1981. The effect of fuel price increases accounts for roughly 40% of the reduction throughout the 1974–1981 period.

[8] The equation used to make these projections (Table 3; 15) is:

$$\text{Annual energy use} = 6.22 - (4.19 \times \text{Energy price}) + (0.0354 \times \text{Fed expenditures}) - (0.0188 \times \text{Energy price} \times \text{Fed expenditures}) + (0.0325 \times \text{GNP}) + (0.443 \times \text{Last year's energy use}).$$

All the coefficients are significant at the five-percent level or better. Note that federal expenditures reduce energy use through their interaction with energy price, which suggests that conservation expenditures (and the nonmarket forces for which they serve as a proxy) become more effective as energy prices rise.

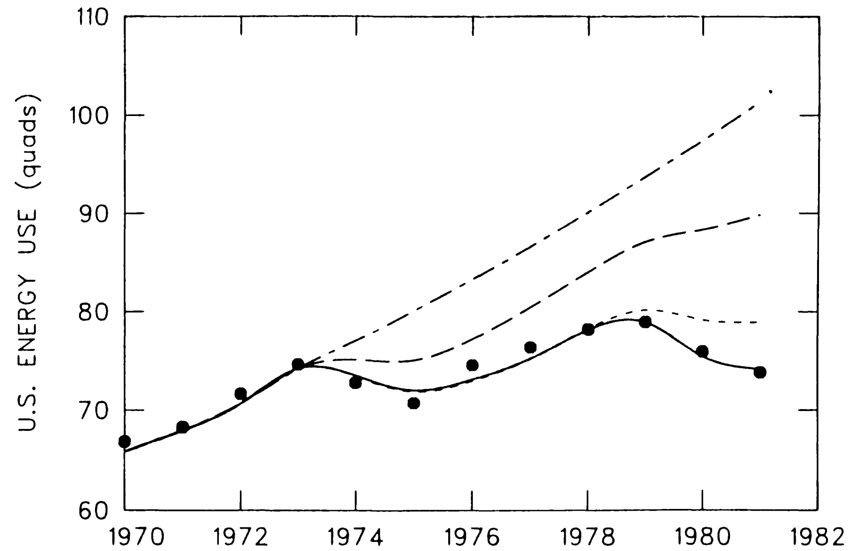

Figure 6 US energy use, 1970–1981, and projections. The top projection assumes that GNP grows at its pre-embargo rate (4.2% per year) and that real fuel prices and federal conservation expenditures remain constant at their 1973 values, respectively. The second projection assumes that GNP follows its actual path and that fuel prices and federal expenditures remain constant. The third projection assumes that GNP and fuel prices follow their actual paths and that federal expenditures remain constant. The bottom projection assumes that GNP, fuel prices, and federal expenditures all follow their actual paths during the 1973–1981 period. The dots are actual energy use. Source: (15).

The estimated effect of conservation programs and other nonmarket forces starts out very small and then grows rapidly at the end of the projection period, reaching five quads in 1981. During this period, DOE's energy conservation budget also grew rapidly, i.e. amost 800% between 1975 and 1981 (Figure 5).

Because of the variety of nonmarket forces that might have affected energy use during recent years, we tested several plausible model formulations that included a time-trend variable (equal to zero before 1973 and equal to year 1972 thereafter) and dummy variables to allow for shifts in price responsiveness after the 1973 oil embargo (15). The results confirm that statistically adequate models can be formulated that do not include federal conservation expenditures. In other words, recent changes in energy use can be reasonably well explained with a model that includes such expenditures or a model that includes time trends and/or dummy variables to capture these recent nonmarket changes.

DOE's Office of Policy, Planning and Analysis also examined recent trends in energy consumption (Figure 7; 17). They used the same data

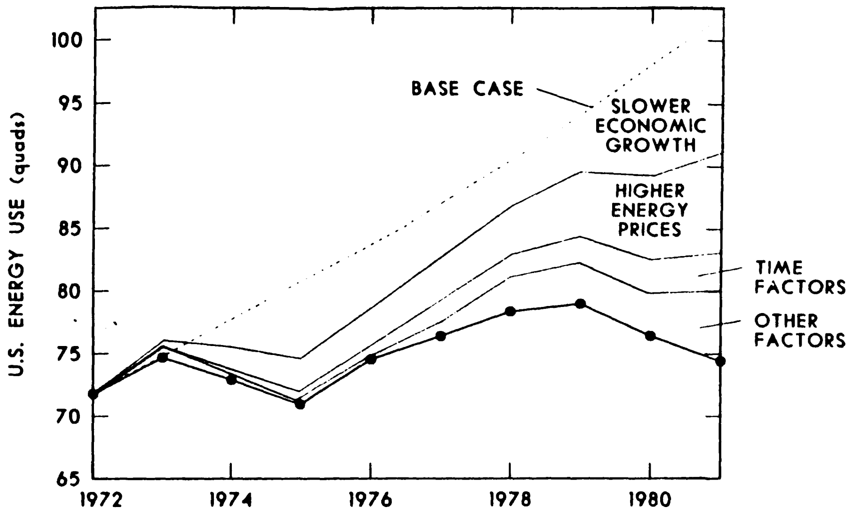

Figure 7 Recent trends in US energy consumption. Source: (17).

discussed above to disaggregate recent changes in terms of slower economic growth, increased energy prices, continuation of historical trends in improved energy efficiencies (see Figure 2), and "other" factors.

Their analysis yields results that are similar to those offered above. Energy use in 1981 was 28 quads below their base case (which projects historical trends from 1972, rather than from 1973, as done above). Slower economic growth accounted for 11 quads of this reduction, higher energy prices for eight quads, time factors for three quads, and other factors for the remaining six quads. According to the DOE analysis, these other factors include accelerated economic trends away from heavy industry, technological advances, energy shortages, deregulation of energy-using industries, increasing public awareness of the energy "crisis," and conservation programs of utilities, the private sector, and governments. They estimate that federal programs and tax credits probably account for "less than 5% of the overall increase in energy efficiency per unit of GNP" (about 0.85 quads in 1981, referring to the DOE's estimate of the 5% saving due to federal programs and tax credits).

This estimate is comparable to one developed by examining the energy-saving estimates for conservation programs reported in the DOE *Sunset Review* (11), as well as the supporting material prepared for that review and previous evaluations of programs administered by DOE's Office of Conservation and Renewable Energy (15). This review suggests that the

DOE conservation programs accounted directly for an energy saving of 0.55 quads in 1981 (Table 2).

This estimate needs to be interpreted cautiously, however. First, many DOE programs were not evaluated and are therefore not included in the energy-saving estimate (see all the blanks in Table 2). Second, the estimates include only the direct effects of DOE programs and do not consider possible indirect energy savings that the programs might yield. Finally, almost all the evaluations on which these estimates are based contain methodological limitations; this makes it difficult to interpret the 0.55-quad estimate with confidence as a lower limit on the likely effect of DOE programs.

The Energy Information Administration (19) analyzed the 3.7% decline in energy use between 1979 and 1980 by using its energy end-use models (Table 3). EIA's results show that approximately 40% of this one-year decline was due to operational changes (e.g. thermostat settings in residential and commercial buildings, reduced transportation vehicle mileage) motivated by energy price increases that year. About 20% was due to technical energy-efficiency improvements (e.g. additional attic insulation in homes, automatic control systems in commercial buildings, new cars with higher fuel economy). Part of the increase in technical efficiency was due to price increases in 1980; part was due to price increases in earlier years. This lag is reasonable given the long lifetimes of the nation's capital stock (homes, commercial buildings, transportation vehicles, factories). Roughly 8% of the energy-use decline was due to the slight decline in GNP between 1979 and 1980. Finally, nearly one-third (0.9 quad) of the decline in energy use is a residual, unexplained by the EIA models. This residual includes errors in the models and data, structural changes in the economy, and the effect of nonmarket forces (including government and utility conservation programs) on energy use.

The results presented in this section show that recent energy-use trends are very different from long-term historical trends. Largely because of higher and rising energy prices, energy use, energy use per unit GNP, and per-capita energy consumption are all far below what historical trends would suggest. A variety of other forces, in addition to energy prices, were also influential in slowing energy growth during the past several years. Because these factors are correlated with energy prices and because they are hard to incorporate in simple econometric models, we are unsure about the relative importance of these factors on slower energy growth and improved energy efficiency. All this suggests the importance of examining energy use and its determinants at more disaggregate levels, the subject of the following three sections.

Table 2 Estimated energy savings due to DOE energy conservation programs[a]

Program[b]	Initial year (FY)	Energy savings objective	Estimated energy savings (1981, quads)
Buildings & community systems			
Building systems	1974	long-term	
ATT		N/A[c]	
TCP	1974	short-term	0.015
Appliance standards	1975	long-term	
FEMP	1975	short-term	0.060
Res./comm. retrofit	1979	short-term	NR[d]
RCS	1979	short-term	NR
Community Systems	1974	long-term	0.005
Small business	1974	short-term	0.012
Energy impact assistance	1978	N/A	
Urban waste	1974	short-term	0.047
Industrial	1974	short-term	0.105
Transportation			
Vehicle propulsion	1978	long-term	
EHV	1976	N/A	
TSU	1975	short-term	0.021
Alternative fuels util.	1978	N/A	
Multi-sector			
ECUT	1974	long-term	
ERIP	1974	long-term	
AT	1977	long-term	
State and local programs			
EES	1977	short-term	0.088
SECP	1977	short-term	0.255
WAP	1978	short-term	0.018
Institutional buildings	1978	short-term	0.018[e]
Electric energy systems			
Systems arch. & integ.	1970	long-term	
Power delivery	1970	long-term	
Generation & storage analysis	1970	long-term	
Energy storage			
Electrochemical	1974	long-term	
Physical and chemical	1974	long-term	
TOTAL			0.554

[a] Source: (15).
[b] Abbreviations:

AT	Appropriate Technology	FEMP	Federal Energy Management Program
ATT	Applied Technology Transfer	RCS	Residential Conservation Service
ECUT	Energy Conversion and Utilization Technologies	SECP	State Energy Conservation Program
EES	Energy Extension Service	TCP	Technology and Consumer Products
EHV	Electric and Hybrid Vehicles	TSU	Transportation System Utilization
ERIP	Energy-Related Inventions Program	WAP	Weatherization Assistance Program

[c] Not applicable—Some programs were not intended to save energy. Applied Technology Transfer, for example, provides economic, administrative and technical support to other BCS programs.
[d] None reported—Even though the program has short-term objectives the program has yet to be implemented nationwide.
[e] Represents the results of an evaluation in seven states.

Table 3 EIA analysis of energy use decline between 1979 and 1980[a]

Short-run price response		
Operations	41%	
Technology	14%	20% Technology
Long-run price response	6%	
GNP	8%	
Other	31%	
Total	100%	

[a] 1980 energy use (76.3 quads) was 3.7% below the 1979 level. Source: (19).

THE RESIDENTIAL/COMMERCIAL BUILDINGS SECTOR

Introduction

Energy use in residential and commercial buildings totaled 26 quads in 1981, equal to one-third of the US total (1, 12, 20–23). Residential buildings accounted for 15 quads, while commercial buildings accounted for almost 11 quads (Table 4). Between 1950 and 1973, buildings energy use grew at about 4.5% per year; between 1973 and 1981 growth occurred at only 0.8% per year (Table 1). Both residential energy use per household and commercial energy use per unit floor area declined at an average rate of about 1.5% per year after 1973. During the earlier 1950–1973 period these measures of energy intensiveness were increasing: at about 2% per year for households and about 1% per year for commercial buildings. Thus, significant changes in energy efficiency have occurred in buildings during the past few years.

Table 4 Energy use in residential and commercial buildings, 1970–1981[a]

	Residential			Commercial		
	Energy use (quads)	Households (millions)	Energy intensity (MBtu/HH)[b]	Energy use (quads)	Floor area (billion ft²)	Energy intensity (kBtu/ft²)
1960	8.3	52.8	157	4.9	15.8	310
1965	10.2	57.4	178	6.0	20.3	295
1970	13.4	63.4	211	8.4	23.9	351
1971	13.9	64.8	215	8.8	24.7	356
1972	14.5	66.7	217	9.2	25.6	359
1973	14.6	68.2	214	9.6	26.6	361
1974	14.4	69.9	206	9.4	27.5	342
1975	14.4	71.1	203	9.5	28.1	338
1976	15.0	72.9	206	10.0	28.7	348
1977	15.2	74.1	205	10.2	29.5	346
1978	15.5	76.0	204	10.5	30.3	347
1979	15.4	77.3	199	10.7	31.1	344
1980	15.3	79.1	193	10.6	32.1	330
1981	15.2	80.7	188	10.6	32.9	322

[a] Sources: (1, 12, 20–23).
[b] HH = households.

Commercial buildings

Little is known about energy use in commercial buildings, perhaps because of their tremendous diversity in design, structure and function. Commercial buildings (e.g. office buildings, schools, stores) house the service sectors of our economy such as retail and wholesale trade, finance and insurance, education, health services, and government activities; group quarters (e.g. jails and hospitals) are also considered part of the commercial sector.

In 1979, the EIA conducted the first national survey of nonresidential buildings and their energy-related characteristics (25). The EIA survey provides a wealth of detail concerning building characteristics (location by census region and weather zone, floor area, heating fuel and equipment type, air-conditioning fuel and equipment type, age, number of floors, etc), occupancy characteristics (hours of use per week, owner vs tenant occupancy, single- vs multiple-establishment building), and adoption of conservation practices and measures in 1979.

Survey results suggest that there were a total of 4.0 million commercial buildings in the United States in 1979. The dominant building types are retail/service, office, warehouse and storage, and automotive sales and services. The number of buildings is less important from an energy point of view than is floor area within the commercial sector.[9] Because of the large size variations both among and within building types (Table 5 and Figure 8), the distribution of total floor area by building type is different from the distribution of the number of buildings by building type. In terms of floorspace, the most important commercial building types are office (15%), retail/service (15%), warehouse (14%), and education (13%).

Table 5 Distribution of commercial buildings and floorspace by building type[a]

	Average floor area (thousand ft²)	Percentage of commercial	
		Buildings[b]	Floor area[c]
Assembly	11.7	11	11
Automotive sales and service	4.3	10	4
Education	40.1	4	13
Food sales	4.3	9	3
Health care	32.6	1	3
Lodging	19.3	3	5
Office	12.2	15	15
Residential	10.1	9	8
Retail/services	9.8	18	15
Warehouse	14.7	11	14
Other	13.1	6	7
Vacant	9.4	4	3

[a] Sources: (24, 25).
[b] The total number of commercial buildings in 1979 was 4.0 million, according to the EIA survey.
[c] The total floor area of commercial buildings in 1979 was about 47.5 billion ft².

Buildings with floor areas of less than 5000 ft² account for more than half (57%) of the total number of buildings, but for only ten percent of the total floor area (Figure 8). Very large buildings (greater than 100,000 ft²), on the other hand, represent only two percent of the total number, but 33% of the total floor area.

Natural gas is the dominant heating fuel in nonresidential buildings, accounting for almost half (49%) of all such buildings with heating systems.[10] Electricity is the primary heating fuel in 24% of the buildings and

[9] The estimate of US commercial floorspace developed by ORNL (21) from F. W. Dodge construction data is considerably less than the EIA estimate (24) (31.1 vs 47.5 billion ft² for 1979). The reasons for this discrepancy are not clear.

[10] 11% of the nonresidential buildings (primarily vacant buildings and warehouses) report use of no heating fuel.

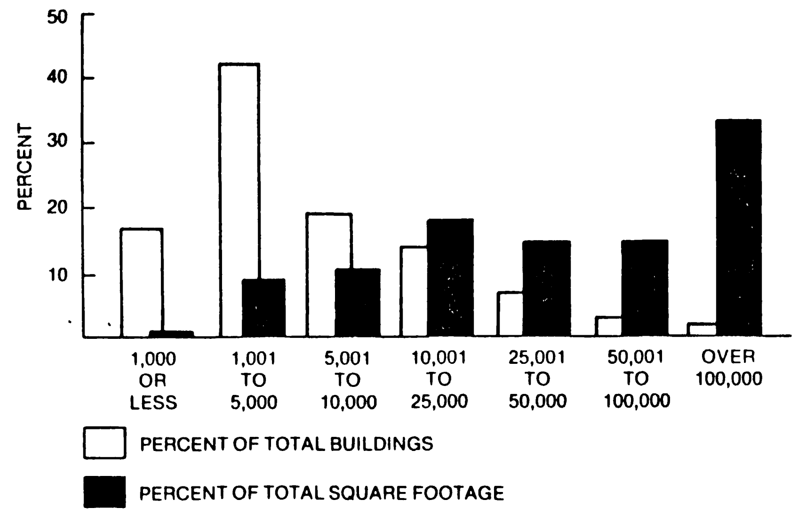

Figure 8 Square footage of nonresidential buildings. Source: (25).

oil in 19%. Liquified petroleum gas (LPG), wood, coal, and steam account for the remainder. The fraction of buildings heated with electricity has increased steadily over time: only 11% of the buildings constructed before 1921 used electricity as the heating fuel, but 48% of the buildings constructed after 1973 did.

Slightly less than two-thirds (64%) of the buildings are air conditioned, with almost all of these buildings using electric air-conditioning equipment. Buildings constructed after 1960 are much more likely to have air conditioning than are older buildings.

Responses to the EIA survey suggest that many nonresidential buildings have adopted conservation measures and practices[11] during the past few years (Table 6). There is considerable variation in adoption of such actions among weather zones. Generally speaking, measures and practices that reduce heating energy use are more likely to be adopted in areas with severe winters; the reverse is true for reduced cooling.

The EIA survey provides valuable information about the condition of commercial buildings at one time (1979)—a "snapshot." Unfortunately, the EIA data tell us little about changes in energy use and energy-related characteristics of these buildings, the cost-effective potential for improving energy efficiency, and the actual progress in reducing commercial energy use.

[11] Conservation measures require capital expenditures to modify and improve energy-using equipment and/or the building structure. Conservation practices refer to operation and maintenance changes that do not involve capital costs.

Table 6 Conservation actions in nonresidential buildings[a]

	Percentage of buildings by weather zone that reported action		
	US average	Maximum[b]	Minimum[c]
Weatherstripping or caulking	36	45	22
Insulation	27	33	17
Treated glass	14	17	9
Reduced heating	74	79	69
Reduced cooling	37	49	28
Regular maintenance	70	78	58

[a] Source: (25).
[b] The highest percentages for adoption of conservation actions occurred in the colder weather zones (with more than 5500 heating degree days), except for reduced cooling, which occurred in the zone with the greatest summer cooling load.
[c] The lowest percentages for adoption of conservation actions occurred in the mildest weather zone [less than 2000 CDD (cooling degree days) and less than 4000 HDD (heating degree days)], except for reduced cooling which occurred in the zone with the greatest heating load (and the smallest cooling load).

The Office of Technology Assessment (OTA) recently completed an analysis (26) of "the prospects for and barriers to increased energy efficiency in the building stock of the nation's cities." Its analysis suggests that technically feasible energy savings in the year 2000 might amount to more than half of the baseline commercial sector energy use. The technical feasibility and economic attractiveness of retrofit opportunities depend on four major factors:

BUILDING SIZE Improving the building shell (walls, windows, roof) is much less important in large buildings than in small buildings. On the other hand, improvements to heating, ventilation, and air-conditioning (HVAC) equipment are likely to yield relatively larger savings in big buildings.

WALL AND ROOF TYPE Certain construction materials and practices are much more difficult to retrofit than are other types.

HVAC SYSTEM TYPE There is enormous variety in the types of systems used to provide hot or cold air, and ventilation to the occupants of commercial buildings; this variation leads to large differences in cost-effective conservation measures.

BUILDING USE Most commercial buildings are occupied for only portions of each day (e.g. office buildings are generally in use from 8 am to 5 pm during weekdays and unoccupied during the rest of the week). Other buildings (in particular, hospitals) are occupied 24 hours a day. Careful controls of HVAC and lighting systems during occupied and unoccupied periods can greatly reduce building energy use.

OTA also discussed the difficulty in predicting the outcome of a retrofit for a particular building. Uncertainty about the likely energy savings leads to underinvestment in commercial building retrofits. Some of the reasons for this uncertainty include: lack of data on actual retrofits; dependence of energy savings on building operation and maintenance; and variations among buildings in design, siting, and construction that complicate estimation of likely energy savings.

Although little is known about the actual performance of retrofits (more on this later), some data are available on the potential for improving energy efficiency in existing buildings.[12] One major source of such data is the federal Institutional Conservation Program (ICP), a program to audit and retrofit schools, hospitals, local government buildings, and public-care institutions (27, 28). ICP data show large variations among buildings in terms of their energy-related characteristics (as was shown more broadly in the EIA survey). For example, although mean energy use among almost ten thousand school buildings from ten states (29) throughout the country was 155 kBtu/ft^2, the 95% confidence limit was 35–275 kBtu/ft^2. (These figures implicitly include differences due to climate, i.e. winter and summer severity.) Similar variations occur for other buildings types. Statistical analysis of energy use at these buildings showed that energy use at schools varies inversely with energy prices and building age, and directly with the number of occupant-hours and the product of cooling degree days and percent of building air conditioned (30).

Data are available from the ICP and other sources on the potential for saving energy through retrofit of commercial buildings (see, for example, recent issues of the *ASHRAE Journal* or *Energy Management*). These data are generally from on-site audits conducted at such buildings. For example, analysis of audit results from Illinois public schools (both elementary and secondary) showed an average reduction, due primarily to inexpensive operation and maintenance (O&M) changes, of almost eight percent with an average payback period of only a few months (31).

Analysis of data from audits of schools and hospitals in Wisconsin showed a potential energy saving of roughly 30% for schools and 20% for

[12] Several interesting papers related to energy use and conservation in residential and commercial buildings were presented at a recent workshop. The workshop, *What Works? Documenting the Effects of Energy Conservation in Buildings*, was sponsored by the American Council for an Energy-Efficient Economy and held in August 1982 in Santa Cruz, Calif. Copies of papers presented at the workshop can be obtained from Jeffrey Harris, Energy-Efficient Buildings Program, Lawrence Berkeley Laboratory, Berkeley, Calif. 94720.

hospitals (32). Most of the estimated energy savings and costs were due to conservation measures rather than to O&M changes.

Analysis of energy audits conducted at 48 hospitals showed an average estimated energy saving of 20% with implementation of O&M measures (33). Because the focus of these audits was on low-cost options (and therefore excluded most of the more expensive conservation measures), the average payback period for these O&M changes was only one year (Figure 9).

Ross & Whalen (34) examined data from 222 buildings for which actual metered energy-use records were available. The intent of their analysis was to determine the actual performance of O&M and retrofit changes in commercial buildings (mostly schools and offices). Almost 95% of the buildings adopted O&M changes. Only about one-third of the buildings installed retrofit measures (insulation, storm windows, energy management systems, and HVAC changes).

There was considerable variation among buildings in the actual energy savings; the average was 19% of preretrofit energy consumption. Although one might expect to see a close correlation between energy saving and capital cost (as was shown in the hospital audits discussed above), this was

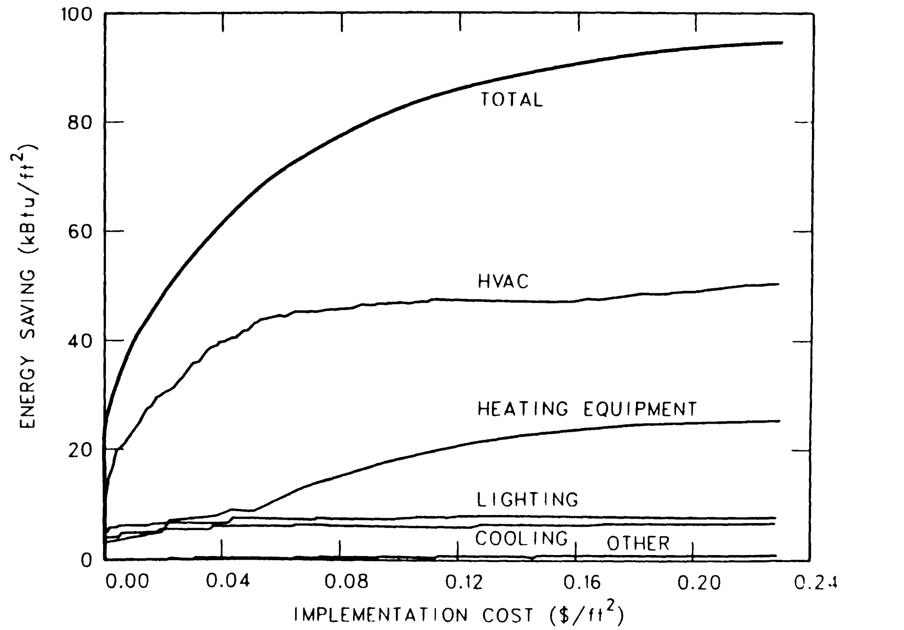

Figure 9 Cumulative estimated energy saving as a function of cumulative implementation cost, by type of audit recommendation. Source: (33).

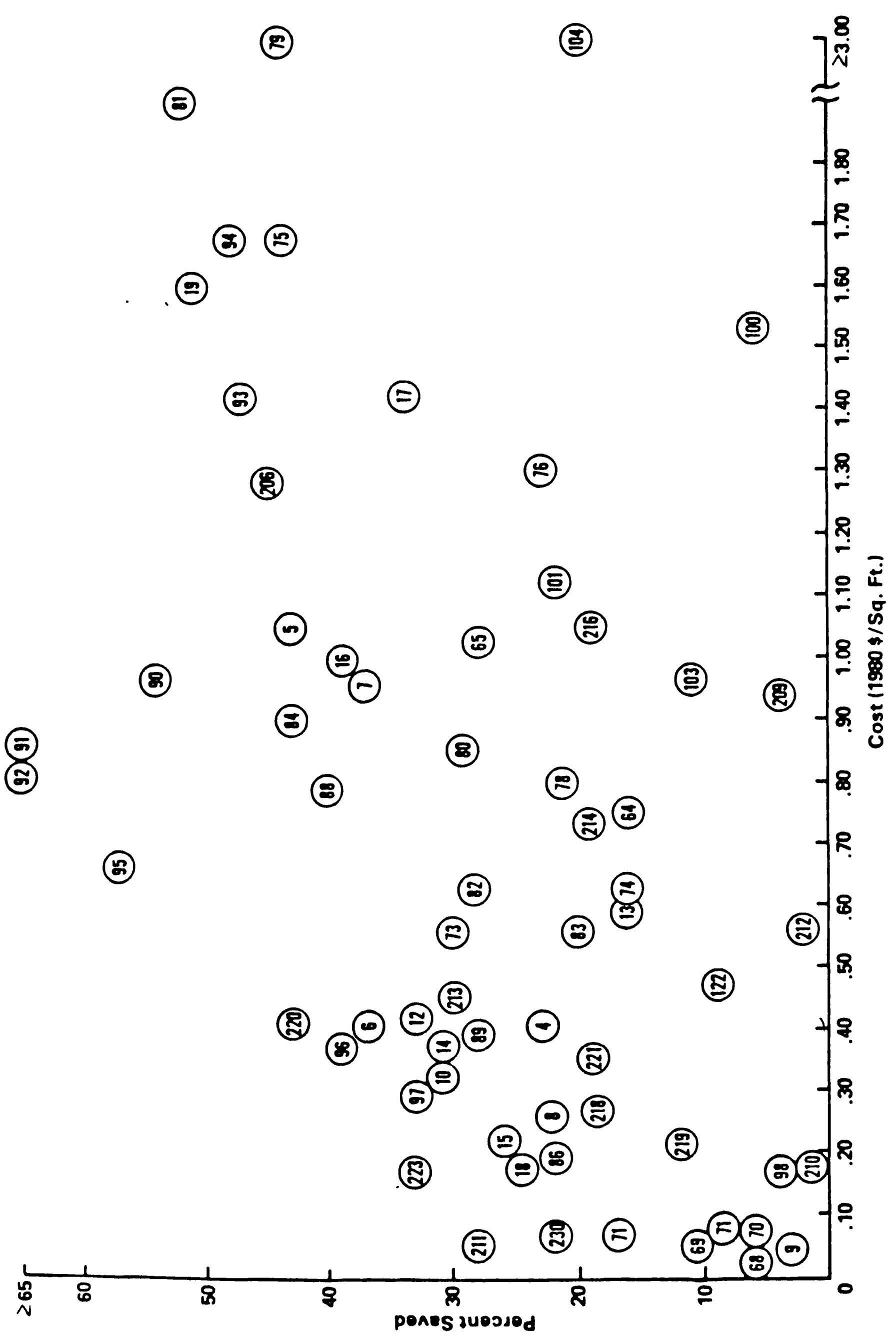

Figure 10 Percentage of baseline energy consumption saved due to retrofit vs retrofit cost. Source: (34).

Table 7 Energy consumption in commercial buildings and percentage reduction due to energy-efficient redesigns[a]

	Energy used[b] ($kBtu/ft^2$)	Percentage reduction due to redesign (%)[c]
Office buildings		
Small	77	49
Large	69	42
Stores	87	33
Shopping centers	98	34
Hotels/motels	96	29
Hospitals	240	40
Schools		
Elementary	58	47
Secondary	85	40

[a] Source: (36).
[b] These figures represent annual energy use (at the building boundary) for buildings constructed in 1975 and 1976.
[c] Hypothetical energy-efficient designs were developed for each of these building types as part of the DOE's efforts to develop Building Energy Performance Standards.

not the case (Figure 10). The average cost of retrofit at these buildings was $0.65/ft², yielding an average payback period of about one year; almost 90% of the buildings experienced a savings that would yield a payback period of three years or less.

The discussion above suggests that there are substantial opportunities for cost-effective retrofit in existing commercial buildings. The limited data suggest that most of the realized savings have occurred primarily through adoption of practices and inexpensive retrofit measures. This suggests that much of the energy-efficiency potential has not yet been realized.[13]

Turning to energy use in new commercial buildings, we again find very limited data. Analyses for DOE related to development of proposed thermal performance standards for new buildings showed the very large potential for upgrading energy efficiency in new buildings (Table 7; 35, 36). The potential for reducing energy use in new buildings ranged from about one-fourth to one-half the energy use for buildings actually constructed in

[13] Although engineering analyses show large potential energy savings in existing buildings, one must be cautious in translating these estimates into actual savings. Questions arise concerning the extent to which estimated savings will be achieved in the "real world" and whether consumers will adopt these measures [i.e. whether consumer economics (including high discount rates and perceptions of risk) are adequately captured in simple cost-effectiveness calculations].

1975 and 1976. In many cases, there was little or no increase in the capital cost for an energy-efficient building (largely because the efficient designs required smaller, and therefore less expensive, HVAC equipment); because there were substantial reductions in operating costs (from reduced fuel bills), the predicted life-cycle cost of the energy-efficient designs were generally substantially less than those for the original designs (37).

Residential Buildings

Much more is known about residential energy use and its determinants than is known about commercial energy use. The EIA conducted detailed surveys of about 5000 households in 1978, 1979, and 1980 (38–40). These surveys provide information analogous to that provided in the EIA nonresidential survey discussed above.

More than half the households (55%) use natural gas as their main heating fuel, 18% use electricity, 16% use oil, almost 5% use bottled gas, and almost 6% use wood (40). During the past few years, the fraction of households using wood has increased sharply while the fraction using oil has declined.

The 1980 EIA survey included interviewer measurements of the area of housing units. The mean value was about 1500 ft^2. Not surprisingly, there is a strong positive relationship between household income and housing unit size.

Many households reported adoption of conservation measures during 1978 and 1979 (Table 8). Caulking and weatherstripping (two relatively inexpensive measures) were the most popular. Almost seven percent of the single-family households reported adding a wood-burning stove during the past two years, a figure reflected in the increasing number of households that claim wood as their primary heating fuel—up from 1.9 million in 1978 to 4.7 million in 1980.

Table 8 Conservation measures adopted by households in 1978 and 1979[a]

	Percentage of households by income group		
	Poor	Average	Wealthy
Caulking	13	23	29
Weatherstripping	10	19	24
Roof or ceiling insulation[b]	9	12	13
Storm doors	5	8	12
Storm windows	4	7	9

[a] Source: (40).
[b] Asked only of households in single-family units.

The federal Residential Conservation Service and other programs aimed at improving the energy efficiency of existing homes provide information on the potential for improving energy efficiency, on the measures and practices implemented by households, and on the actual energy savings achieved because of these conservation actions (41–44).

A group at the Lawrence Berkeley Laboratory (43) (LBL) examined data from 65 North American retrofit projects that included information on *actual* pre- and post-retrofit energy consumption (Figure 11). Their analysis showed an average reduction in annual space heating energy use of 24% arising from adoption of these retrofit measures. The median energy saving is 28 MBtu at a median cost for measures of \$1100. The LBL group estimated that, on average, a \$1000 investment will cut energy use for space heating by 25%; a \$2000 investment will cut energy use by 40%.

Data from DOE's Building Energy Performance Standards program (discussed above) and from the National Association of Home Builders (45) show how the thermal performance of new homes (especially single-family homes) has increased during the past several years. In a similar fashion, DOE's appliance efficiency program yields valuable information on recent improvements in the energy efficiency of residential appliances and heating equipment (46).

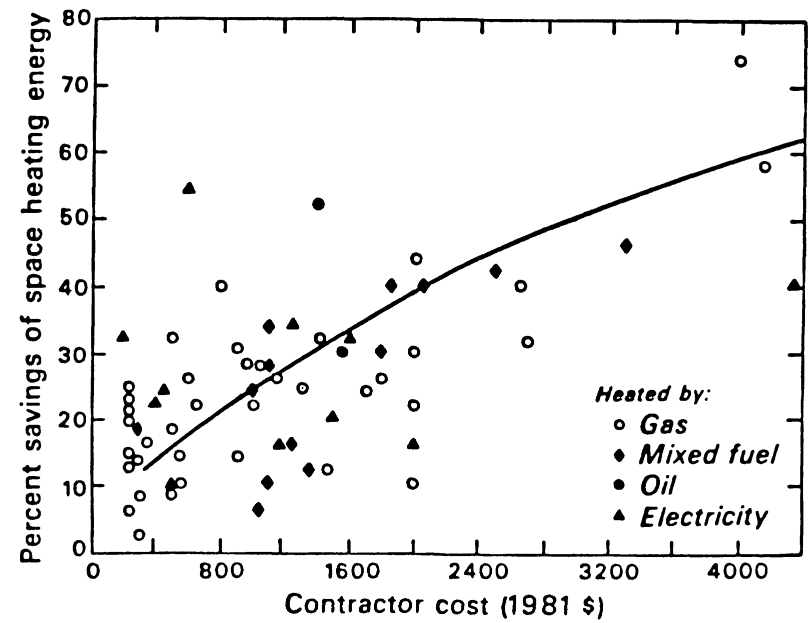

Figure 11 Percent of space-heating energy consumption saved by retrofit vs contractor cost for retrofit. Source: (43).

A recent analysis conducted at Battelle's Pacific Northwest Laboratory (47) examined overall changes in residential energy use between 1973 and 1980 and tried to allocate the changes to different factors. The analysis estimated an overall reduction in 1980 residential energy use of almost 2.3 quads relative to a base case forecast from 1973 to 1980. Almost one-fourth of this saving was due to increases in the efficiency of building shells (both new and existing). Appliance efficiency increases accounted for another ten percent. The unexplained portion of the saving accounted for almost two-thirds of the total; this includes errors in the data and analysis, fuel switching (e.g. from oil to electric heat), and operational changes (e.g. thermostat reductions on space and water heating systems, less use of hot water). The analysis also concluded that the effects of changes in dwelling unit size and of regional migration were very small.

THE INDUSTRIAL SECTOR

Introduction

The industrial components of the US economy nominally embrace agriculture, construction, manufacturing, and mining. In terms of energy consumption, the latter two sectors are much the larger and account for more than 90% of industrial energy use. Our discussion thus concentrates on these two sectors.

Today, mining and manufacturing industries account for approximately 40 percent of total US energy consumption (1, 22). Historical trends in industrial use of energy between 1947 and 1973 show that consumption grew quite steadily at an average rate of about 3.2% per year. Yet from 1973 through 1981, there has been growth and decline with no overall gain. As with total US energy consumption, aggregate industrial energy consumption in 1981 was actually slightly below that for 1973.

In 1975, a federal government program was begun to monitor the energy intensity (energy use per unit of production) of the ten most energy-intensive industries (Table 9). For each of these industries total energy use declined between 1972 and 1980, while output increased. For each of the ten industries there was a decline in energy intensity, indicating that efficiency in the use of energy increased.

At least three unique historical events of the past decade are significant to our consideration of energy consumption trends. It is well known that in the early 1970s, petroleum prices began a series of sharp increases, instigated by the Organization of Petroleum Exporting Countries (OPEC). This led to real price increases (relative to the general economy) for all fuels. In late 1973, the OPEC nations imposed a petroleum embargo on the United States. Although the embargo was of relatively short duration, industrial

Table 9 Growth in energy consumption and manufacturing production for ten energy-intensive industries (1972–1980)[a]

		Overall increase (%)	
SIC code		Energy use	Industrial production
20	Food and kindred products	+2.3	+27.7
22	Textile mill products	−16.0	+3.1
26	Paper and allied products	−7.3	+17.2
28	Chemicals and allied products	−2.5	+43.9
29	Petroleum and coal products	−5.1	+10.6
32	Stone, clay, and glass products	−12.6	+22.3
33	Primary metals	−15.5	−9.3
34	Fabricated metal products	−20.9	+20.3
35	Machinery, except electrical	−12.0	+40.2
37	Transportation equipment	−23.0	+7.9

[a] Source: (55).

users developed concerns about future petroleum availability. In 1977, natural gas supply curtailments forced a temporary shutdown of several US manufacturing plants. It is logical to assume that these conditions may have caused industrial energy conservation activities to occur.

We are interested in this chapter in identifying the factors that explain energy conservation trends and to quantify their contributions. There are at least five separate (but overlapping) kinds of activity that can produce changes in the level and intensity of industrial energy consumption: (*a*) a change in the level of industrial production; (*b*) a change in the composition of industrial output favoring more or less energy-intensive products; (*c*) replacement of existing production facilities with more or less energy-efficient processes (technological change); (*d*) switching from one fuel to a more or less energy-efficient fuel (fuel quality); and (*e*) increased or decreased attention to energy management in industrial operations (energy "housekeeping").

In the short term (i.e. less than five years), the level of industrial production will have the strongest influence on total industrial energy use. Also, attention to energy management tends to bring short-term responses. The other three activities however, normally involve substantial new capital investments and take effect over a longer term. In fact, since capital investment rates in the more energy-consumptive industries have slowed in the past decade (48), one would expect somewhat lesser contribution to date from these three activities.

Our analysis begins by examining trends in the use of individual fuels and the reasons for changes in the fuel mix. We then characterize the effect of differential industrial growth rates on overall energy consumption. Finally, we disaggregate the energy-use efficiency improvements into two elements—the long-term trend component (average rate of energy intensity decline, 1947 to 1972) and the accelerated improvement since 1972. Conceptually, the accelerated improvement represents the response to energy price increases and other stimuli such as government energy programs over the past decade.

Trends in Individual Fuel Use

Between 1947 and 1980, industrial use of solid fuels decline steadily, with some year-to-year exceptions (see Figure 12).[14] In 1947, the use of solid fuels by industry amounted to more than 7.2 quads. By 1973, this use had fallen to 5.5 quads. Despite what would appear to be strong price motivation to use coal as a substitute for much higher priced oil after 1973, the use of solid fuels by industry continued to decline throughout the late 1970s until its use reached a record low of 4.5 quads in 1980. On average, the decline over the entire 34-year period amounted to about 1.0% per year.

This decline appears to be driven by continuing abandonment of coal as a major fuel by virtually all industrial establishments other than coke plants. The only exceptions to this generalization are a few industries (primarily the Portland cement and lime industries) in which the production processes themselves are uniquely adapted to particulate capture or sulfur absorption.

Partially offsetting this decline in the use of coal, however, is the steady growth in the use of wood and solid waste for process energy, primarily as a substitute for petroleum products in the forest products industries. Wood and waste energy consumption is estimated to have grown at a rate of about 3.5% per year since 1947.

Industrial use of natural gas between 1947 and 1970 grew at a rate of 6.4% per year, outpaced only by the growth in electricity. The most striking feature of these trends, however, is the sharp departure from past trends beginning in 1971 and continuing through 1980.

In 1971, the growth in industrial use of natural gas came to an abrupt halt. In that year suppliers and distributors of natural gas advised customers that supply constraints would not allow the servicing of new customers. By 1972, again because of expected shortfalls of supply of natural gas, interstate pipeline curtailments were announced amounting to

[14] Here, solid fuels are defined to include bituminous coal, lignite, anthracite, net coke imports, wood and waste energy consumption, and all gaseous and liquid fuels derived on site from solid fuels (coke oven gases, black liquor, etc).

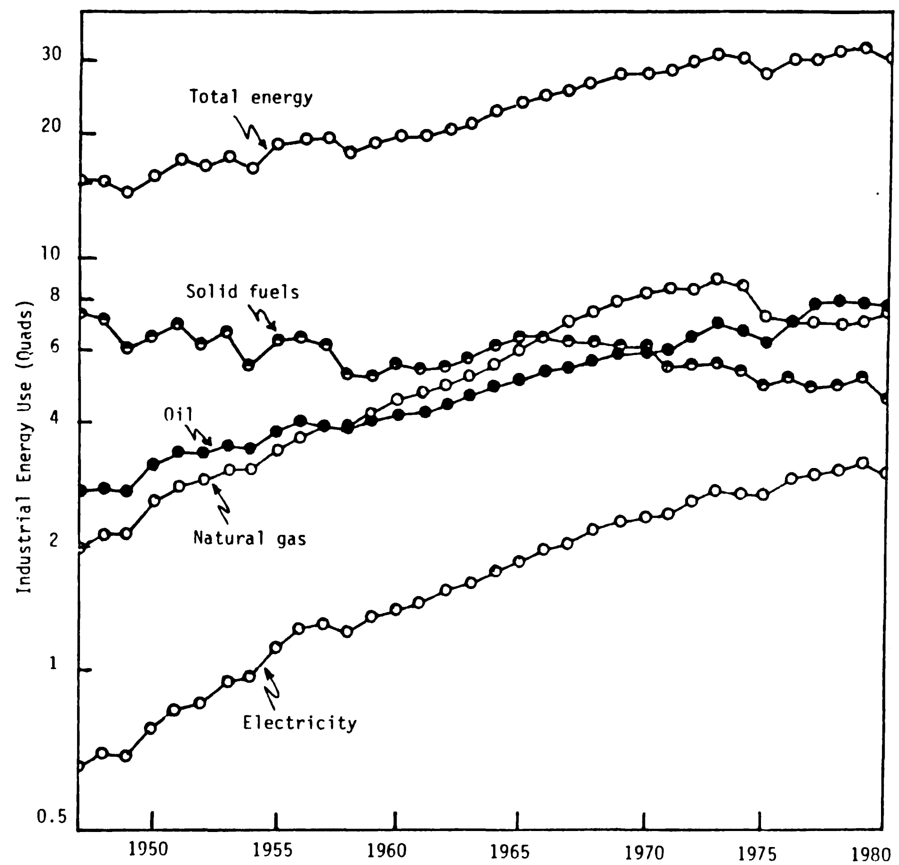

Figure 12 Consumption of fuels and electricity (at 3412 Btu/kWh) in US manufacturing and mining. Source: (52).

about six percent of total US natural gas consumption (49), and similar levels of curtailment were later announced for all years from 1973 through 1976. Finally, the winter of 1976–1977 proved to be a very difficult period for industrial users of natural gas, in which curtailments actually forced many industries to shut down temporarily.

While announcements of expected curtailments in the earlier years often did not materialize into actual supply interruptions because of production adjustments, fuel substitution, conservation measures, and unusually warm winters, the effects were much the same as curtailments. Industry responded to the announcements by contracting for delivery and substitution of alternate fuels, primarily oil, despite its considerable price disadvantage at the time. The result was that industrial use of natural gas (excluding the lease and plant fuel involved in oil and gas production) dropped precipitously from a high of about nine quads in 1973, to a recent low of about seven quads. Only in 1980, when supplies once again became more readily available, did the use of natural gas begin to rise again (50).

Between 1947 and 1980, industrial use of petroleum grew at an average rate of approximately 3.6% per year. Although there were cyclic phenomena during this period associated with economic booms and recessions, and although there were sharp temporary downturns in the use of oil in the 1973–1974 period and again in the 1979–1980 period, use of oil continued to increase. During the 1973–1980 period, the real price of oil to industry more than tripled. The steady growth in oil use in the face of what otherwise would appear to be strong price motivations for its decline is likely related to the already noted abandonment of coal and curtailments in the availability of natural gas.

Between 1947 and 1980 industrial use of electricity appears to have undergone at least three rather distinct periods of growth.[15] From 1947 through the mid-1950s, use of electricity grew at a rate exceeding 10% per year, perhaps reflecting the postwar modernization and growth of American industry. From about 1958 through the early 1970s, this growth rate slowed somewhat, but remained strong at about 6% per year. From about 1973 through 1980, however, the growth rate in electricity demand slowed to less than 2% per year.

Finally, the growth rate in total energy consumption by industry appears to have virtually flattened out in the postembargo period. By contrast, before 1973 total energy consumption had grown consistently at about 3.2% per year. Industrial output has continued to grow during the postembargo period, albeit at a slightly slower rate. The consumption of all fossil fuels combined, excluding those consumed by industry for the purpose of generating electricity, actually declined in the 1973–1980 period, suggesting that phenomena other than simple fuel switching from coal and gas to petroleum products are likely to be significant. Such phenomena include improvements in energy use per unit output, structural changes in the economic mix of industrial production away from the energy-consumptive industries, and other factors. In the next section, we examine these and attempt to estimate their relative importance.

Effects of Conservation and Other Factors

In examining what happened to industrial use of energy over the last ten years, one must consider many events that are likely to have had a major impact on energy consumption. Events directly related to energy include the continuing regulation of natural gas, accompanied for the first time by

[15] Electricity includes both sales of electricity to industry by electric utilities and self-generated power.

widespread curtailments during periods of supply shortages, the enactment in 1970 of the Clean Air Act, and the rising costs of the clean burning of coal, the Arab embargo of crude oil in 1973–1974, and two sharp increases in the price of world oil, first in 1974 and another in 1979, accompanied both times by increases in the prices of other fuels.

Because industrial demand for energy is essentially a demand derived from both the level and composition of industrial production, one must consider, as well, events that are likely to have affected energy consumption less directly but not less importantly. Among these are the general slowing of economic activity (gross domestic product—GDP) both in the United States and abroad, and shifts in the composition of industrial output away from energy-intensive products (as manufactuters attempt to recover increased production costs by raising prices). Factors influencing these phenomena, aside from higher energy prices, include the rising competitiveness of manufacturing industries abroad, particularly among labor-intensive industries (which are often highly energy consumptive as well), the growing export of materials-intensive industries to locations of mineral deposits abroad, and the unprecedented increases in the real cost of capital.

Finally, industrial energy consumption is affected by the efficiencies of production technologies and their controls. Recent developments along these lines include the extensive market penetration of computers and microprocessors for more efficient process control and the advent of new and more energy-efficient technologies. Partially offsetting these factors, however, is the decelerated retirement of obsolete production capacity.

While it is difficult, if not impossible, to separate clearly the impact of any one phenomenon, it is possible to characterize apparent reductions in industrial energy demand into several generalized categories, namely the slowdown in the economy, shifts in industrial output mix, and net gains in energy efficiency. The last category can be further delineated into gains consistent with past trends and those that appear to be accelerations, and therefore, attributable to the events of the 1970s.

To estimate the relative contribution of each factor, we hypothesize a base case trend in industrial energy use, compare this to actual energy use, and attempt to characterize the difference between the two. Our base case between 1972 and 1981 assumes (for comparison only) a constant energy use per unit of industrial output equal to the level observed in 1972. Industrial output, as measured by the Federal Reserve Board's index of industrial production for mining and manufacturing industries [which excludes natural gas and electrical utilities (51)], is then allowed to grow at 4.0% per year, which equals that observed for the 1953–1972 period.[16]

[16] The Federal Reserve Board indices for mining and manufacturing for years 1953 and 1972 were 56.3 and 118.5, respectively.

Table 10 Energy trends in industry (quads)[a]

Year	Base case E_1	FRB index[b]	Output adjusted E_2	Shift factor f_s	Adjusted for shift E_3	Technical trend factor f_t	Adjusted for historical trends E_4	Actual energy use E_5
1972	29.3	118.5	29.3	1.000	29.3	1.000	29.3	29.3
1973	30.5	128.8	31.8	1.010	31.5	1.008	31.3	30.8
1974	31.7	128.4	31.7	1.006	31.5	1.016	31.0	30.1
1975	32.9	116.1	38.7	1.021	28.1	1.024	27.4	27.7
1976	34.3	137.0	33.9	1.016	31.4	1.032	30.4	29.7
1977	35.6	137.0	33.9	1.034	32.8	1.041	31.5	30.4
1978	37.1	145.3	35.9	1.042	34.5	1.049	32.9	30.8
1979	38.5	151.7	37.5	1.054	35.6	1.057	33.7	31.3
1980	40.1	145.8	36.0	1.072	33.6	1.066	31.5	30.0
1981	41.7	149.8	37.0	1.083	34.2	1.074	31.8	28.6

[a] Sources: (17, 52).
[b] Manufacturing and mining index.

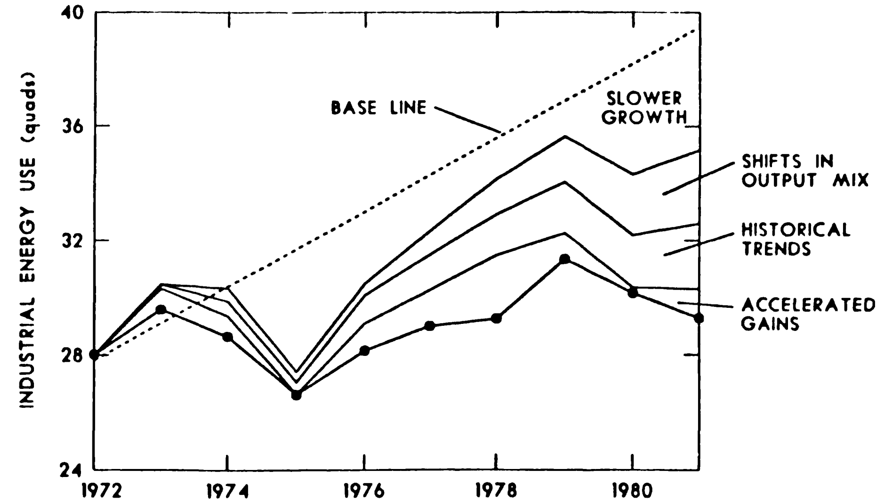

Figure 13 Energy use in US industry, 1972–1981. The top projection (E_1) is a pre-embargo baseline. The second projection (E_2) is adjusted for the slower growth in GNP. The third projection (E_3) accounts for shifts in the mix of industrial output. The fourth projection (E_4) accounts for the historical trend in industrial energy-efficiency increases. The circles (E_5) are actual industrial energy consumption. Source: (17, 52).

Because energy efficiency per unit output is arbitrarily held constant, the hypothetical energy demand of our base case (E_1) increases at the same rate, that is, 4.0% per year (Table 10 and Figure 13).[17]

To estimate the effects of the slowdown of industrial production observed from 1972–1981, we developed a second hypothetical case (E_2) by again holding energy use per unit of output constant, but allowing industrial production to vary as it actually did during this time period. We suggest that the difference between the base case (E_1) and the hypothetical case (E_2), is an approximation of the relative (but not absolute) energy-reducing effects of the economic recessions and general slowdown in US industrial production.

To estimate the effects of shifts in output mix, we construct two different measures of industrial production and observe the year-to-year differences. The first is a value-added weighted measure. The second is an energy-weighted measure. Both are derived from identical underlying data on industrial production from 472 mining and manufacturing industries.[18]

[17] Growth in industrial energy demand for this 1953–1972 period was actually 3.2% per year.

[18] These underlying data are from past surveys of the *Census of Manufacturing and Mineral Industries*, US Department of Commerce, and *Industrial Production*, Federal Reserve Board. A more detailed explanation of this technique is presented in (52).

A cumulative measure of structural shifts in the mix of industrial output either toward or away from energy-consumptive industries is determined by comparing the annual increases or decreases in the two aggregate measures of industrial production. If in one year the energy-weighted index increases more slowly than the value-added weighted index, then a shift away from the energy-consumptive industries is observed in that year. A shift factor, f_s, is constructed by compounding the observed year-to-year differences from 1972 through 1981. Using this shift factor, f_s, a third hypothetical case for industrial energy demand is developed (E_3). The difference between E_2 and E_3 approximates the relative importance of this shift phenomenon as it affects industrial energy demand.

At this point, actual energy demand (E_5) is compared to the hypothetical case (E_3). The difference approximates the relative importance of energy-efficiency gains, that is, improvements in energy use per unit of energy-weighted output. Some of these gains, however, may be considered as consistent with long-term historical trends established during periods of declining energy prices. Others may be considered as accelerated gains, that is, gains above and beyond those that would have been expected had past trends simply continued. To estimate these two effects, we apply a factor for steadily advancing technological change, equal to the difference between our hypothetical case of 4.0% per year of energy growth and the actual historically observed trend in energy growth of 3.2% per year for the period from 1947 to 1973. This reduction in energy intensity occurred when energy prices were declining and several energy-intensive industries were increasing their share of total industrial output (53). It is therefore ascribed to technological process improvements associated with evolutionary industrial development. The technological trend factor, f_t, grows at the compound rate of 0.8% per year.

We conclude from these estimations that in 1981 slower economic growth had the largest impact on industrial energy demand, accounting for approximately two-fifths of the observed reduction in energy demand from our hypothetical base case. Improved energy use per unit of economic output (value-added weighted measure) accounted for the remaining three-fifths. Of this apparent gain in efficiency, almost two-thirds appears to be due to energy-efficiency improvements of production processes, and one-third to shifts in output mix away from the energy-consumptive industries. Of the actual efficiency gains themselves, two-thirds are consistent with historical trends, and one-third appears as accelerated gains above and beyond that which would have been expected had historical trends simply continued. Recasting these results somewhat to focus only on the events of the 1970s, by discounting the historical trends in efficiency improvements, we observe that by 1981 the slowdown in economic activity accounted for about half of the apparent reduction in energy use from a more realistic base case (3.2% per year), while shifts in output mix and accelerated efficiency gains appear to have shared responsibility for the remainder about equally.

Although the apparent reductions in energy demand can generally be characterized as above, the specific factors responsible for these reductions and their relative importance remain unclear. They are, perhaps, not separable. Energy's dramatically increased price after 1973 certainly is a strong factor in motivating the accelerated efficiency gains. It is likely, as well, to be a contributing factor in the observed shift in output mix, but is probably not exclusively responsible. Price may also be a factor in the slowdown of economic growth. Many of the other factors mentioned earlier, however, are also believed to have had major impacts on the structure of industrial production and the nature of industrial energy demand, perhaps outweighing the effects of price. As such, they too should be given serious consideration in any attempt to forecast future demand.

Conclusions on Industrial Sector

Industrial energy conservation activities are likely to continue at a significant level. Although real energy prices are more than twice their former value, relatively little capital investment for increased energy efficiency appears to have occurred (54). Industrial investment in new capital stocks has been substantially depressed over the last decade. Commentators suggest that regulatory uncertainties and high interest rates have contributed to this condition and both of these factors may be diminishing. As obsolete production equipment is replaced, new equipment will show higher energy efficiencies.

In support of these conclusions we observe that within the government industrial energy conservation program, three of the major energy-using industries have set new conservation improvement goals for 1985 (Table 11). These goals are quite ambitious in that much of the easier-to-obtain savings (e.g. housekeeping improvements) have been realized and there cannot be a large replacement of capital stock in only five years.

Table 11 Energy efficiency[a] improvement[b]

Industry	Actual (%) 1972–1980	Target (%) 1980–1985
Chemicals	22	8
Petroleum	19	7
Aluminum	10	10

[a] Reduction in total energy use per unit of production.
[b] Source: Office of Industrial Programs, US DOE.

THE TRANSPORTATION SECTOR

Introduction

From 1950 to 1970 total energy use for transportation increased at an average annual rate of 2.9% from 8.6 to 15.3 quads. The annual rate of growth increased from 2.3% during the 1950s to 3.5% in the 1960s. In contrast, the two dramatic petroleum price increases, first in 1973–1974 and again in 1979–1980, and the ensuing economic recessions left energy use in 1980 at about the same level as in 1973 (Figure 14). According to DOE estimates (1),[19] transportation energy use peaked in 1978 at 20.6 quads. Energy use for transportation in 1982 was probably roughly the same as in 1981 (19.2 quads).

It is obvious from a study of transportation energy trends that energy use did not simply stagnate during the past decade. Instead, the transportation system responded to two severe blows in 1973–1974 and 1979–1980. In the intervening years (1976–1978) when real prices stabilized and the economy resumed growing, transportation energy use temporarily reverted to a pre-embargo growth rate of 4.3%. In light of these facts, one may wonder whether, apart from two temporary setbacks, anything has really changed. A closer look reveals that significant changes occurred but that the degree of response varied greatly by mode and that the nature of the response changed over time.

Trends in modal energy-use shares since 1970 reveal a shift from passenger to freight modes (Table 12). The most striking aspect of this is that automobiles and light trucks accounted for all of the decline in the share of energy use for passenger travel. Every other mode held its own or increased in proportion to the total. Automobiles and light trucks are the only transportation vehicles for which direct efficiency standards were specified by federal law.

The trend in patterns of modal energy demand is reflected in patterns of fuel use. As recently as 1978 gasoline supplied 72% of transportation energy. Diesel fuel and jet fuel supplied 12% and 8%, respectively. Only two years later, gasoline's share had dropped almost eight points to 64%. The shares of other fuel types increased in roughly equal proportions. Automobiles and light trucks are the predominant users of gasoline, accounting for over 90% of its use in transportation in 1980.

From this evidence one might conclude that all the energy conservation in transportation can be attributed to light-duty highway vehicles. This is

[19] Ref. 62 (p. 13), using more detailed data, estimates that civilian energy use peaked at 20.2 quads in 1979.

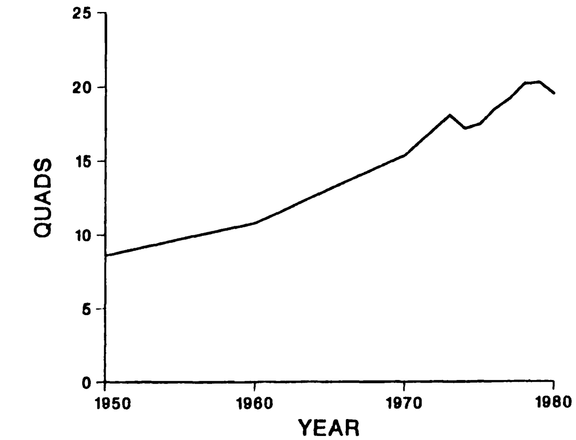

Figure 14 Transportation energy use, 1950–1980. Source: (1).

not the case as an examination of trends in energy intensiveness (the energy required to produce a unit of transportation service) reveals. Gross comparisons of energy intensiveness, such as we make, can be misleading owing to the many factors that determine modal intensities (65). In addition the data for many key determinants (e.g. automobile occupancy, truck ton miles, etc) are notoriously weak. Nonetheless, the data can be informative about gross trends, provided their shortcomings are kept in mind.

Except for commuter rail, which accounts for less than 0.5% of total passenger miles, domestic air carriers show the greatest decrease in energy intensiveness, 21% from 1973 to 1980 (Table 13). There is considerable variation in air energy intensiveness from year to year. Energy intensiveness dropped ten percent from 1973–1974 and increased three percent from

Table 12 Percent of Transportation Energy Use by Mode 1970–1980[a]

	Autos and light trucks	Heavy trucks and buses	Air	Water	Pipeline	Rail
1970	75.8		8.6	5.4	6.5	3.7
1973	78.2		7.6	5.0	5.5	3.6
1974	78.2		7.3	5.2	5.4	3.8
1975	67.3	11.8	7.3	5.4	4.8	3.4
1976	67.9	11.2	7.4	5.9	4.3	3.3
1977	67.4	11.4	7.5	6.3	4.1	3.3
1978	65.9	12.6	7.4	7.0	3.9	3.1
1979	64.2	12.3	7.9	8.1	4.2	3.3
1980	61.3	13.7	8.1	8.8	4.6	3.4

[a] Source: (62).

1979–1980. The reason is that air carrier energy intensiveness is quite sensitive to operating parameters, especially load factors (percent of available seats occupied).

Rail energy intensity actually increased from 1973–1977 but then declined sharply in 1979 and 1980. The primary reason for the decline is more efficient utilization of capacity (58, 64). Loading per car was seven percent greater in 1979 than in 1975. Increased shipment of coal, which is inherently more efficient per ton-mile than other commodities, was partly responsible for rail freight efficiency gains. Improved energy efficiency in 1979–1980, resulted in an energy saving of 8.6% (58).

Data on marine energy use and ton-mile movements are subject to gross inaccuracies and thus not suitable for detailed interpretation. These inaccuracies are reflected in the erratic behavior of the energy-intensity time series. Likewise there is little one can say about the efficiency of pipeline transport. No historical series is available for crude oil and product pipelines.

Highway Vehicles

Automobile energy intensiveness per vehicle mile shows a gradual and steady decline of 13% from 1973–1980. Data on automobile occupancy rates are scarce and somewhat questionable; however, existing data indicate declining occupancy rates that counterbalance half of the improvement in vehicle fleet fuel economy through 1980. In a study covering 1972–1979, Pollard (64) concluded that automotive energy use per passenger mile actually increased about 12% due to a 15% decline in vehicle occupancy rates. Probably the auto occupancy data are best regarded as too weak for such use. (In the remainder of this section auto efficiency is measured on a vehicle-mile basis.)

Total truck energy efficiency per vehicle-mile improved 13% from 1973–1980 but most of that was due to improved efficiencies for light trucks. Both single-unit and combination (tractor-trailers) trucks are included in Tables 13 and 14. Single-unit trucks account for over 85% of all truck miles according to the 1977 *Truck Inventory and Use Survey* (67). Acknowledging a "high noise level in truck data," Pollard (64) estimated that fuel efficiency per vehicle mile actually declined two percent for combination trucks between 1972 and 1979. He estimated that overall energy intensity was reduced, however, owing to an eight-percent improvement in operational efficiencies due to higher load factors. These perceived changes are probably within the noise level of the truck data. Estimates (70) made by the US Department of Transportation (DOT) appear to contradict Pollard's estimates. Analysis of data on sales of energy-efficient equipment on heavy trucks [over 33,000 lbs, gross vehicle weight (gvw)], published by the joint DOT/DOE Voluntary Truck and Bus Fuel Economy Program (68),

Table 13 Energy intensities of passenger modes, 1970–80[a]

	Rail			Air		Bus				Automobile		
	Rail transit[b]	Commuter rail[c]	AMTRAK	Certificated air carriers	General aviation	Transit buses[d]	School buses	Intercity buses				Motorcycle
Year	(Btu/PMT)	(Btu/PMT)	(Btu/PMT)	(Btu/PMT)	(Btu/PMT)	(Btu/PMT)	(Btu/VMT)	Btu/VMT	Btu/PMT	Btu/VMT	Btu/PMT	(Btu/PMT)
1970	2,430				10,594	2,370	17,710			9,140	4,260	1,512
1973	2,460	3,900	3,760	7,650	8,598	2,470	16,820	22,840	1,020	9,470	4,700	2,274
1974	2,810	4,040	3,240	6,870	9,549	2,430	16,850	22,300	960	9,310	4,680	2,273
1975	2,940	3,040	3,680	6,870	10,112	2,700	16,960	22,280	990	9,240	4,740	2,273
1976	2,940	2,680	3,400	6,440	10,379	2,830	16,890	22,620	1,010	9,110	4,770	2,271
1977	2,690	2,940	3,570	6,900	10,653	2,890	17,710	22,890	980	8,960	4,790	2,465
1978	2,440	3,160	3,680	5,900	13,169	2,880	16,980	23,010	980	8,840	4,760	2,480
1979	2,610	2,890	3,470	5,840	9,024	2,750	16,980	23,190	960	8,750	4,680	2,490
1980	2,630	2,540	3,170	6,044	13,954	2,701	16,345	23,096	986	8,254	4,395	3,518

[a] Source: (62).
[b] Because of their great size, this column is essentially the average figure for the New York and Chicago rail transit systems. New rail systems (i.e. BART and METRO) have a much higher level of amenities in cars and stations, and hence may have much higher energy intensity.
[c] Includes small number of intercity operations.
[d] Large system-to-system variations exist within this category.

Table 14 Energy intensities of freight modes [a]

Year	Class I railroad Btu/revenue ton-mile[e]	Domestic waterborne commerce Btu/ton-mile	Air cargo[c] Btu/ton-mile	Trucks[d] Btu/vehicle-mile
1970	650	540		15,404
1971	700	500	29,400	15,448
1972	710	520	28,770	15,237
1973	660	580	27,190	15,247
1974	670	480	24,620	15,108
1975	680	550	25,610	14,894
1976	680	470	24,150	15,055
1977	670	460	26,860	14,890
1978	640	380	25,400	14,961
1979	620	440	23,660	14,636
1980	590		19,606	13,439

[a] Source: (62).
[b] Blanks in table indicate insufficient data to calculate an energy-intensity value.
[c] All-cargo carriers only. Does not include belly freight carried in passenger aircraft.
[d] Includes both single unit and combination trucks. Note that the truck energy-intensity figures are given in Btu/VMT, not TMT as is calculated for the other modes.
[e] A revenue ton-mile refers to one ton of freight carried one mile. Gross ton-miles include the weight of the equipment.

suggest new truck fuel economy improvements on the order of 15% from 1973–1980 (Table 15). About one-fifth of this is due to increased market penetration of diesel engines in new trucks (87%–96%), a trend that began decades ago. The rest is due to increased use of fan clutches, fuel economy diesel engines, radial tires, and retrofit devices to improve aerodynamics. Fan clutches were, in effect, required to meet government noise regulations. Without increased use of fan clutches the improvement would have been only ten percent. According to the DOE study, energy conservation through increased use of all of the options reduced energy use by all trucks over 10,000 lbs gvw by 2.2 billion gallons in 1980 (0.3 quads), about 11% (68). This estimate seems high given only a 15% improvement in new trucks by 1981 and an average truck lifetime of over ten years. Still an improvement of five to ten percent could be inferred from these data.

Disagreement between the two sources reflects the sorry state of truck stock and utilization data. Statistics on the installation of energy-saving equipment are relatively solid and the energy savings estimates attributed to the equipment are reasonable. It is very likely that heavy truck efficiencies improved five to ten percent since 1973 but the proof is far from conclusive.

Gasoline consumption has taken a dramatic turn in the past four years.

Table 15 Fuel economy improvements due to the use of fuel-saving equipment on new heavy trucks (trucks over 33,000 lbs gvw only)[a]

Option	Estimated MPG improvement (%)	Market penetration (%) 1973	1977	1980
Diesel engine	35	87.3	95.0	95.7
Fuel economy diesel	7	15.4	50.1	58.7
Aerodynamic add-ons	6	0.8	11.2	15.3
Radial tires	6	3.2	23.2	40.7
Fan clutch	6	4.0	47.7	87.7
Road speed governor	7	—	—	1.5
Tag axles	2	—	—	0.9
Overall % gain over 1973		—	10	15

[a] Source: (68).

Before 1979 there had been only three instances of declining gasoline demand: the Great Depression (1932–1933), World War II (1942–1943), and the OPEC oil embargo of 1973–1974. In each case consumption quickly rebounded and continued growth. 1981 was the third consecutive year of declining gasoline consumption and partial data for 1982 indicate that demand will once again be lower than the previous year's 104 billion gallons (13 quads) despite a five-percent or greater reduction in the real price of gasoline. Most important of all, it is now widely recognized that the current gradual decline is likely to continue even if the economy rebounds and gasoline prices do not rise above their present levels. The reason is the dramatically improved fuel economy of new automobiles and light trucks. In every year since the federal Corporate Average Fuel Economy Standards have been in effect the sales-weighted fuel economy of new autos has exceeded the standards imposed on each manufacturer (Figure 15). Despite 10%–20% shortfalls (63) between the EPA test fuel economy values (upon which the standards are based) and actual in-use fuel economy, the real improvement has been steady and dramatic. New cars are now 67% more efficient than the average car on the road in 1973, and 50% more efficient than the average car today (61). Light trucks (less than 10,000 lbs gvw) have likewise made impressive gains.

For the most part, the impact of these dramatic gains in fuel economy has yet to be felt. The reason is the slow turnover of the automobile and light truck stock. Typical vehicle lifetimes are ten years for automobiles and even longer for light trucks (60). The impact of fuel economy improvements to date on gasoline demand has been estimated by two different studies

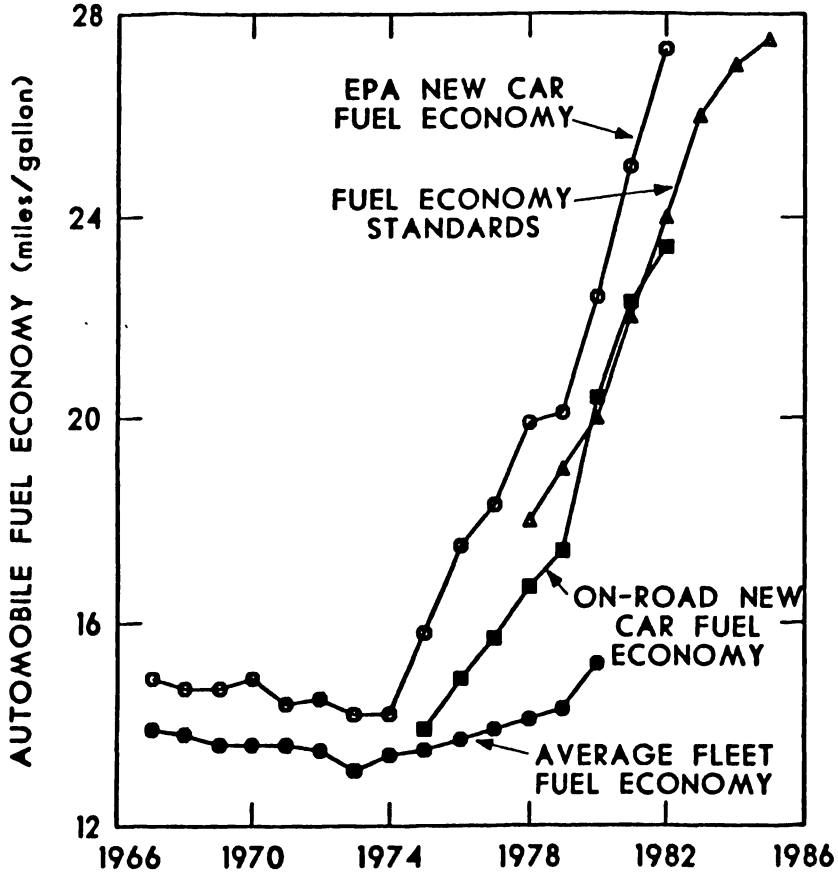

Figure 15 Trends in new car and fleet fuel economy. Source: (61).

employing quite different approaches (57, 59). Both studies attribute about half the difference between current and business-as-usual (or base case) demand to new car fuel-economy improvements. McNutt & Difiglio's study (57) estimates reduced energy demand "by comparing actual demand with an assumed 'base case' demand that would have occurred if historical patterns in vehicle design and use had continued unaffected from a 1973 base year." Factors identified as contributing to reduced demand (Figure 16; 1 million bbls/d = 1.916 quads) were increased fleet mpg due to new car design changes, reduced vehicle travel, reduced vehicle (interior) size, reduced speed of travel (55 mph speed limit), and increased fleet mpg due to operational factors (e.g. tire pressure, maintenance, etc).

Table 16 compares the attribution of the 1979–1981 declines in passenger car gasoline consumption based on an engineering analysis (57) with that of

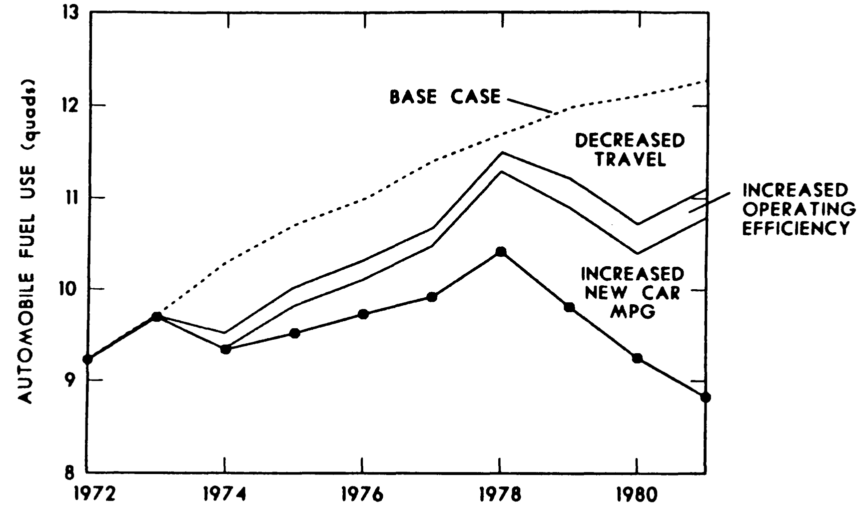

Figure 16 Estimated components of passenger car fuel savings. Source: (57).

an econometric analysis of total highway gasoline use (59). The latter estimated the response of total highway gasoline use during 1978–1980 to price and income changes, improvements in light duty vehicle fuel economy, demographic trends, dieselization of light-duty vehicles, and the fuel supply shortages of summer 1979. Since short-run household income and fuel price effects consist almost entirely of reduced travel and operational mpg improvements, a rough comparison between the two studies is possible. Given the differences in approach, the conclusions are very close. Reduced travel and other short-run options exerted a downward pressure on demand of six to seven percent annually between 1978–1980. New car fuel economy improvement had a somewhat smaller annual effect. While Greene & Kulp (59) did not specifically analyze 1980–1981 changes it did provide a forecast that indicated a three-percent reduction due to new car fuel economy improvement, other things equal. McNutt & Difiglio (57) indicate a larger reduction. They also indicate about a two-percent increase due to increased automobile travel, clearly a response to lower fuel price and slight gains in income and population.

From both studies it is clear that the majority of the reduction in gasoline use between 1978 and 1980 resulted from less travel. This reduction in vehicle travel was primarily a response to higher gasoline prices. On the contrary, in 1981 and 1982, reductions in demand were primarily due to improved vehicle efficiency.

Between the 1978 and 1981 model years, new passenger car fuel economy improved 5.3 mpg from 19.9 to 25.2 mpg (Figure 15, based on the combined

Table 16 Estimated percent changes in gasoline use due to various factors[a]

	Passenger car gasoline[b]			Total highway gasoline[c]		
	New car MPG improvement	VMT reduction	Operation and maintenance	New vehicle MPG improvement	Short-run price	Short-run household income
1980–1981	−5	+2	0	−3[d]	NA	NA
1979–1980	−2	−6	0	−2	−4.3	−1
1978–1979	−2	−6	−1	−1	−4.3	−1

[a] Sources: Difiglio & McNutt, Table 4 (57) and Greene & Kulp, Table 2 (59).
[b] Source: (57).
[c] Source: (59).
[d] Inferred from date in Table 5 (59).

city-highway EPA estimate). According to a study by the Department of Transportation (69), almost half of this was due to weight reduction (2.35 mpg). Other significant gains were achieved by reduced vehicle performance (0.8 mpg), changes in transmissions (0.58 mpg), reduced aerodynamic drag (0.37 mpg), more diesel engines (0.25 mpg), and a variety of other items including reduced accessory loads, tire-rolling resistance, and drivetrain losses (0.95 mpg). To what extent these changes reduced consumer satisfaction with new vehicles is not well understood.

Reductions in gasoline use in 1981 and 1982 occurred despite reductions in the real cost of gasoline and increased vehicle travel. This distinguishes the present period of declining demand from all previous historical periods. Dramatic improvements in new car fuel economy are only just beginning to cause significant improvements in fleet fuel economy. As a result, gasoline demand is virtually certain to continue to decline until well beyond 1985 even if prices go somewhat lower and incomes grow substantially.

Airlines

The air carriers made impressive efficiency gains without efficiency regulations. Because detailed statistics are available for air carriers, it is possible to identify the various operational and aircraft efficiency improvements that have resulted in systemwide reductions in energy intensity of one-third from 1973–1981. Table 17 shows actual air carrier fuel use from 1967–1981 and what fuel consumption would have been had the energy efficiency of air transport continued at its 1973 level. According to this simple calculation, efficiency improvements alone conserved well over five billion gallons (1 billion gallon = 0.135 quads) of jet fuel in 1981. Unlike the automobile sector, there has been no econometric study to determine what curtailment of travel occurred owing to higher fuel prices (via their effect on ticket prices) and recessions.

Two studies quantified the contributions of technical aircraft efficiency, operating efficiency, load factors, seating capacity, and aircraft fleet composition to higher efficiency of air travel (58, 66). Smith (66) estimated the contribution of each factor by calculating how much fuel would have been needed to deliver actual revenue passenger miles in a particular year had the factor remained at its 1973 level. The difference between this hypothetical figure and actual energy use is the savings attributed to the factor (Figure 17).

Load factors (percent of available seats occupied) increased from 52%–59% from 1973–1980 and declined only slightly in 1981. Two factors, economic deregulation of the airlines and fluctuations in the economy, strongly influenced load factors over this period. Deregulation permitted the airlines to drop less profitable, inefficient routes that (almost by

Table 17 Fuel consumption and energy intensity for certificated route air carriers, 1973–1980[a]

Year	Actual fuel use[b] (10^6 gal)	Energy intensity[b] Btu/PMT	Fuel use based on 1973 energy intensity (10^6 gal)	Fuel savings (10^6 gal)	Fuel savings as a percentage of total predicted fuel use
1973	10,699.8	8,280	10,699.8	0	0.0
1974	9,553.8	7,430	10,652.5	1,098.7	10.3
1975	9,506.6	7,405	10,629.9	1,123.3	10.6
1976	9,808.1	6,990	11,767.1	1,959.0	16.6
1977	10,292.9	7,240	12,639.7	2,346.8	[illegible]6.8
1978	10,639.3	6,970	14,537.0	3,897.7	26.8
1979	11,296.8	5,680	16,474.7	5,177.9	31.4
1980	10,953.5	5,678	15,973.0	5,019.6	31.4

[a] Source: (58).
[b] Includes fuel used by all cargo carriers and the fuel consumed in transporting belly freight. Excludes charter carriers.

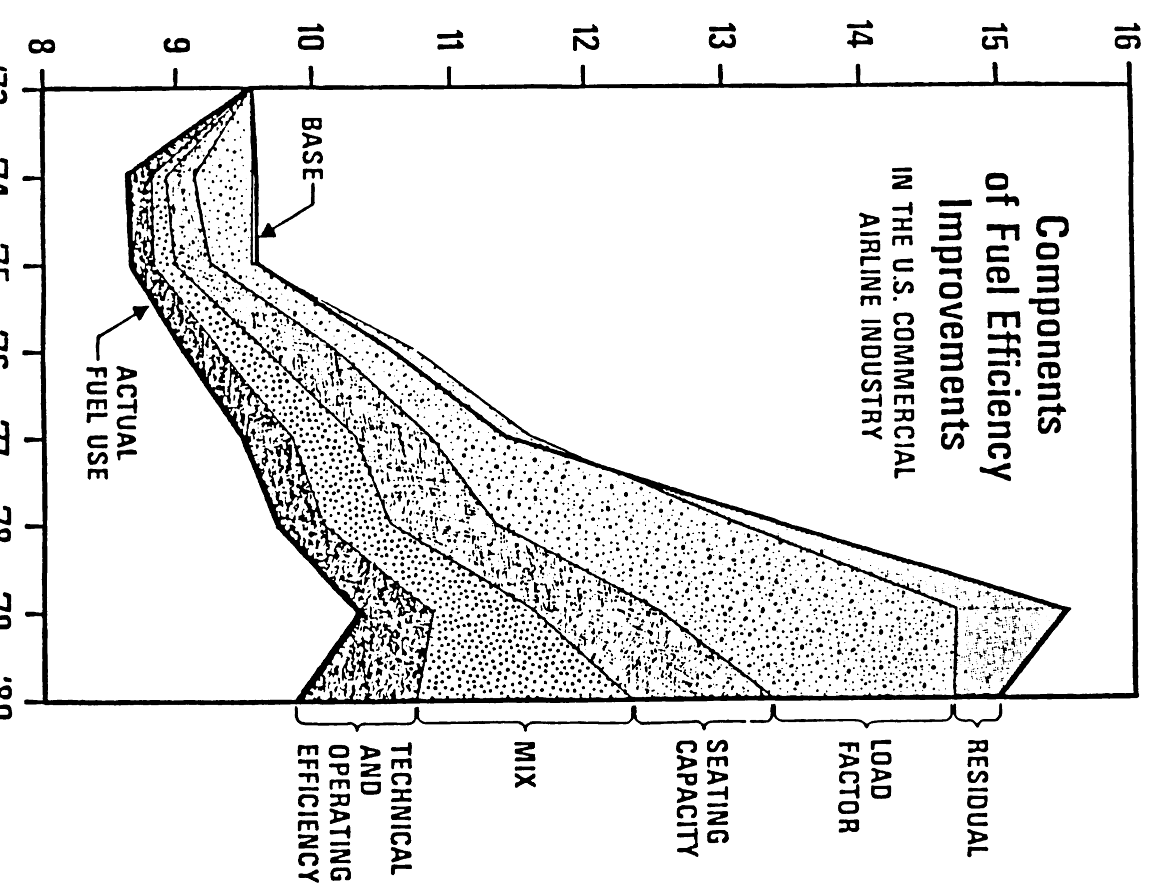

Figure 17 Components of fuel efficiency increases in the US commercial airline industry. Source: (66).

definition) have low load factors. Load factors declined during the 1975 and 1980–1981 recessionary periods as demand for air travel slackened, and increased only one percent through October 1982. Efficiency gains from improved load factors, in contrast to gains achieved through changes in the aircraft stock, are short-run improvements and can be lost as quickly as they are won. While load factors are likely to improve again as the economy improves, it is not likely that they will play an important role in future air-carrier energy savings.

All of the remaining factors are related to changes in the stock of aircraft. Gains due to seating capacity were achieved by adding more seats to existing aircraft configurations. From 1973–1980, the average number of seats on a Boeing 747 increased from 328–378; eight seats were added to the 727-200, the most widely used aircraft during that period. Energy savings achieved by adding seats to existing models, however, are also limited and are probably close to having been exhausted. Included in technical and operating efficiency improvements are anything from engine retrofits to lower cruise speeds to taxiing procedures. Numerous actions have been taken by air carriers to improve operating efficiency from steeper angle of descent in landing (prolonging more efficient, high-altitude cruising) to reducing plane weight by removing the paint. Mix changes include both the number of different models in the aircraft fleet and the intensity of their use. Increasing use of wide-body aircraft such as the 747, DC10, and L1011, contributed significantly to reducing energy intensities. Three- and four-engine wide-body aircraft were 20%–35% more efficient than their narrow-body counterparts in 1979 (58). Included in the estimated mix-shift savings is the effect of engine and other efficiency improvements associated with the introduction of new aircraft models. By 1980, the mix-shift change was the largest component of air carrier energy savings. This trend is virtually certain to continue as short-run savings opportunities are exhausted and as the newer (probably 30%–40% more efficient) 757 generation aircraft replaces older configurations.

Smith (66) asked whether the efficiency improvements observed between 1973 and 1980 were due to petroleum shortages and higher fuel prices or were simply part of an already existing trend of efficiency improvement. He found that a trend line of seat-miles per gallon estimated based on 1967–1972 data almost exactly predicted future seat-mile per gallon improvements through 1978. No real gain over the historical trend occurred until 1979, the year in which fleet mix and technical and operating efficiency improvements turned sharply upward.

Summary of Transportation Sector

For every transportation mode that has data sufficient to make an assessment, there is evidence of energy conservation. The relative importance of reduction in travel vs efficiency improvement has been evaluated only for light-duty highway vehicles. Here it appears that the majority of energy savings to date have resulted from reductions in travel. However, increasing new vehicle fuel economy and declining real fuel prices made efficiency improvement the dominant factor in the two-percent gasoline-use decline in 1981 and an estimated one percent decline in 1982. Furthermore automobile and light truck fleet fuel economies are now increasing at an accelerating rate. As a result highway gasoline demand will probably continue to decline even in the face of price declines or economic growth. For heavy trucks it appears that fuel economy gains have been made although weak data make the case difficult to prove. In addition, fleet fuel economy gains appear far more limited in the near future than for autos and light trucks.

Air carrier energy efficiency probably improved more than any other mode since 1973. Yet air carrier efficiencies were improving before 1973 and it may be that most of the improvement is the continuation of previous trends. This makes the gains no less real but alters the perception of air carriers' responsiveness to fuel price shocks.

Finally, it appears that future efficiency gains in both the highway and air modes will be achieved through the gradual introduction of more efficient equipment. Only in the case of light-duty vehicles, however, is there a clear indication that these efficiency gains will lead to continued declines in energy use regardless of economic conditions.

SUMMARY AND CONCLUSIONS

Before summarizing our findings, we briefly mention some of the important caveats associated with this (and any related) effort to analyze recent changes in national energy use (13–17). First, the level of detail and quality of historical data on energy consumption are generally poor. The data used in our analyses were collected by different agencies, for different purposes, at varying frequencies, with different sampling strategies, and with different definitions for similar terms. As a consequence, it is difficult to analyze differences across data sets.

Second, the tools used in these analyses suffer from similar limitations. The models were developed at different times, for different sponsors, with different purposes in mind. Also, the models were developed with use of data whose limitations were noted above.

Third, although there have been substantial changes in energy-use trends during the past several years, the detailed differences in energy use that we examined were small, generally only a few percent of the baseline. Given the uncertainties in the models and data, unambiguously identifying small changes is difficult and uncertain.

Fourth, the analyses presented here dealt with energy use at a rather aggregate level. In particular, we did not examine changes by fuel type. Shifts, particularly from fossil fuels to electricity, might have had important effects on overall energy use and efficiency.

Even more difficult than identifying the changes in energy use is the allocation of these changes to different underlying causes. For example, there is some evidence that the effects of government programs on energy use depend on the effects of energy prices (15). Similarly, increasing energy prices surely affected macroeconomic conditions (reduced GNP) during the past few years and probably stimulated government and utility conservation programs; such feedback effects are not included in our analyses.

These limitations (and others not mentioned) strongly suggest the need for additional research. Work is needed to develop better data sets, improve our understanding of the differences among data sets, improve existing energy end-use models, and update and sharpen the sector-by-sector analyses discussed here.

Roughly speaking, US energy use in 1981 (74 quads) was 28 quads below what it would have been had pre-embargo economic and fuel price trends continued unchanged. Nearly half of this substantial energy-use reduction can probably be attributed to slower economic growth during the past few years (reflected in reduced use of energy-using equipment). In particular, slower growth in industrial output cut energy use in that sector by almost five quads in 1981. Slower growth in commercial activity and in transportation demand reduced energy consumption in these sectors also.

Improvements in overall energy efficiency (including both operational and technical changes) accounted for more than half (16 quads) of the 1981 energy reduction. In the industrial sector, the observed efficiency improvements were due to two factors: a shift in output mix from relatively energy-intensive to nonenergy-intensive goods, and reductions in energy use per unit output. About half the reduction in energy use per unit output was due to continuation of long-term historical trends in technical improvements; the other half was due to post-embargo changes in energy prices and other factors.

The substantial improvements in automobile energy efficiency were due in large part to improvements in new car fuel economy (67% increase in mpg between 1973 and 1981) and secondarily to operational changes in the use of existing cars. A similar mix of changes occurred in the commercial airline industry: some of the observed improvements in energy efficiency were due to new aircraft and some were due to improved operation of existing aircraft (especially increases in load factor).

Efficiency increases in residential and commercial buildings were due, in part, to operational changes such as reduced thermostat settings and better control of lighting in commercial buildings. In addition, retrofits to the shell of existing buildings, improvements in design and construction of new buildings, and efficiency gains in heating and other equipment used in buildings all contributed to technical efficiency gains.

It is often difficult to separate technical from behavioral changes. For example, improving new car fuel economy by making cars lighter (and perhaps smaller) might be considered a technical improvement or, if the loss of amenity to consumers is substantial, a behavioral change (perceptions of reduced safety, less interior room). Similar ambiguities occur in other sectors also (e.g. smaller furnaces in homes, automatic timers that lower temperatures in office buildings at night).

Although it is difficult to determine the factors that "caused" these energy efficiency improvements, it appears (based on the simple analysis discussed in the second section) that about 11 quads of the 16 quads efficiency improvement can be attributed directly to the effects of rising fuel prices (15). The remaining five quads were due to a variety of nonmarket forces, including government and utility conservation programs, occasional fuel shortages, and structural shifts in the economy unrelated to rising energy prices.

For example, improvements in new car fuel economy were surely motivated both by rapid increases in gasoline prices and by the federal Corporate Average Fuel Economy Standards. Similarly, improvements in airline load factor were probably due largely to the major increases in jet fuel prices (which strongly motivated the airlines to reduce costs per passenger-mile). In addition, deregulation of commercial airlines made it possible for them to modify their routes and schedules (which in turn, improved load factors).

Many households have, in recent years, weatherized their homes by adding attic insulation, storm windows, caulking, and weatherstripping. These efficiency improvements were motivated by a combination of higher heating fuel prices and a variety of government and utility programs that encouraged such retrofit (e.g. state and federal tax credits, home energy audit programs).

Several conclusions emerge from this study. First, energy use trends during the past few years were dramatically different from those during the pre-embargo period. Energy use declined in 1980 and again in 1981; data for the first half of 1982 show another decline. This is in stark contrast to the pre-embargo period when energy use was increasing steadily at three to four percent per year.

Second, it appears that almost half the reduction in energy use (relative to pre-embargo trends) was due to slower economic growth. Although the relationship between energy use and GNP is far from fixed (Figure 2), energy use is related to economic activity, all else being equal. The poor performance of the economy led to reduced energy consumption.

Third, more than half the reduction in energy use was probably due to increases in energy efficiency (i.e. reduced energy consumption per unit output). These efficiency increases occurred because of both technical improvements in industrial processes, transportation equipment, and buildings; and operational improvements (housekeeping) that reduced energy consumption. It appears that the role of technical improvements has been steadily increasing since 1973, as new efficient capital replaces old less efficient capital. For example, most of the immediate postembargo gasoline savings were due to reduced automobile travel; however, by 1981, the effect of new car fuel economy improvements exceeded the effect of reduced travel.

Finally, interpretation of the factors that stimulated these efficiency improvements is difficult and ambiguous. It appears that increases in fuel prices were the primary motivating force. However, nonmarket forces were also important stimuli to improved energy efficiency.

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CHAPTER 5

RESOURCES AND RESERVES: OIL AND GAS PARTICULARLY

5.1 INTRODUCTION

Energy resources have been described as renewable or non-renewable, economic or uneconomic, discovered or undiscovered, etc., and we will have occasion to deal with all these terms, some of which depend very much on the describer's outlook. Examples of ambiguities and paradoxes have appeared in Chapters 1 and 2, where resources may be perceived as adequate or inadequate depending on time perspectives.

Figure 5.1, adapted from work by (Hubbert, 1974) dramatizes the point. As will be shown later, the total fossil fuel resources expected to be eventually recoverable amount to the equivalent of 10^{13} (10 trillion) tons of coal. If world energy use increased by a factor 3 above its present value of almost 10^{13} watts (10 terawatts or TW), that whole resource would last 400 years, a short time compared to recorded human history.

Even more dramatically, suppose we insist on a strictly steady-state world. The coal was produced over a period of about 200 million years. Making 10^{13} tons last that long would imply an allotment for each presently living person of about 1 kg of coal (plus 50 ml of oil) not per day, per month or even per year, but for a lifetime. We are running one part of the photosynthetic cycle backward at about one million times its normal forward rate.

After a brief account of the difference between reserves and resources and how they are categorized, this chapter continues with more detailed information about oil, the uncertain supply of which in the early to mid 1970's caught the attention of a hitherto uncaring world. Then follow some comments about natural gas and coal, but coal will be discussed mainly in a separate chapter. Also, uranium (mentioned briefly here) and nuclear fission require separate chapters. Solar power and certain questions about solar-related renewable resources also will be found in Chapter 8.

5.2 RESERVES AND RESOURCES: THE McKELVEY DIAGRAM

Petroleum, coal, and minerals are conventionally categorized as reserves or resources, each often divided into sub-categories. Surprising to some, the terms bear no simple or direct relation to all that exists in the ground, so to speak.

Figure 5.2 illustrates how the terms are used; it is a McKelvey diagram, so-named after a former director of the U.S. Geological Survey. Consider something coming from the earth, for example petroleum. Prior exploration has turned up deposits whose extent and amount are well known, and whose extraction costs make them economically attractive at present. Broadly speaking, these are reserves, and also broadly speaking they can be used as collateral for bank loans.

Exploration turns up more than that. Some deposits, though not well mapped, will be uneconomic to recover at present prices--too deep, too low grade, technically difficult to process (tar sands vs. Saudi Arabian oil, for instance). Other deposits may be surmised to exist, with varying degrees of uncertainty, on lightly explored fringes of well mapped deposits, or on the basis of a few exploratory drill-holes, or even only on similarity of one unexplored geologic structure to other mapped and productive ones.

All these things are classed as resources.

The logic of the McKelvey diagram now becomes clear. Reserves occupy the upper left-hand corner, and resources the rest, classed along axes of increasing cost and/or uncertainty. No sharp or fixed limits divide economic from uneconomic or known from unknown, so the dividing lines are not sharp either; materials flow across them as knowledge grows and costs and technology change. The lower and right side boundaries of the figure merge imperceptibly into the background of natural average abundances.

Tables of known resources often show only about ten year's supply, not usually determined by actual paucity of resources, but by the economic time perspective~~s~~ ~~s discuss~~ discussed in section 2.3. These reserve depletion times are generally longer than the economic time perspective, to encourage stability in the business and technological sectors, but often not by much. Present value of things not to be sold for 20 to 30 years is much discounted, and extensive present exploration for such long term reserves is economically unattractive, especially if the question is only one of reasonable price increase or uncertainty about precise location. Also, large mapped and announced resources can drive the price of material down, and in some jurisdictions the leaseholders can be taxed, even while the reserves remain in the ground. Presently uneconomic or uncertain resources, even if suspected to exist on a leased tract, do not carry these economic disadvantages, so a fine balance exists between enough exploration and delineation to provide reserves for economic and technological stability, but not so much as to work to the disadvantage of the resource exploiter.

This tradition of privacy and proprietary knowledge sometimes leads to successive and wasteful drilling by different groups of the same region, either searching for different materials or for the same material at different times. It also has led to the U.S. government having little idea about U.S. reserves and resources, except what was reported by the private exploiters.*

Reserves become depleted by extraction and use, and replenished by three main methods: (1) exploration, discovery and delineation of new deposits; (2) rising prices, which make known but hitherto unattractive deposits now attractive; (3) improved extraction methods, so that hitherto unattractive deposits now become feasible to extract. Thus, we see reserves of some materials remaining at (say) ten years supply, for decades. Of course, resources and hence reserves can eventually become depleted, as we will see in the next sections.

The reserves and resources are often categorized more finely, for example, on the uncertainty axis as "known," "probable," "possible," "hypothetical," with definitions of these terms varying with different materials. They can also be categorized as economically marginal (say up to twice present costs), or sub-marginal.

5.3 PETROLEUM RESERVES AND RESOURCES

Modern methods of petroleum exploration, by which the total amount ultimately recoverable could be estimated within a factor of (say) two or three, started in the late 1940's, and since the late 1950's most estimates have hovered around 2000 billion barrels (375 billion metric tons). The stability of these estimates, during a period when large new deposits were found in the Middle East, Mexico and elsewhere, could be regarded as a tribute to the estimating ability of petroleum geologists, moderated somewhat by the fact that the estimates are not truly independent, but tend to build on each other.

Even so, in most countries where oil exploration and extraction is in private hands, the governments, until very recently, have not known very well what reserves and resources were in the country. This was the case in the U.S. in 1973, when the federal government realized that most of its information and interpretation came from what the petroleum industry chose to publish.

Many analyses of reserves and resources appeared in the 1970's, and much of the data of this and subsequent sections are taken from these sources: (Nehring 1978); (Moody and Esser 1975); (Moody and Geiger 1975); the Congressional Office of Technology Assessment (OTA 1980a), which reviews several analyses; British Petroleum (BP ~~1979)~~ 1982, 1984) which ~~has~~ have both good illustrations and data summaries.

Table 5.1 shows the "published proved" reserves of both oil and natural gas at the end of ~~1979,~~ 1983 according to B. P. and the Oil and Gas Journal, 31 December, ~~1979.~~ 1983. ~~In this table, Mexico is listed with Latin America, and 31 billion of the 56.5 total belong to Mexico.~~ The U.S.S.R. published reserves are, in my opinion, an understatement of what the U.S.S.R. knows to exist.

The OPEC countries deserve special mention and Table 5.2 shows OTA data of their published oil reserves, 1979 production rates, and years that these reserves would last at those production rates. The dominant position of the Arab OPEC countries (OAPEC) is clear. Without really attempting to explore their entire land, Saudi Arabia has nearly 50 years of known reserves at an extraction rate of nearly 10 million barrels per day -- about equal to the U.S. production rate in 1979, whose reserves at that rate were about 9 years.

Discussion of oil ultimately recoverable provides an opportunity to describe how it exists in the ground and how it is recovered. Contrary to some amateur opinions, oil does not exist in the ground in otherwise empty liquid "pools," despite the occasional use of that word to describe mapped deposits of it. The oil, formed from ancient aquatic plants, exists in the minute interstices of sedementary rocks with porosity comparable to that of a concrete sidewalk. Most oil found to date resides in structural traps, an oil-bearing porous sandstone that is overlaid by impervious rock; part of this geologic structure has been faulted and tilted. The oil, being lighter than water (which often occurs in the same deposits) migrates to the upper region where it is trapped, hence the name structural traps. These regions and much information about them can be discovered by modern geologic methods.

Most oil deposits also contain natural gas; some contain a great deal. Also, natural gas deposits contain "natural gas liquids" which augment global petroleum production by a few percent (but more in the U.S.).

These oil deposits range from very large to very small. The super giant fields have, by convention, more than 5 billion barrels; for example, Prudhoe Bay in northern Alaska. Giant fields have 500 million barrels or more, medium ones perhaps 50 million and small ones 5 million. In the U.S., as the giant fields became depleted and oil sold in 1980 at $35/barrel or more, attention turned increasingly to small fields. Opinions have been expressed that much oil exists in these small fields; this is principally a U.S. view, based on an atypically large number of small fields in part of the Gulf of Mexico region.

Worldwide, the situation is different. Geophysics shows us that about 600 potentially oil-bearing basins exist, of which about 400 have had exploratory drilling. Oil and gas has been produced from 160 of these, and 80% of all oil ever produced comes from 25 basins. Thus, two hundred basins, nearly all in difficult or inhospitable locations, remain to be explored.

Oil-productive basins will contain many oil fields. About 20,000 separate fields of all sizes have been discovered, but 90% of all oil ever produced up to 1975 came from 1700 of them, and about 75% of it comes from 280 giant oil fields.

The porosity of the strata and viscosity of the oil both vary over wide ranges. The viscosity is conventially measured in "American Petroleum Institute Degrees" (API°), with 40° or above being very light, 35° being normally light, less than 25° being heavy and 10 - 7° being tar-like, kerogen in oil shale, etc.

These different qualities affect the fraction of oil actually recovered, which can vary from 70 - 80% in some Texas fields to only a few percent for heavy oils. The present industry average is about 30%, rising at a fraction of a percent per year because of improved recovery methods. The largest additions to U.S. reserves come, at present, from peripheral discoveries near presently known deposits, and improved recovery from existing fields.

Because the specific gravity of crude oil is about 0.85, and that of the overlying rock is about 2.5, the differential pressure of about 17,000 pa. per meter of depth (0.8 psi per foot) tends to drive the oil upward through drill holes; so accidental blowouts occasionally occur. As the field becomes depleted, pumps augment the flow. After that, secondary recovery methods are normally applied, especially in the U.S. and other resource-depleted regions. The most common methods are injection of gas (often re-injection of associated gas), and water under pressure (water flooding) into auxilliary wells that drive the oil toward a collection well. Beyond this, tertiary recovery methods now start to come into vogue; heating the oil by controlled burning of a small fraction of it is the only method much used yet, but other methods, such as detergents to release the oil from the rock, are being tried. These more heroic measures may yield about 2 - 10% of the oil in place (beyond the 30% recovered by the primary schemes.)

With these and (inferentially) other complexities in mind, examine now a typical recent estimate of ultimately recoverable world oil. Table 5.3 taken from (OTA 1980a) shows Nehring's 1978 estimates (he modified them slightly in 1979) and for comparison the Moody/Geiger estimates done for the Mobil Oil Company in 1974. The two analyses are recognizably similar, and the totals are close. Regarding confidence levels, Moody and Esser in 1975 give a median value of 2030 billion barrels, with 95% chance of more than 1700 billion, 5% chance of more than 2500 billion. Nehring's similar limits are 1700 - 2000 - 2300, but the present true state of knowledge does not warrant that much accuracy. For example, some recent estimates of Mexico's ultimate yield are 120 billion barrels, up considerably from earlier guesses.

An upper limit of about this magnitude is easy to derive, as follows: Over the earth's surface, there exist about 25 million square miles of prospectively productive areas. The U.S. has several such regions, and extensive experience with them has shown that the yield comes to 45 - 60,000 barrels per square mile. A world total of 1200 - 1500 billion barrels comes from this simple view, and more sophisticated analyses give the somewhat larger current estimates. Grossling's (1974) estimate of 2500 - 6500 billion seems highly inflated.

The IIASA (Häfele 1981) report lists factors that could change these estimates, of which the principal ones were:

Leading to less:

- Fewer giant fields than expected
- Global recovery rate cannot be increased 50%
- Exploration too costly
- Much less oil far offshore, in polar seas, etc.
- Bad political climate

Leading to more:

- A new "Middle East"
- New types of deposits
- New drilling and production techniques (e.g., replace the drill heads without pulling up the pipe string, a recently developed technique)
- Better enhanced recovery

In any event, oil will be more costly, as the world moves toward oil in smaller fields, toward oil in offshore and deep offshore regions, and toward "difficult" oil such as tar sands.

Concluding this section, Figure 5.3 from the BP report shows graphically the global production and reserves. Note the dominance of the Middle East.

5.4 ESTIMATING OIL AND GAS RESOURCES

How were the numbers in Section 5.3 obtained? The vast majority (≈90%?) of exploration for underground resources has been for oil and gas. Eventually, oil and gas fields must be proved in, so to speak, by detailed drilling into the presumably petroliferous strata. Before starting that expensive step, oil and gas geologists use many methods of estimating what might exist at particular places. This section gives a brief account of some of them, taken mainly from (White and Gehman 1979) and Clark*.

Different disciplines develop specific terms for things. In oil and gas exploration, a prospect is a location of a single potential pool or field. A play is a group of geologically similar prospects. A basin is a large volume of sedimentary rock that contains one or more plays. Different estimation methods apply on these various scales. Many of them use very sophisticated computer techniques, for example, to compare the geology of thoroughly drilled areas with those in some new area.

5.4.1 Areal Estimation

This simple low-cost method is suitable for initial estimation over small or large areas. The surface geologic structure is compared to similar ones elsewhere: sandstone, shale, apparent inclination of strata, vertical faults (hence the likelihood of petroleum trapped beneath impermeable overlying strata), for example. The method requires use of geologic maps, and gives answers based on rough calculations, of the general nature: prospective yield = (basin area) x (% potentially productive) x(barrels per productive unit area). The method takes no account of depth, and has been largely supplanted by volumetric methods.

5.4.2 Volumetric Estimation

Here also known regions are compared with the region of interest. It requires more data: number and size of prospects, stratigraphy, porosity, thicknesses and other geophysical information. It is also simple to use, most suitable for deposits with simple and uniform geometry. The method aims to determine (for example): prospective yield = (basin area) x (sediment thickness) x (barrels per unit volume). If particular stratigraphic traps are known within the basin, the estimate is more reliable. As White and Gehman write, there are pitfalls. Yields from explored basins range from 0 to 4 million barrels per km^3; selecting from this wide range for a particular untested basin is critical and difficult.

5.4.3 Geochemical Material Balance

This special form of volumetric analysis deals with the fundamentals of petroleum generation, migration and entrapment, requires much more information, and can give more reliable estimates. For example, the prospective yield might be estimated as: (drainage area) x (source thickness) x (% organic content) x (% transformed into hydrocarbons) x (% migrated) x (% trapped) x (% potentially recoverable). A few factors, each with large uncertainties (methods 5.4.1 and 5.4.2) are replaced here with many factors, each of which can in principle be estimated more precisely. As an example, the transformed fraction of organics depends on the pressure-temperature-time history of the deposits (which describes the low-temperature pyrolytic process that formed the oil or gas); the fractions migrated and trapped depend on geologic history. This method applies best to particular prospects and plays, where the data are available.

5.4.4 Extrapolation of Discovery Rates

This method was highly developed by (Hubbert 1962, 1967, 1974). There are several versions. In one, the discovery rate (barrels per foot of exploratory drilling) is plotted against total cumulative production of oil, as in Figure 5.4, after (Davis 1958), one of the earliest estimates of this kind. The declining curve corresponds to depletion of easy-to-find rich deposits. Note the fluctuations; much care and knowledge about how they arose must be applied if the extrapolations are to be meaningful.

Alternatively, discovery rate barrels/year can be plotted versus time, as well as production rate (which lags discovery by about 10 years in the U.S. for reasons given in Section 5.2). The area beneath is cumulative discovery (or production), and judicious extrapolation into a bell shape (as in Figure 5.1, but with real data) gives an estimate of the ultimate total and yield versus future time (Hubbert 1962, p. 60).

Clearly these techniques apply only to large regions, and tend to ignore improvements in discovery or extraction techniques.

5.4.5 Delphi Estimation

Named after the place of the Greek oracles, this technique is based on interacting collective expert opinions. All available data are helpful. Usually, each expert first offers an independent estimate, sometimes with associated supporting opinions. The leader then prepares a summary (to preserve anonymity) which is distributed for a second round of opinions. Figure 5.5 shows a hypothetical set of five opinions at the 0, 0.2 ... 1.0 probability levels. The process continues until some consensus emerges. It is easy to introduce unwanted bias, and for estimates to gravitate toward a group mean.

5.4.6 Chemical Detection

Modern chemcial techniques are sensitive enough that traces of hydrocarbon gases percolating upward from underlying deposits can sometimes be detected at the bottom of a drill hole only 100 meters deep. If the thermal history and other data pertaining to the region are known, it is possible to estimate what lies beneath. This method is applicable to specific prospects.

For regions that show exceptional promise, data files on all these and other methodologies can be combined (at considerable expense) to provide specific resource estimation by deposit, commodity, tonnage, grade, and area.

Uncertainties attend all these estimates. Oil or gas potentially in the ground does not translate easily to an estimate of what can be profitably recovered; the strata may be relatively non-porous; the oil may be very viscous; it may not even be there. Thus estimates based on simple techniques (for example areal surveys) usually need to be down-rated to account for the risk that analogies with known producing areas can be wrong. After all, most of the earth's surface does not have appreciable oil or gas beneath.

5.5 PRODUCTION: NOW AND LATER

Figures 5.6 ~~and 5.7, both~~ to 5.8, all from BP, show the production and movement and consumption of oil. From these figures we see:

- The dominance of the Mideast, as shown especially in the flows of Figure 5.7, whose widths correspond to annual volumes
- The dependence of Western Europe and Japan on imports
- The overall increases during the decade ~~1969 - 79~~ 1960 - 1982.

Figure ~~5.8~~ 5.6 displays these production data during the ~~1971~~ 1960 - ~~79~~ 82 period. Note the small dip in OPEC production in 1974 - 75, caused by the price increases, and the recovery soon after. The OPEC total production throughout all the period ~~shown in the figure~~ 1970 - 1980 never strayed far from 31 million barrels per day (mb/d), and conventional wisdom as late as 1980 had it staying at about that level, or perhaps slightly higher, throughout the 1980s. In 1982, the OPEC countries, to their surprise and displeasure, could only sell, hence only produce oil at the rate of about 17.5 mb/d, showing how susceptible are forecasts to error, even when made by experts in the field. This drop in OPEC production will be discussed again later in this section.

The centrally planned economies in 1979 produced: U.S.S.R. 11.7 mb/d, Eastern Europe 0.4 mb/d, China 2.0 mb/d, making a global total of about 66 million barrels/day. At that rate, 2000 billion barrels would last 83 years, but the world would run short very unevenly.

We now discuss these and other data both with respect to regions and with respect to future trends.

5.5.1 United States

Table 5.5 shows present and future expected production rates in the developed non-Communist world, according to OTA, including the sources of U.S. future production. OTA is not alone in this opinion of lower total U.S. production in the year 2000. ~~Ac-~~ Hayes (1979) reports that : ~~cording to (Hayes 1979)~~: the National Academy of Sciences Committee on Nuclear and Alternative Energy Systems (CONAES) in 1978 guessed 6 mb/d; the Dept. of Commerce suggested 6.2 and M. K. Hubberd 4.0; nothing has happened since to modify these estimates substantially. The U.S. Federal Energy Administration in 1974 predicted 11.4 mb/d domestic production in 1990 at $11/barrel, a somewhat extreme example of the naive optimism of the times. The Exxon World Energy Outlook 1979 guessed 6.3 mb/d in 2000.

The trend in the U.S. toward smaller fields, additions from marginal regions and enhanced recovery methods will continue. In 1980, 500,000 active wells produced an average of 20 barrels/day each. These data stand in dramatic contrast to those of the Mideast, where 4000 wells could produce 20 million barrels/day, an average of 5000 b/d for each one.

5.5.2 Canada

Principal future sources appear to be the Arctic seas and tar sands, which together might provide 2 mb/d in the year 2000; but the harsh environment and difficult extraction promise that the oil will be expensive. Oil collection in the Arctic seas is particularly difficult. Icebergs not only endanger crude oil carriers, but in many places scour the rocky bottoms of the channels making undersea pipelines for either oil or gas infeasible.

5.5.3 Western Europe

Almost all the oil appears to exist in the North Sea. The U.K. withdrawal rate increased rapidly through the 1970s (see Table 5.4) and the projected rate of 1.9 - 2.8 mb/d in the mid-1980s should deplete their resources substantially by the turn of the century. The other principal developer is Norway, which until 1981 proceeded slowly, but planned to speed up development thereafter. Until now, no work has been started north of the 62° parallel because of difficult conditions and the possibility of ecologically and economically damaging spills.

5.5.4 Less Industrialized and Industrializing Non-OPEC Countries

With the sole and important exception of Mexico, almost the entire future expected oil discoveries will be used internally, for example, oil in the south Atlantic below the 40° parallel off the coast of Argentina, or in the indubitably large Chinese deposits (in Taching in the northeast, and others in the far west and in the South China Sea). The principal and important effect of such finds and consequent yields will be to permit national and regional development that would have been much more difficult or even impossible otherwise. The rise in international oil prices from \$2.50/barrel in 1970 to \$35 - \$40 in 1981 shrivelled ~~in~~ the plans and prospects of many small countries with small or no foreign exchange reserves.

5.5.5 OPEC Non-Mideast Countries

The largest countries in this category are Nigeria and Indonesia. The former, with population of about 80 million and 1979 production of 2.3 mb/d, and the latter with 120 million people and 1.6 mb/d, can produce 0.03 and .013 barrels per inhabitant per day compared to 1980 U.S. consumption of 0.07 b/d. These countries, like the non-OPEC LDCs, are not wealthy, but developing rapidly and their surplus available for export will shrink with time.

Venezuela is in a similar but not so extreme condition, and has very large reserves of heavy oil in the form of tar sands.

5.5.6 The OPEC Mideast

These countries in 1980 produced about 40% of the free world's oil, and could, in principle, produce much more. Before turning to the drop in OPEC production in 1981-82, it is useful to discuss OPEC, and especially mideast OPEC in general, and why OPEC production was unlikely to rise much above the 1970s level of about 31 mb/d, and the Mideast part of it much above 20 mb/d, even if economic and other circumstances had not changed in the early 1980s. For most non-Mideast countries, limited reserves will limit production through the 1980s. For the Mideast countries, political, economic, and social forces, all intertwined, will limit the output. For example, Saudi Arabia in 1980 preferred a production limit below its recent ~~14~~ 10 mb/d, but maintained the higher rate in order to prevent what it then considered destabilizing global price rises. Kuwait plans to limit its production to 1.5 mb/d, at which rate its known reserves (Table 5.2) would last 120 years. All this needs some explaining.

Contrary to some conceptions, OPEC started not in the Middle East but from Venezuela initiatives in 1960, at a time when conditions were dictated by the multi-national oil companies. These companies (Esso, Anglo-Iranian Oil, Texaco, Mobil, Shell, etc.) so controlled extraction technology, shipping, and markets that they could and did unilaterally set very low prices ($1.50/barrel, for example) and no producing country could oppose them. In 1953, the short lived Mossadeq government in Iran was overthrown and the Shah reinstated, largely as a result of oil company pressures.

Consider now suspected reserves and resources of even 1000 billion barrels of oil in all OPEC countries, of which perhaps half of it might be extracted in the period 1960 - 2010. At prices prevailing through the 1960s, the total income would have been about one trillion dollars, or roughly speaking $20 billion per year, to be divided up among many countries. But even in the 1960s, the industrialized countries were running a trillion dollar/year economy, fueled to an increasing extent by Mideast and other OPEC oil.

The oil income to the OPEC countries would be much too meagre to finance a shift from economies temporarily solvent by ephemeral oil income to economies sustainable for the long term, which could only come by massive investments of the sort common in the industrialized world. The OPEC countries knew that they could not catch up with 1960s prices.

By the early 1970s, the industrialized countries had become much more dependent on OPEC oil than hitherto; the U.S. switched from being an oil exporter to roughly neutral to an increasingly strong importer. In the meantime, the OPEC partners had increased their technical, economic, and political skills. While no precise event can mark the turning of power from the industrialized countries and the multi-national corporations to OPEC, the negotiations between Libya and Occidental Petroleum in 1971, where the latter agreed to price demands that would have been rejected a few years earlier, is a good indication of the change. By 1973 the industrialized states, importing 9.3 billion barrels/year, had become vulnerable, and the Arab-Israeli war late that year merely provided a handy excuse and dramatized what was bound to happen soon anyway. Oil prices rose to $10.00 per barrel on 20 December 1973*, principally by urging of the Shah of Iran, who had vast projects (mostly military) on which to spend the money.

At last the Mideast OPEC states had under their control adequate wealth for development and the plight of other OPEC states was, at least, ameliorated. Five hundred barrels at $10, then $20, then $35 per barrel comes to $17 trillion, a vast sum, 6 or 7 years of the U.S. GNP in 1980, enough to support a 50 year development plan in the Mideast. Once embarked on that path, the countries could not turn back to the era of former lower prices, no matter what international economic or military pressures might be applied; to give up the only visible path to a state of development enjoyed by their customers was unrealistic, and even worse, unfair.

The Mideast OPEC countries, after some trials, gradually discovered the rate at which they thought they could effectively use this vast new income; realization of those limits leads several of them -- Kuwait particularly, but others too, to limit their income and stretch out the resource to match the long time perspective needed in constructing a whole society; see Chapter 2, Section 2.3 for a more general discussion of this point. Reinforcing this conservation is the realization by both Mideast suppliers and OECD consumers that they are interdependent; excessively rapid oil price rises stifle industrial production, cause economic distress and thereby endanger Mideast security and progress. Furthermore, much of the physical labor in several Mideast countries now comes from aborad; 50% of the Kuwait population is foreign and 70% of the labor is migrant. The presence of so many workers from outside the area increases the political fragility and erodes the traditional Mideast social system, especially in Saudi Arabia, Libya, the United Arab Emirates and Kuwait.

Attesting to this developmental caution are these OPEC crude oil productive cpapcities: 41.4 mb/d installed, 34.7 sustainable on a long-term basis, about 31 mb/d actually used in 1980. Almost 3 mb/d of this excess installed capacity resided in Saudi Arabia, giving it considerable leverage in OPEC discussions.

This interdependence was emphasized by the OAPEC countries in late 1979 at the Third Annual OPEC Seminar on Future Energy Markets, in Vienna and, along with increasingly effective programs in the industrialized countries to reduce their use of imported petroleum, contributed to the leveling of OPEC oil prices in the early 1980s and even to modest price decreases.

The dominance of OPEC, especially OAPEC countries in the oil markets will continue. The multi-national corporations, once the de facto, if not de jure global directors, now serve increasingly as the agents of the producing countries. In 1980, about half the OPEC sales were directly to consumer governments, and the erstwhile flexibility to direct oil tankers to changing markets (as happened in the 1973 oil embargo) is now largely lost.

The multinational corporations became more vulnerable in other ways too. Industrializing Mideast countries now build their own refineries and petrochemical plants, using more and more of the associated gas that less than a decade ago was almost totally flared, and that lighted the night more than did the world's largest cities. OPEC countries order their own tankers and, within limits, force their customers to accept a mix of crude oil and refined products shipped in nationally-owned OPEC tankers. All this bodes ill for aging refineries in the U.S. and Europe and for large crude carriers, many of which were ordered in the early 1970s. In 1979, the global tanker fleet totalled about 330 million deadweight tons, but demand remained at 200 - 220 million for nearly a decade. Reopening of the Suez Canal (which cannot accommodate very large ships) and the increase in point-to-point sales of specific OPEC products have worked to the disadvantage of very large tankers, which now slow-steam, wait in port for orders, or sail partly loaded.

The drop in total OPEC production from about 31 mb/d in 1979 to 22 mb/d in 1981 and 17.5 mb/d in 1982 was startling and for the most part unexpected. In particular, the economic recession in the OECD countries led to enforced curtailment, accelerated efforts to use expensive petroleum more effectively, switch to alternative fuels where possible, and switch to domestic petroleum sources preferentially. But in addition, programs to use energy resources (especially petroleum) more effectively were begun in the early-to-mid 1970s, and much re-emphasized after the second major OPEC price increase of 1979-80 (when oil sold for $35-40 per barrel). Such programs to use oil more effectively -- better insulated houses, smaller cars, etc. -- took several years to become effective; see the sections on time perspectives in the earlier chapters. But bit by bit they eroded the demand for oil. Neither the OPEC countries, nor most of the OECD countries, nor the major oil companies foresaw that these two major causes -- a recession and permanent shifts in oil use -- would bring the price of oil below $30/bbl in 1982, and OPEC in disarray.

Regarding these recent changes, the good news to OECD countries and bad news to OPEC ones are obvious; but there is more to it, of unsettling nature. Saudi Arabia can no longer control OPEC production or prices, and other Mideast countries may attempt to take over the leadership and seize a larger share in the total production, by force majeure if necessary. Iran, with 35 million people, a potentially large productive capacity, and a large military establishment, comes easily to mind.

5.5.7 The U.S.S.R.

Only 0.4 mb/d comes from Eastern Europe (principally Rumania); the U.S.S.R. dominates the Soviet bloc. Figure 5.9 shows U.S.S.R. production 1970-79, which has been fairly constant from the traditional Urals-Volga Region, and rapidly increasing from West Siberia.

The Russians pin their hopes on this source, and different opinions about the prospects lead to different opinions about events to come in the 1980s. U.S.S.R. industrial goals stated during the early and mid-1970s suggested that a substantial increase in oil production was to come, probably backed by reserves known to the Russians but not publicly announced (there have been no official announcements of reserves since 1971). But the West

Siberian basin, for all its promise, is a difficult place to work, and some hold the opinion that production is falling short of the goals.

In 1978, the U.S.S.R. exported almost 3.2 mb/d, 30% of its total production; 1.8 mb/d went to other Communist countries (mainly Eastern Europe), and 1.3 went to non-Communist ones (mainly Western Europe) for hard currency. If the U.S.S.R. production does not permit these exports to continue, severe trouble portends because the Soviet bloc would face an economic loss of some $110 million hard currency per day, consisting of $54 million in imports from OPEC for Eastern Europe, plus $39 million in foregone U.S.S.R. income, at $30/barrel. The September 1981 doubling of U.S.S.R. gasoline prices, and recent increasing U.S.S.R. interest in effective energy use attest to the worry.

5.6 ~~5.5.8~~ Some Global Oil Projections (all caps)

The most important conclusion to be drawn from all these data is that global production will not rise very much; despite its temporary eclipse, OPEC will continue to have much leverage. The OTA in 1980 estimated, for the world outside the Communist area, that production then at 51.5 mb/d would lie in the range 45 - 60 mb/d in 1985 (a seemingly safe projection) and 40 - 60 mb/d in the year 2000. These numbers depend on price, global attitudes toward conservation, global political climate, and global economic circumstances. Other estimates are similar. British Petroleum, in a report "Oil Crisis Again," in September 1979 suggested 43 - 51 mb/d and Exxon's World Energy outlook (December 1979) suggested 60 mb/d, all for the year 2000. None of these estimates include synthetic fuels from coal, oil, shale, etc.

Not all future estimates have fallen into this range. The U.S. Department of Energy's Energy Information Agency (EIA) in its 1978 report to the Congress, figured 56 - 63 mb/d outside the Communist area in 1985, and 70 - 90 mb/d in the year 2000. Those estimates have now been revised downward, nearer to the others stated above. The errors in the 1978 numbers arose from neglect of political and social factors discussed briefly in Section 5.5 (especially with respect to OPEC), and a narrow econometric view that price would be the main supply determinant. That is not true when the price much exceeds the cost of production (as in Saudi Arabia where the production price at some wells is $0.50/barrel), and the supplier has plenty of present income. In such cases, it benefits the producer to leave the oil in the ground, to be used at a rate that matches the developmental time scale.

Another set of ideas, popular in some places in the early and mid 1970s, was that the price of oil was bound to decline (first from its $3.00/barrel price, then from $10/barrel, etc.) as the OPEC cartel fell apart or as the industrialized countries refused to deal with them or as the industrialized countries built up an oil reserve sufficient to withstand any OPEC embargo and starve them financially, etc. Sure enough, the price declined somewhat in 1981-82, but from a much higher level and surely not permanently. Both suppliers eagerly and consumers reluctantly have modified their economies and social structures too extensively to be able to turn back very far for very long.

5.7 Unconventional Oil: Tar Sands and Oil Shale (all caps)

Beyond applying methods to increase yields of petroleum-in-place, one can contemplate extracting liquid hydrocarbons from large deposits of minable material. Though the yield per ton of solids may be low, the apparent simplicity of just heating it to obtain oil has stimulated much activity. The volatile fortunes of many of these enterprises - especially oil shale - reflects the extreme volatility existing at the economic margin of the oil industry.

The largest present activity is the exploitation of large "tar-sand" deposits in northern Alberta, Canada. There, near Lake Athabasca, a weak sandstone bed deposit 40 meters thick, permeated with a heavy bitumen, covers many square kilometers and is overlain by a thin soil overburden; open-pit mining techniques have been adapted to the operation: the overburden removed, the soft rock gathered in long windrows, then carried by conveyor belts to the processing plant, where about 120,000 tons of rock per day yeild about 50,000 bpd of crude oil. This net yield is somewhat lower than the net yield expected from the higest grade Colorado shales. The early-1980s goal was close to 200,000 bpd from the region, but that did not come to pass.

Developing the Alberta tar-sands has been difficult. Winter temperatures fall to -40°C; the tar-sand is exceedingly abrasive and tends to stick to the equipment. The spent "sand" contains fine particulates that do not settle out in simple post-treatment settling pools, and re-vegetating the reclaimed land during short but intensive growing seasons presents peculiar problems.

Another operation, more nearly akin to true mining, proceeds in a heavy-oil field in the Komi Autonomous SSR, west of the Ural mountains. The oil is too viscous for normal extraction, so shafts and galleries have been sunk and shafts excavated just above the reservoir, about 150-200 meters below the surface. Steam injection into the oil-bearing strata below the galleries then warms the oil, which can then be pumped to the surface. The U.S.S.R. hopes to produce six million barrels/year at this site, and more elsewhere.

Because of the vast amount of material that must be handled cheaply, and the generally weak geologic structures that contain the oil, underground mining methods developed for coal generally will not work. Many techniques similar to those used for shale are applicable here, and test programs in the Colorado-Utah area are supported with that idea in mind.

Essential to many of the schemes is the presence of a formation of strong rock below the oil-bearing stratum, preferably not more than 30 meters below it. Then tunnels can be built into the underlying strong rock, and the oil above can be extracted by various techniques. One is simply to bore holes upward; gravity drainage then usually produces more than would pumping from the surface. Stoping, shown in Fig. 5.10, in the present context, may also be feasible, if either enough undisturbed oil-bearing rock can be left to support the layers above it, or if the surface be permitted to subside.

Among all the potential fossil fuel resources, few have had as checkered--even bizarre-history of developmental swings from optimism to pessimism and vice versa as oil from oil-bearing shales. The amount of fossil organic material in the U.S. is vast, and in China, Brazil, and some other places is very substantial. But in the U.S. at least, both its financial and technological (dash) prospects have always appeared to reside just beyond the limit of present practicality. As a result, activity in the field swings wildly, depending on private and public perceptions of future petroleum prices and availability, on fears or complacency about dependence on foreign supplies, and on many national and local political circumstances. Events in the late 1970s and early 1980s recapitulate, more dramatically than usual, this boom-and-bust history of oil shale in the U.S.

Oil shale is a sedementary deposit (technically a marl-stone) containing complex organic material derived from ancient plant matter (the same origin as coal); but it is less carbonized, fairly uniformly diluted through thick deposits, and can be heated to drive off a mixture of complex hydrocarbons somewhat akin to thick petroleum. The hydrocarbon inclusion is sometimes called kerogen, which has less hydrogen than petroleum but more than coal, and beyond that no fixed composition. Being an inclusion in the inorganic shale, it tends to incorporate many other materials as impurities.

The amount of this material is enormous, far exceeding U.S. deposits of conventional petroleum, but extracting it is difficult, especially without environmental damage. Therein lies the paradox.

Oil shale deposits cover about 20% of the U.S., the most extensive being of Davonian-Mississippi~~o~~an antiquity, lying between Texas and New York. They cover about 650,000 km^2 and contain 160 km^3 (10^{12}bbl) of oil, in rock yielding less than 50 l/ton (14 gal, or 0.3 bbl/ton). These deposits are too irregular and unproductive to invite exploitation.

Principal U.S. interest has centered on the Green River formation (see Fig. 5.11 for map) near the Colorado-Utah-Wyoming junction. The total area is about 44,000 km^2, and contains over 300 km^3 ($2x10^{12}$bbl) of oil in place. The richest part of this is in Colorado, especially the Piceance Basin area, where over 10^{12} bbl lie; about half of that is contained in shale averaging over 105 liters/ton (about 30 gal or 0.71 bbl/ton), much of it in beds ranging from 3 m to 600 m thick. The kerogen content is thus about 10% at most. Some deposits have no overburden and some have several hundred meters. The oil-rich shale will burn sulfurously in a fire, leaving a powdery alkaline ash. Most of the land in which the richest deposits lie is Federally owned, for example the northern half of the Piceance basin, with many deposits exceeding 300 m thick.

The only known way to extract this vast store is by destructive distillation of the shale, either by mining and retorting it at the surface, or by heating it underground and catching what comes out.

The most conventional and best-understood method is aboveground retorting (AGR); the shale is mined either by open-pit methods if the overburden is thin or weak, and otherwise by underground methods somewhat similar to coal mining, but on a much larger, unprecedented scale. Stoping might be appropriate for thick deposits, with selectively blasted solids falling in a controlled way through narrow bottom holes to ore-loading machinery; the shale is structurally weak, and can easily be crushed to a size suitable for removal and retorting.

Several retorting processes have been developed. Directly-heated methods typically depend on the gravity flow of shale, crushed to 10-50 mm size, down a retort, where from the top it is successively preheated by gases rising from below, then pyrolized in a hotter lower zone; then after sinking even further, the carbon-rich remainder burns with injected air to provide the heat input for the process. Sometimes the direct combustion is replaced by hot gas injection (using some of the product gas) or even by dropping heated ceramic balls through the shale (the Tosco-II process). The spent shale leaves the retort at the bottom; unfortunately, it expands and disintegrates during the retorting process, and the volume of spent shale exceeds that of the raw material by about 20%. Thus the vast residue (two tons or more per net barrel of product) cannot all be returned to the mine from whence it came.

The problem of dealing with spent shale is only one of many environmental difficulties. The spent shale is usually very alkaline, often containing large amounts of natural sodium bicarbonate (nahcolite), dawsonite (which can with difficulty be made a substitute for bauxite, from which aluminum is produced) and other materials. No market exists for such vast quantities of these materials in northwest Colorado, so they must be disposed of close to the retorting site. Leaching of this material increases the alkalinity of streams that are already often too alkaline (the inverse of the acid drainage discussed in connection with coal mining). Thus land restoration is troublesome, and water in that region for extensive recovery operations will be difficult to find. The Congressional Office of Technology Assessment in a review of oil shale prospects (OTA 1980b) believes that water could be made available, and other present environmental requirements satisfied, for an industry of at least 500,000 bbl/day through the year 2000, in the Colorado-Utah-Wyoming corner. However, additional reservoirs would be needed, and rapid increases in water use for other purposes would have to be avoided.

The environmental impacts are not limited to water, not to on-site or near-site effects. Air quality degradation can arise from dust, hydrogen sulfide, sulfur dioxide, nitrogen dioxide, carbon monoxide, and various hydrocarbons. The difficulties of controlling them will be similar to controlling emissions in coal conversion (synfuels) plants; see Chapter 6.

Producing shale oil and burning it produces much more carbon dioxide than does conventional oil; if shale oil ever became a large contributor to global energy needs, this would aggravate the problem of global buildup of atmospheric CO_2, and subsequent climate changes. The excess CO_2 arises from two causes. First, some of the shale consists of carbonate minerals, which depending on the retorting process and kind of shale, could be calcined to release CO_2. Second, some of the kerogen is oxidized in the retorting process, so the net yield of oil is reduced. (Sundquist and Miller 1980) estimate that the production and burning of shale oil could produce 1.5-5.0 times as much carbon dioxide per unit of energy as would come from conventional oil.

The influx of many people into the dry and unsupportive region will be an additional burden. The OTA reports and an excellent series of summaries in (Mining Engineering 1981) give good accounts of these and many other matters. Apparently it will be difficult to produce more than about 500,000 bbl/day. The resource is there, but other considerations intervene.

The difficulties with above ground retorting (AGR) lead many companies to develop either modified in-situ (MIS) methods or true in-situ (TIS) methods. In the MIS method, about 15-40% of the shale is removed, generally at the bottom of the shale bed, to form a void into which the remainder of the shale above is to fall, first by blasting, then later by collapse. The porous shale at the bottom is ignited and a controlled burning and top venting pyrolizes the shale rubble in-situ. The oil and gas leave by vents and extraction pipes artfully placed. This technique is fairly well advanced, and initial underground tests have been carried out.

The problem of disposing of spent shale is partly solved in the MIS process; the bulk of it stays underground, and the initially mined fraction can either be surface-retorted (thus recreating the problem on a reduced scale) or discarded without retorting (giving reduced yield). However, problems of land settling, leaching of pollutants into underground aquifers, and control of gaseous emissions at the surface still remain.

The true in-situ processes (TIS) are in much earlier stages of development; they too depend on burning some of the material underground, and require that the shale be made permeable, generally through massive fracturing, with controlled use of explosives. Some shale deposits are natually permeable, caused by ground water leaching; whether they can be de-watered and processed by hot gases or superheated steam is still an open question.

How close is shale oil to commercial practicality? As stated in the opening paragraph of this section, that depends on who asks, who answers, and when. In the early 1970s, cost estimates were $4-5/bbl. just a little above the cost of petroleum at the time, but many environmental and technological problems were seriously underestimated. About 1980, the advent of an $80 billion Federal synfuels program exhumed enthusiasm of earlier years, and a 1980 Federal goal to produce 400,000 barrels/day from oil shale in 1992 at a cost of some $16 billion was based on expectation of continually rising oil prices through the 1980s. That cost comes to $40,000 per daily barrel, which with early 1980s interest rates set the cost at about $20/barrel for interest charges alone. The total cost appeared to be more like $40-50/bbl, putting its prospects very much in jeopardy in 1980-82 as oil prices declined temporarily from a high of about $40 down to about $30. Furthermore, perhaps some production difficulties -- environmental requirements particularly--can never be met at any price with known technologies. Then either shale oil would not be developed, or the environmental requirements would have to be relaxed. Oil from shale is presently produced in China and Brazil, apparently with less worry about environmental effects than in the U.S.

This extreme boom-and-bust sensitivity is vividly demonsrated by comparing the 1980-81 plans and activities for the Green River shales, and what happened to them in 1982. Mining Engineering, January 1981, gives a detailed summary of the situation then. Here is a condensation of it.

- Paraho Development: Utah, Southeast of Vernal (see Fig. 5.9). Surface mining and retorting. Plan 10,000 bpd in 1984.
- Occidental Oil Shale Co. - Tenneco Oil Shale Co. Center of Piceance Basin. Modified in-situ (MIS) ~~inch~~ retorting of mined shale via Lurgi retorts. 55,000 bpd in 1988, for $5-6 billion.

- Union Oil. Piceance Basin. Room and pillar (R&P) mining and above ground retorting (AGR). Exploring MIS. Started to build 50,000 bpd plant for $2 billion.

- Exxon-Tosco Colony. Piceance Basin R&P and AGR. 47,000 bpd by mid-1980s for $2 billion. Atlantic Richfield Oil Company sold its interest to Exxon.

- Rio Blanco Project, by Gulf Oil and Standard of Indiana, on Piceance Tract C-a. Originally R&P and AGR, now MIS, with a first trial burn initiated in 1980. Indiana Standard paid the Federal Government $210 million in 1974 to lease this 21 km^2 tract, a very high price at the time. The production schedule is unclear, with projected costs of $1 billion.

- Thompson-Ramo-Wooldridge for the Naval Oil Shale Reserve. Piceance Basin and Vinto basin. Study underway with Gulf R&D, Tosco, C.F. Braun Co. and Kaiser Engineers to be complete in in 1984 for $64 million.

- MultiMinerals Corp., Piceance Basin, MIS, wish to recover nahcolite and dawsonite as well (why?); 50,000 bpd in 1987 for $700 million (they were very optimistic).

- Equity Oil - U.S. Detp. of Energy. Piceance Basin. True in-situ, because the structure there is permeable. Test program only.

- Geokinetics - Dept. of Energy, Utah. TIS, with balsting to create permeability. Test program with burning started 1981.

- Pacific Property: Superior Oil and Sohio, and Cleveland Cliffs Iron Co. Piceance Basin. Underground mining and AGR with nahcolite and dawsonite recovery.

Most of these grand plans collapsed by 1982, partly because of temporarily lower petroleum prices in 1981-82, and partly because of decreased federal interest in supporting synfuels projects. Such developments were to be left much more to the market-place than before. In May 1982, the largest and most visible project--the Colony development--collapsed virtually overnight as the Exxon Corporation withdrew its support, after about $400 million had been spent. The only large enthusiast left in mid-1982 was the Union Oil Company.

What are the prospects for U.S. oil shales? On the one hand, we see a vast potential resource, and on the other hand, a host of difficulties that would arise in attempts to exploit it on a large scale. To be sure, 500,000 bpd seemed possible and even likely in 1981, given all the committed investments. Perhaps 1,000,000 bpd could have been produced with greater difficulty, at (say) $50/bbl. But even 1,000,000 bpd was only about 6% of the U.S. daily use in 1981 and 2.5% of total U.S. energy use.

Inspection of the activities and investments committed up to 1981 suggest that the various on-site participants had in mind an industry much larger. Those programs appeared to look more like development than final production.

Further conflict between development and environmental interests seems likely, not resolvable without substantial modification of views on one side or the other. But whatever the outcome, it seem very unlikely that the major fraction of U.S. oil demands could be met by shale oil in the next several decades, even if the price of oil exceeded $50/bbl. However, if history is a guide, shale oil in the U.S. will attract enthusiasts again sometime in the next one or two decades. As a corollary, it appears also very unlikely that oil-shale-related CO_2 emissions in the U.S. will contribute much to the global atmospheric buildup. Local and regional environmental and resource limits seem more likely to intervene first.

While that may be the outcome for the U.S. Green River formation, the story is more complicated, especially for heavy oil, and oil shale elsewhere. The Canadian tar-sands industry grows rapidly, and large tar-sand deposits exist also in Venezuela and elsewhere. Large oil shale deposits exist in Brazil (though not comparable to the U.S. ones). In some countries, oil production has provided a much larger fraction of foreign exchange than it has in the U.S., and with dwindling conventional supplies, attention turns increasingly to unconventional ones (e.g., Brazil). Thus the development pattern outside the U.S. may proceed quite differently, less constrained by considerations that have existed in the U.S. If that be the case, then very large amounts of unconventional petroleum may be produced this way, at a cost probably not exceeding thirty 1980-dollars per barrel, if the environmental restrictions are relaxed. The incentives to proceed that way are great in several countries.

Is it a good way to proceed? To those to whom the cost of oil is not very burdensome, and who have become sensitized to environmental problems, the idea may seem unattractive. But to people elsewhere who live in a harsher and less pecunious real world, \$30-40/bbl oil to be paid for by inadequate foreign exchange is unattractive; for them the priorities will be different. Also at this larger scale the question becomes tied to the issue of global environmental quality in the next century, and the paths of energy development in the presently less-industrialized countries of the world. That broad topic falls into focus better in the context of discussions about global CO_2 buildup from all sources, taken up in Chapter 3.

5.8 ~~5.5.10~~ Natural Gas

All caps

Natural gas (methane, CH_4) is relatively very clean, easy to burn in simple equipment, and is the basic stock for much of the petrochemical industry. Yet its development has, in most parts of the world, lagged behind that of petroleum until relatively recently because of the difficulty of transporting it economically in bulk.

Railroad tank cars and seagoing tankers for shipping oil have been in use for decades. Land transport of natural gas had to await the development of methods of manufacturing and laying large-diameter pipelines, now by continuous trenching and on-site welding techniques. Furthermore, customers must exist at the receiving end. Therefore, prior to the 1940s, natural gas was rarely sought, often deplored when found, and often flared (i.e., burned) when it accompanied sought-for oil. These impediments to natural gas use were especially strong in the Mideast, and large amounts have been flared. Now associated gas is usually re-injected into the oil fields to maintain underground pressure. Gas pipelines cover the U.S. and Canada, Western Europe and the U.S.S.R., and a pipeline runs from Iran to the U.S.S.R. A pipeline was planned to bring Canadian and U.S. Arctic gas to Eastern Canada and U.S. markets, and the U.S.S.R.-Europe gas pipeline was politically notorious in the early 1980s.

Sea transport of natural gas is expensive in LNG tankers. The gas must be liquified and the whole process is much more complicated and potentially hazardous than shipping oil in crude oil carriers.

These transportation considerations lead to a circumstance peculiar to natural gas: when it can be transported easily by pipeline to appropriately large users, it may be relatively cheap; but where it must be transported by sea, it will be expensive.

Another difference exists between oil and gas fields: the gas flows relatively freely through porous rock, so 75 - 80% of the gas is usually recovered without difficulty and only in very tight formations are stimulatory procedures needed.

Gas reserves, resources, and use are measured in cubic feet (1000 BTU/ft^3), and other units. 1980 U.S. domestic consumption was about 20 x 10^{12} ft^3 (20 quads), 25% of total energy use.

Table 5.6 shows world consumption, from BP data, during the period ~~1969-79~~ 1973-83. It has been remarkably constant overall in the Western Hemisphere, but has grown substantially in Western Europe and the entire Eastern Hemisphere, representing in part the introduction of large pipelines and the development of the U.S.S.R. gas fields. The world total for ~~1979~~ 1983, ~~1297~~ 1329 million tons of oil equivalent, corresponds in energy content to ~~26~~ 27 mb/d of oil, compared with ~~65~~ 58 mb/d of actual petroleum consumption at that time.

Natural gas reserves and resources are presently changing, upward in most regions, dramatically so according to many estimates. One reason is the trend toward decontrolling its price, especially in the United States. The control came about originally in 1938, when natural gas pipelines were placed under federal regulations as "natural monopolies." This federal control was extended in 1954 to producers of gas for interstate trade; as late as 1970, interstate gas prices were kept as low as 20¢/1000 ft^3 (20¢/GJ). That created a strong market and discouraged both exploratory drilling and annunciation of new discoveries. When oil prices rose in 1973, uncontrolled intrastate prices rose correspondingly ($1.40/1000 ft^3 in 1975), and the interstate supply started to dry up.

The apparent shortage led to measures by the U.S. Government to curtail natural gas use, especially by industry, in the middle-to-late 1970s, an action that perversely exacerbated problems of oil supply, and all in the face of large amounts of gas in the ground in the U.S. GUlf States.

This brings us to what might be called "conventional" estimates of U.S. and global reserves and resources as shown, for example, in Table 5.7, from IIASA. Those totals are approximately equal in energy content to the expected reserves and resources of petroleum. About two-thirds of the total gas reserves and resources appear to reside in the Soviet Union or the Mideast, especially Iran, a circumstance that underlies the ploy described in Section 2.4.

Several recent developments could change these reserve and resource estimates by large factors. Rising U.S. gas prices stimulate new drilling, which will probably produce a considerable amount of new gas in regions known as historic producers. But two quite new sources have appeared. One is gas in deep formations, typically below 5 km. The so-called overthrust belt of the Rocky Mountain region, a term that refers to one section of continental crust having been shoved over another in ancient times. At such depths, rock overlying gas deposits appears to be relatively impermeable, so that large amounts of ancient gas may be trapped beneath. Present U.S. estimates of eventually producible resources range as high as 1500 tcf (45×10^{12} m^3, 75 years supply at early 1980s rate of consumption).

Far more problematic is a vast amount of methane dissolved in hot geopressured brines along the U.S. Gulf coast. Estimates run from 85 to 1400 trillion m^3 (535 - 8000 billion bbl oil equivalent), the upper number being four times the total expected oil resource. To be sure, much exists, but can it be extracted in a reasonable way? The gas comes up with the brine, which is too hot and corrosive, unsuitable for discharge into the Gulf of Mexico. Thus it must be reinjected, an expensive undertaking.

Can the deep gas and geopressured gas be produced in acceptable ways, at acceptable prices? Recent advances in deep drilling techniques make some deep deposits available now, and future developments will probably do the same for the geopressured methane.

Many coal seams contain trapped methane, a continual hazard in coal mining. It has been suggested that this gas can be collected and used commercially, but that energy source must forever remain small compared to the energy from coal, which vastly exceeds that of the methane trapped in the seam.

As interest in natural gas increases, deposits are found in regions unexplored before, for example, in Pakistan and Bangladesh. This is particularly fortunate, as those countries have no excess foreign exchange with which to purchase oil, and have been energystarved. Assistance from countries with well-developed gas technology to develop these indigenous resources for indigenous use will significantly improve global stability and contribute to decreasing extreme economic disparities.

Consequences of the 1960s - 1970s price control, regulation, and deregulation were still felt in the mid-1980s. The price rose, but in early 1984 was still, on the average, below oil prices. How to decontrol it without creating both economic confusion and socially objected-to profits is a problem that the U.S. ~~f~~ F ederal government has failed to resolve. The amount is large: 20 trillion cubic feet per year, suddenly raised in price by $2.50/1000 ft^3, means additional domestic transfers of $50 billion/year.

In the 1960s, many electric power plants in the U.S. Gulf states were built to burn gas. In the mid-1970s, such use was excoriated. In the mid 1980s, owners of the Cincinnati Gas and Electric company's almost-completed Zimmer nuclear plant stopped construction, and considered converting it to burning gas.

5.9 ~~5.3.11~~ Coal (all caps)

The issues surrounding coal are so complex and often misunderstood as to require a separate chapter; in fact, they spill over into others, for example, environmental impacts. But it is useful here to state briefly the coal reserves and likely resources, to compare with those of oil and gas.

Tables 5.8 and 5.9 show recent estimates, taken mainly from data of the 1978 World Energy Conference, as interpreted by the IIASA group. Different estimates vary somewhat, depending on when they were made, opinions about recoverability and future price, but all those variations are relatively insignificant when put against one salient fact: a great deal of coal exists, compared to oil and gas, so very precise estimates are not even necessary at the present time.

The total recoverable resource appears to amount to about 10,000 billion tons; equivalent in energy content to about 40,000 billion barrels of oil, some 250,000 quads, 1000 years total energy supply for the world at its present rate of energy use. The reserves are correspondingly large, about 500 billion tons at present.

The U.S.S.R., U.S, and China lead in resources and they, plus Western Europe and Australia, dominate the 1980s reserves. That distribution differs markedly from that of oil and gas: the Mideast has very little coal and neither, it seems, does Mexico. The U.S.S.R. appears to be very well endowed with all fossil resources. The large U.S. coal resources and reserves stimulate vast plans for its use, to be discussed in the coal chapter.

Tables 5.8 and 5.9 show significant coal deposits in some otherwise energy-poor regions, for example, Botswana and neighboring African ~~regions~~ countries. More recent data show substantial amounts in Indonesia, particularly Sumatra, and, as has become the situation with natural gas, more seems likely to be found when it is searched for.

5.10 ~~5.5.12~~ A Final Comment (all caps)

Different analyses and interpretations yield different opinions about the recoverable fossil fuel resources and the result can be expressed in many ways. The IIASA estimates, expressed in Terawatt-years (TWyr) for all the fossil resources are shown in Table 5.10 (their Table 12.1). Except for oil shale, the estimates do not differ importantly from numbers given elsewhere in the book and the table shows the totals in persepctive. Present total global energy use is almost 10 TWyr/yr, and may grow to 20 - 35 in the next half century, depending on circumstances. As seen from a short-term perspective, there is no pressing fossil fuel problem, but just one of shifting from one set of fossil resources to another, during the next half-century or so.

But, such a view would be fatally wrong because:

(1) The times required for the deep technological, ~~and~~ economic and political changes are long, as considered already in Chapter 2 and elsewhere.

(2) The global environmental damage, chiefly climate changes from buildup of atmospheric carbon dioxide, would probably be irreversible and intolerable if carried out on a time scale shorter than many centuries.

(3) These fossil organic resources make much better chemical feedstock. Already several percent of the total production of oil, gas, and coal goes for that purpose, a rate of withdrawal and eventual oxidation that comes much closer to matching global capacity to absorb it.

Nevertheless, much more of it will be burned.

FOOTNOTES - CHAPTER 5

5.4 In the early 1970's I proposed to the U.S.G.S. that all exploratory drill cores be required to be kept, and that after a fixed period of a few years, they be taken over by the U.S.G.S. and made available for public examination. The idea was turned down.

5.10 Dr. Alan Clark of the East-West Resource Systems Institute, to whom I am grateful for instructing me.

5.19 A footnote in Chapter 6 remarks on these events.

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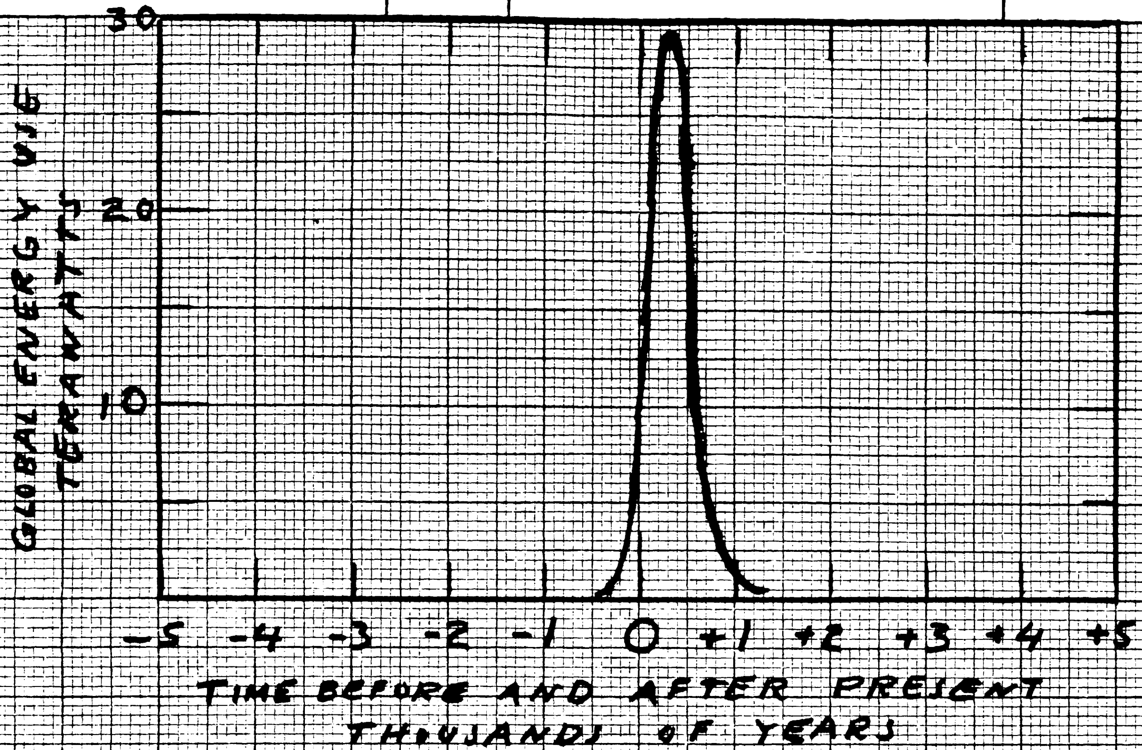


FIG. 5.1 How long the world's fossil fuel resources might last. The area under the curve represents the energy in 10^{13} (10 trillion) tons of coal, equivalent to all fossil fuels ~~presently~~ expected to be eventually recoverable. Present global energy use is about 10 terawatts.

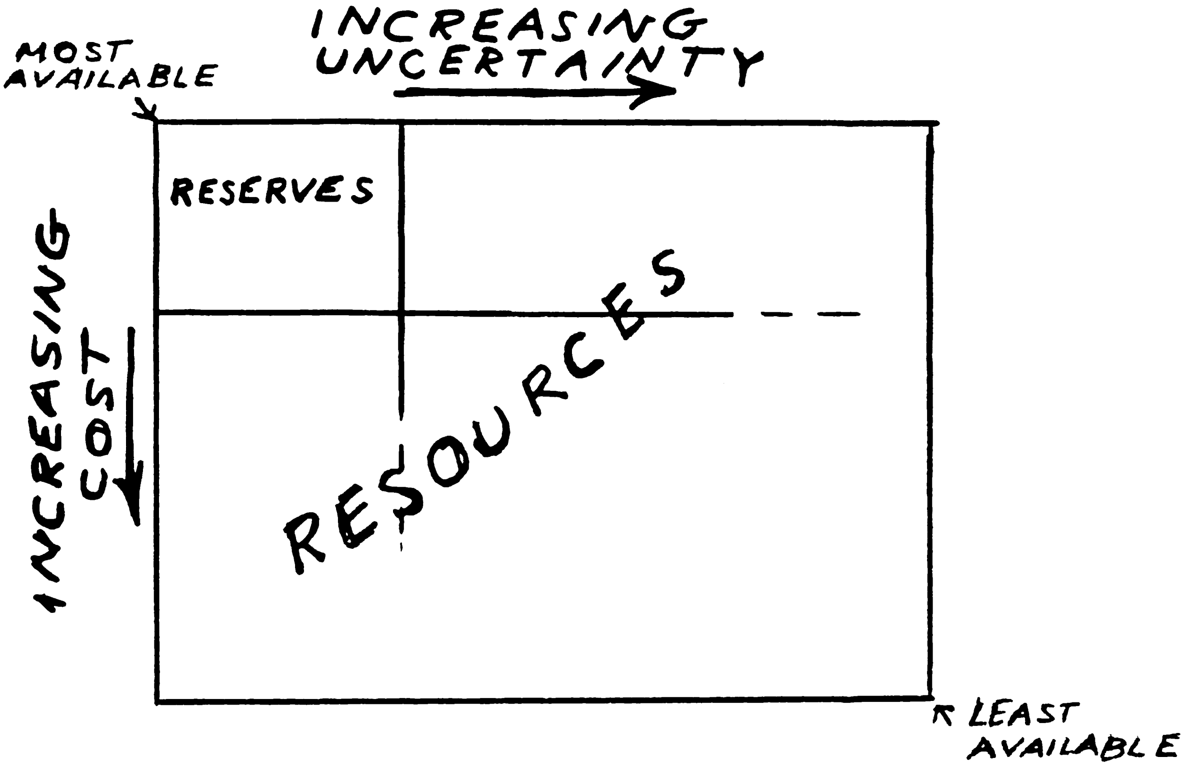
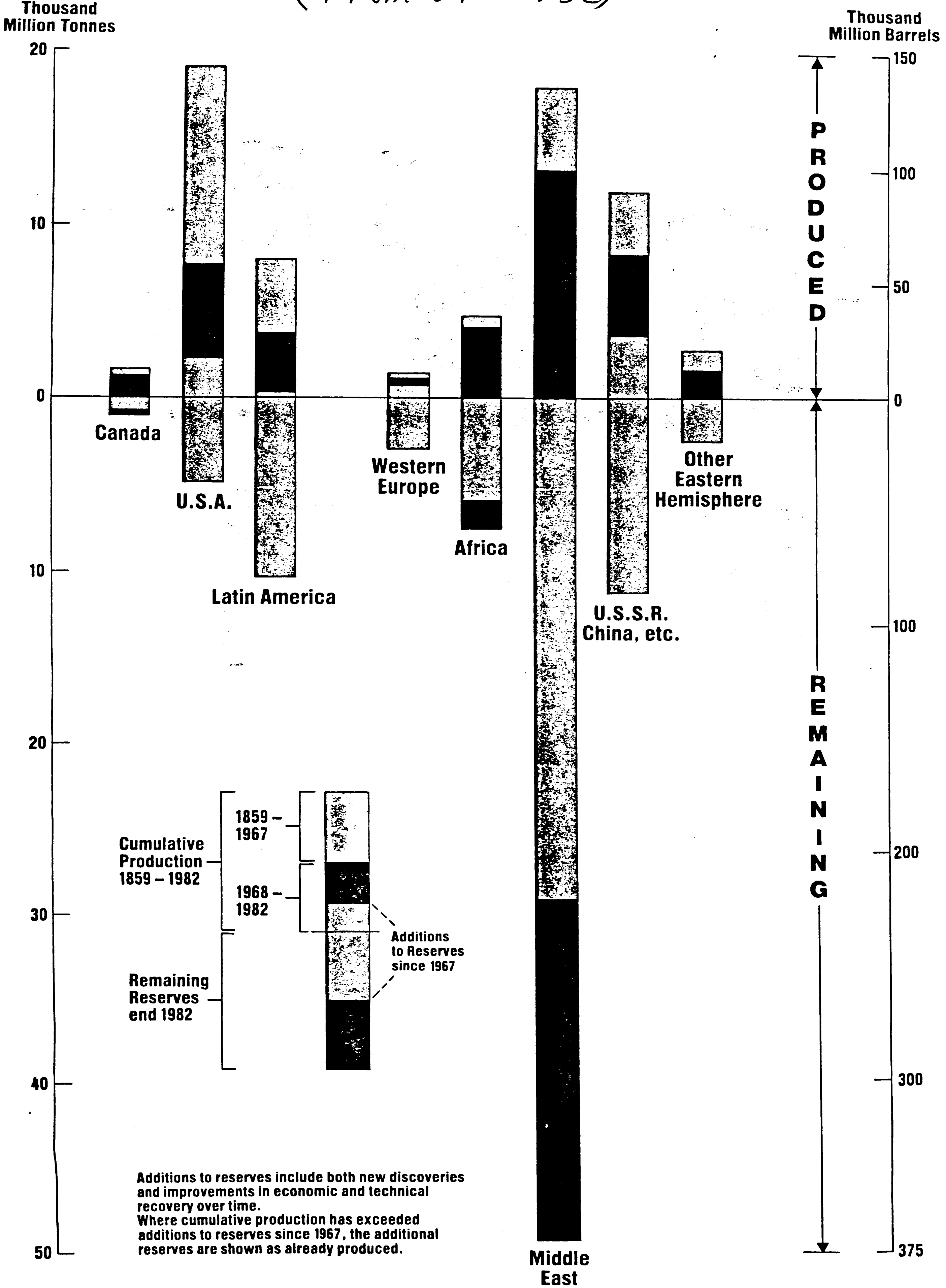


FIG 5.2 THE McKelvey BOX, For ~~classifyin~~ categorizing Reserves and resources

Total Discovered Oil 1859-1982

(From BP 1982)



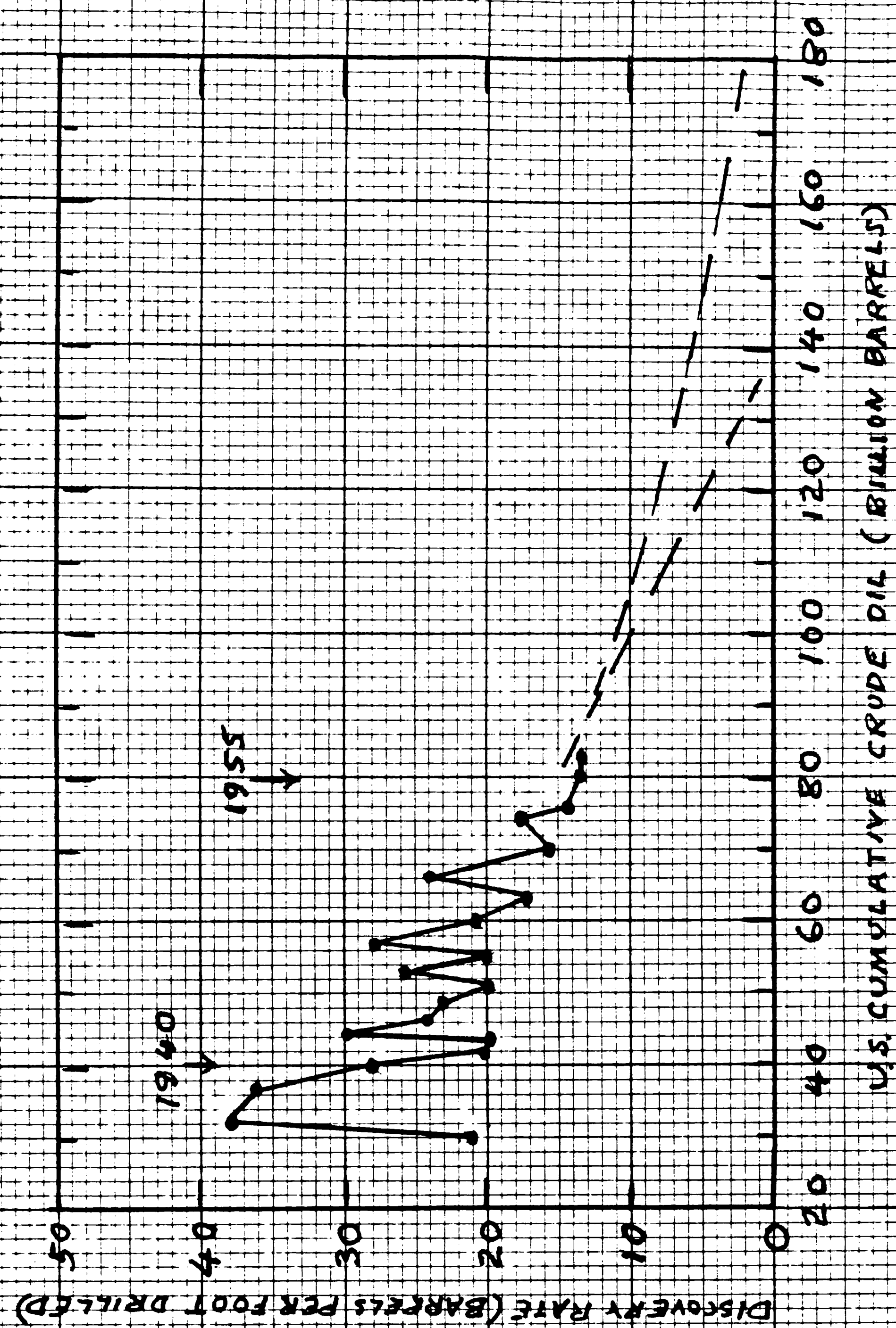


Figure 5.4 Extrapolation of oil discovery rate in the U.S. (after Davis 1958)

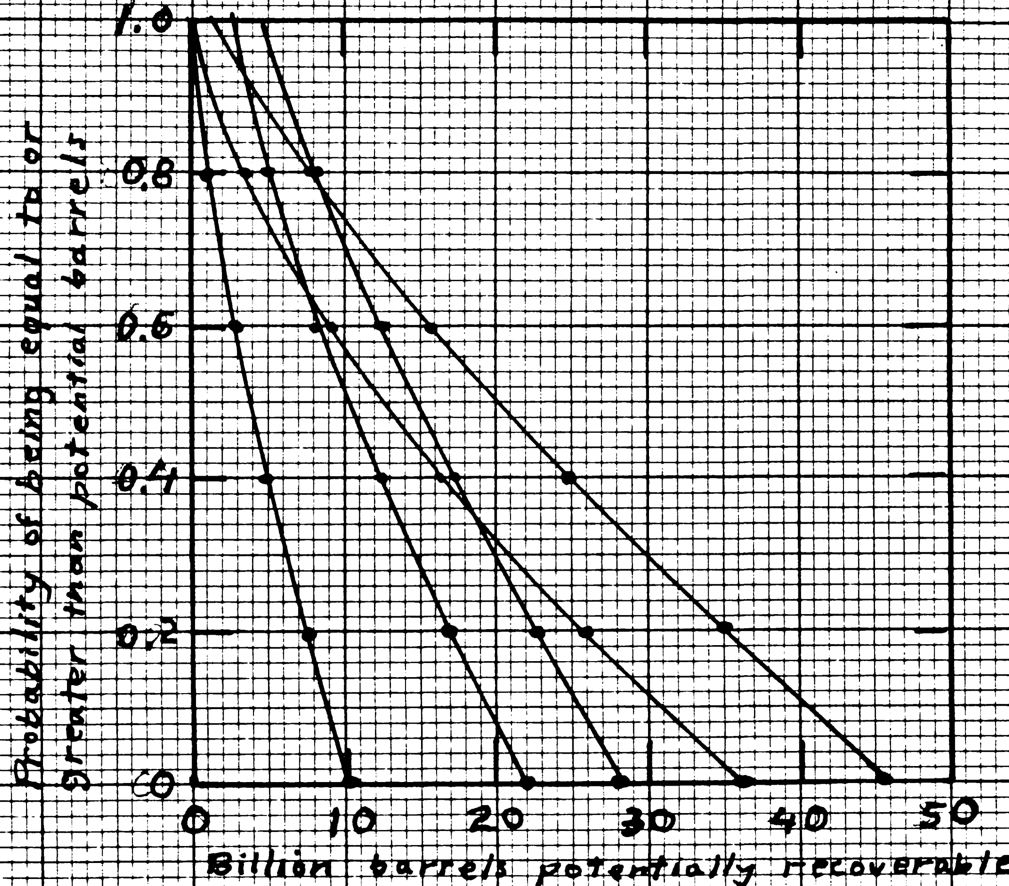


Figure 5.5 Delphi estimation: five opinions about a (hypothetical) ultimate yield.

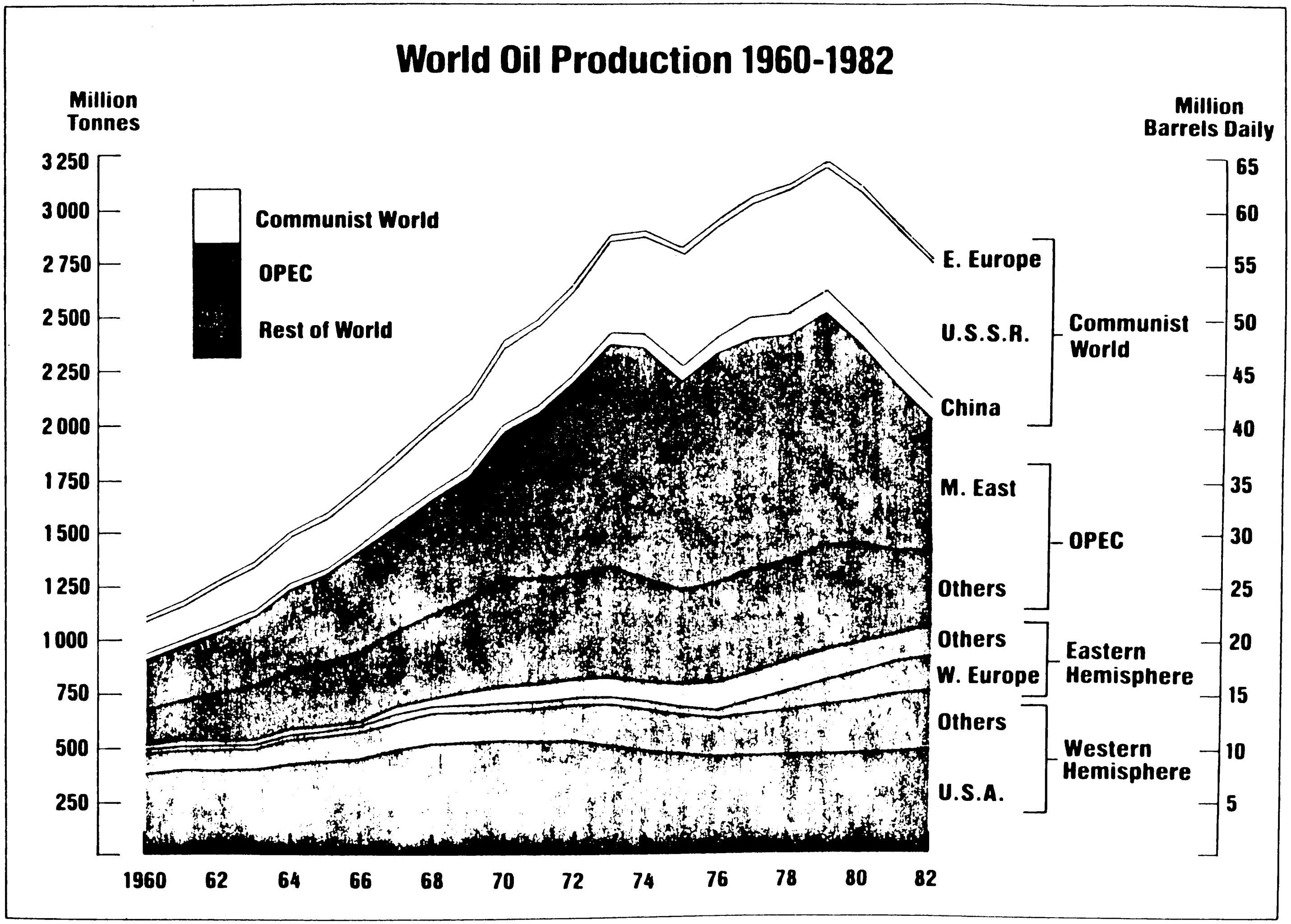


Fig 5.6 From (BP 1982)

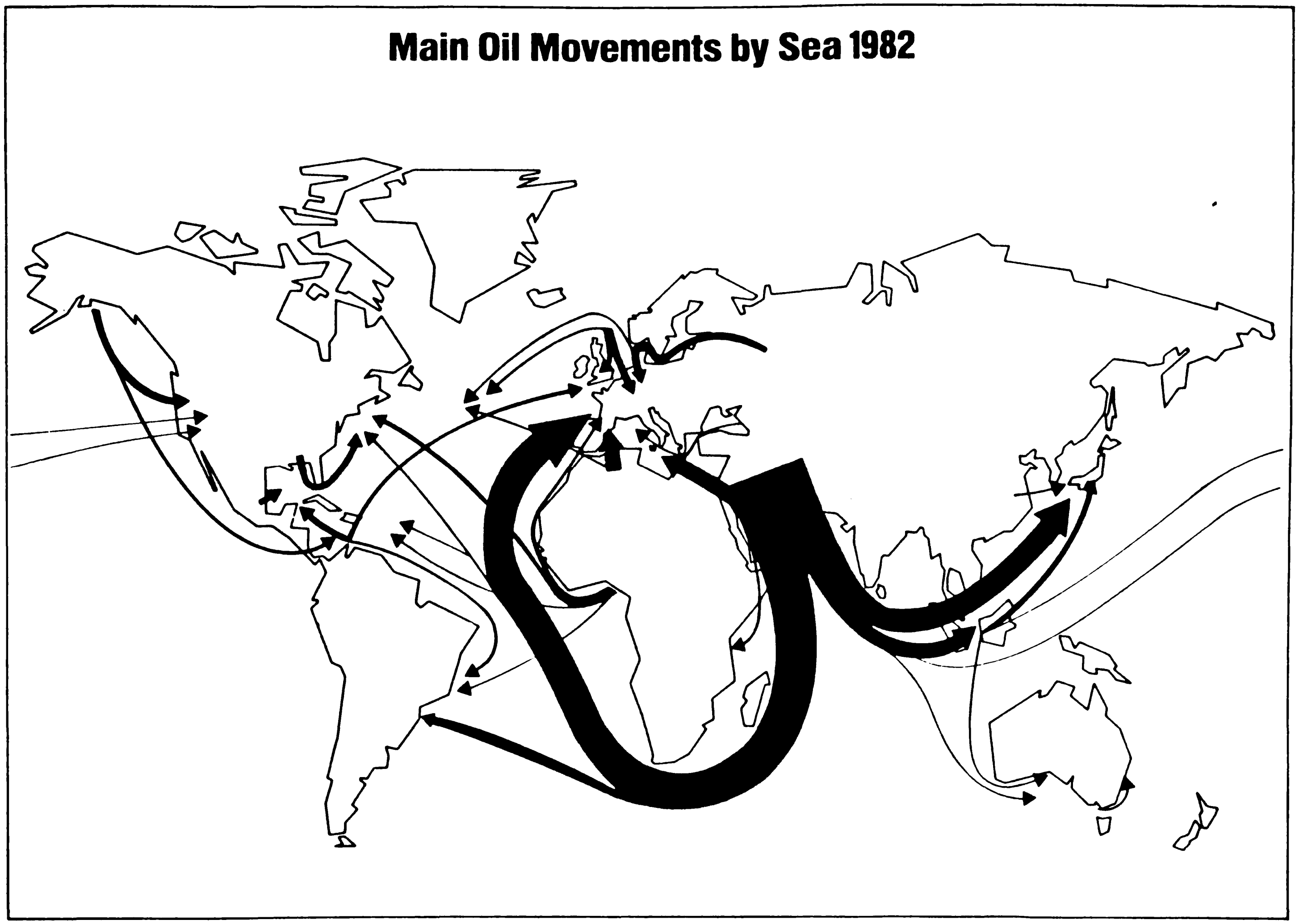


FIG ~~5.6~~ 5.7 From (BP 1982)

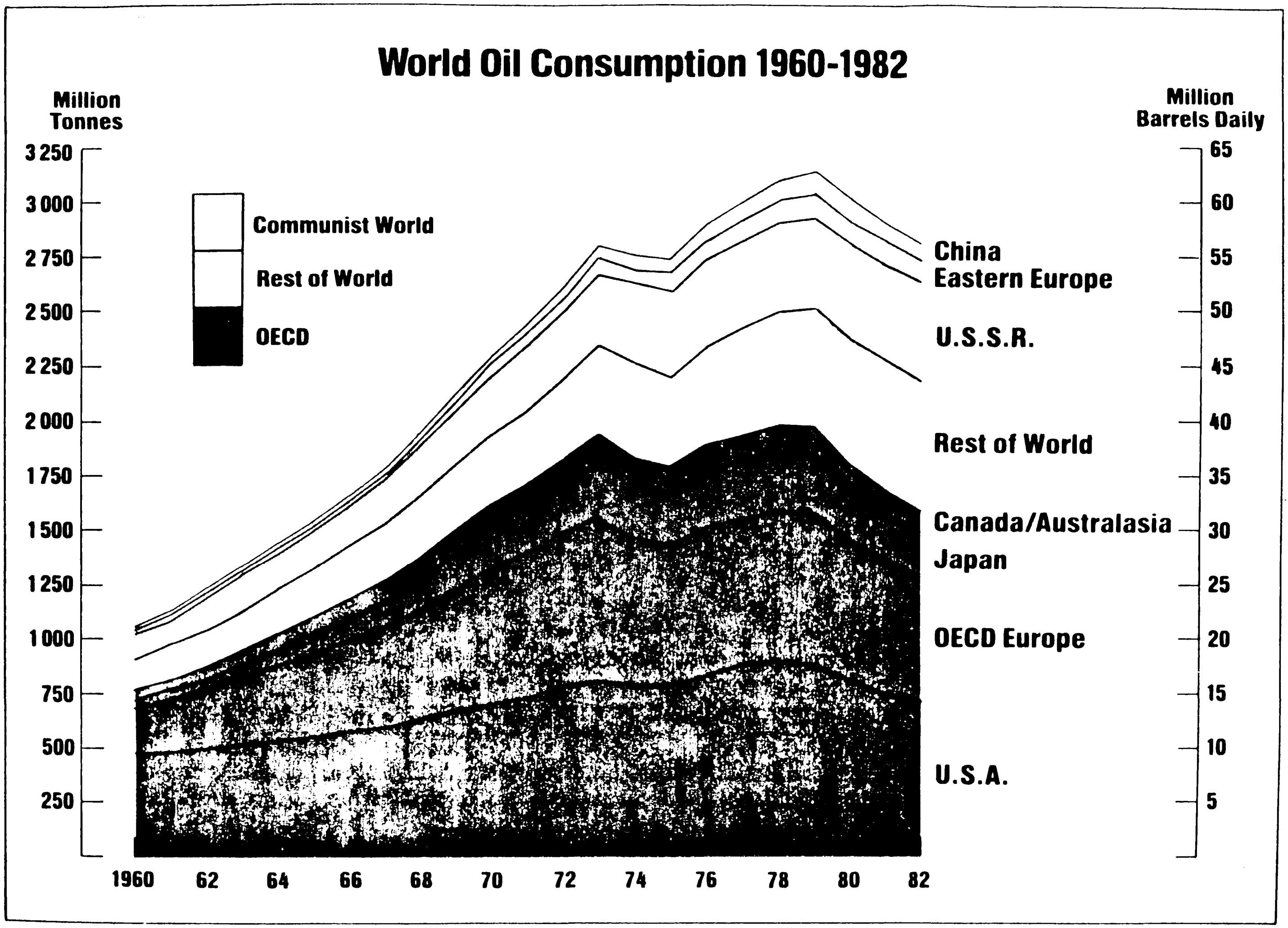
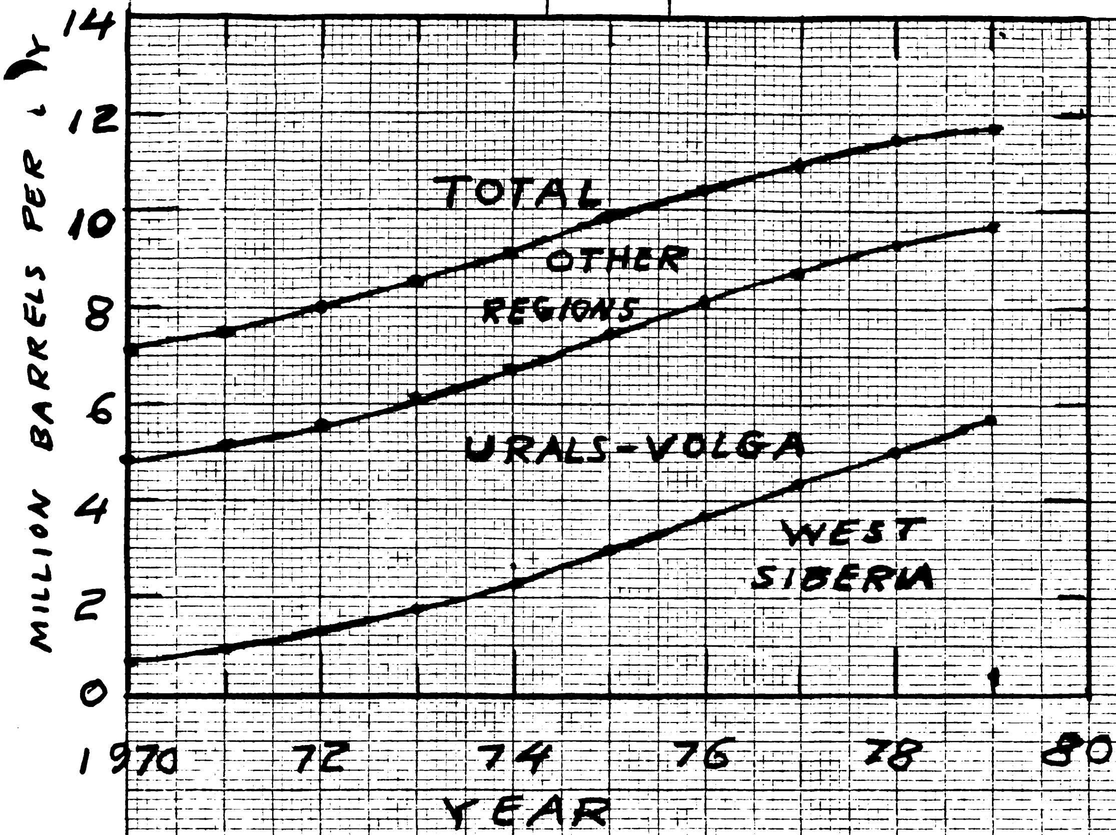


Fig. 5.8 From (BP 1982)

ISSUE | DRAWN | ENGR | TITLE | BELL TELEPHONE LABORATORIES INCORPORATED | NO. OF SHEETS PER SET | SEE SHEET 1 | SHEET



USSR CRUDE OIL PRODUCTION 1970-79, INCLUDING NATURAL GAS LIQUIDS (≈ 2% of total)
SOURCE: INTERNTIONAL ENERGY STATISTICAL REVIEW, ER IESR 80-009 27 MAY 1980, US CENTRAL INTELLIGENCE AGENCY

FIG. 5.9

PRINTED IN U.S.A.

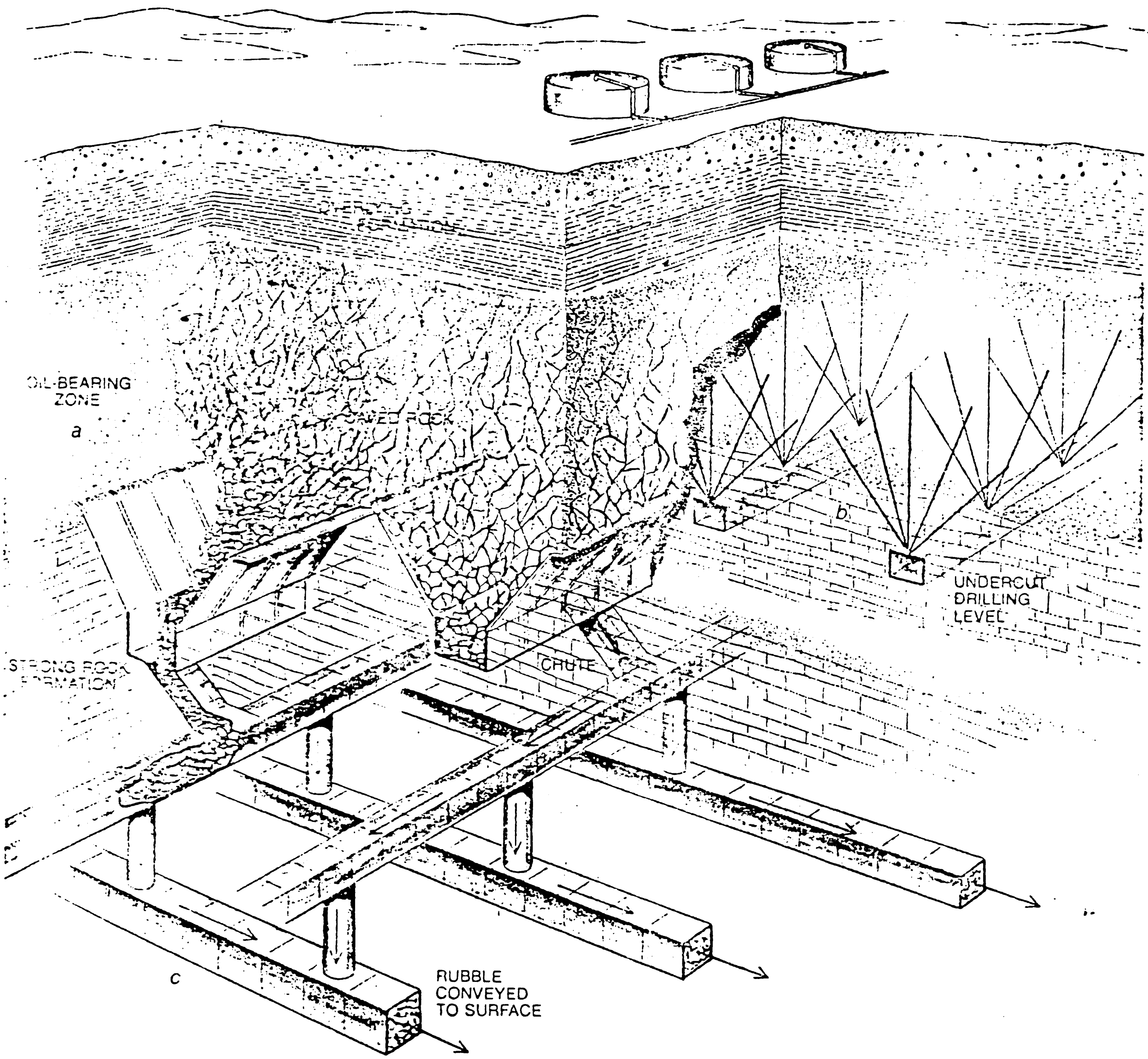


Figure 5.10 A proposed scheme for mining oil from weak rock, by stoping. From Richard A. Dick and Sheldon P. Wimpfen "Oil Mining" in Sci. Amer. vol. 243 No. 4 (October 1980) pp. 182 et seq.

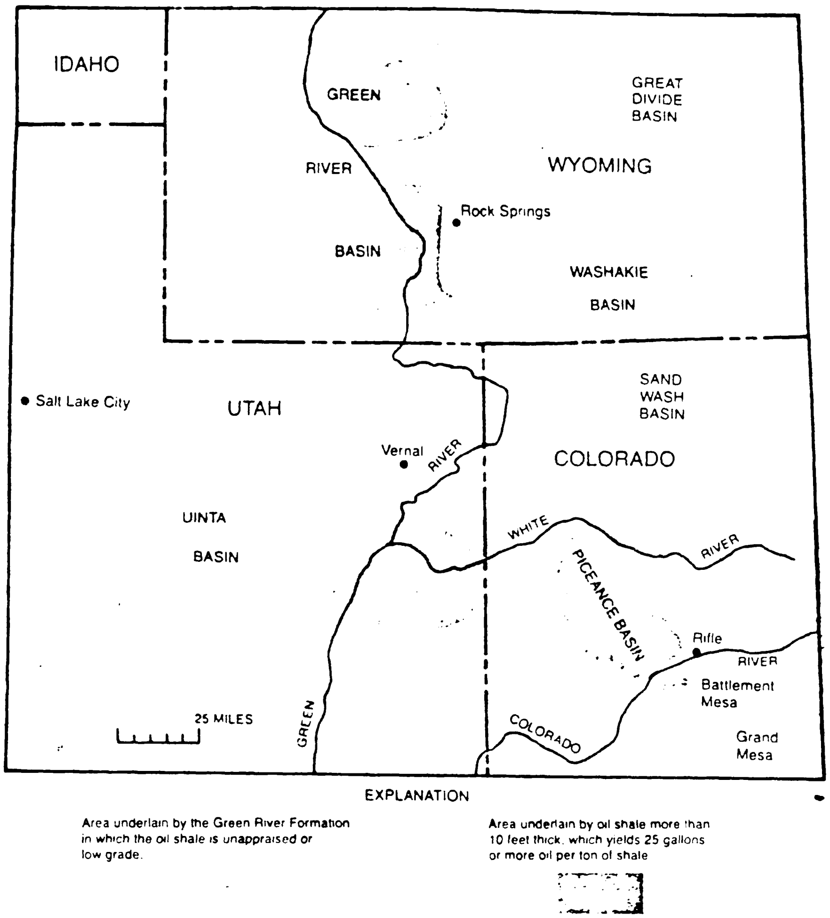


Figure 5.11 Oil shale deposits in the Green River Formation. From D. C. Duncan and V. E. Swanson Organic-Rich Shales of the United States and World Land Areas, U.S. Geol. Survey Circular 523 (1965); as reprinted in An Assessment of Oil Shale Technologies, U.S. Congress Office of Technology Assessment Summary Report OTA-M-117 (June 1980).

TABLE 5.1

PUBLISHED PROVED RESERVES AT END OF 1983

Country/Area	OIL 10^9 Tonnes	OIL Share of Total %	OIL R/P Ratio	NATURAL GAS 10^{12} $Meter^3$	NATURAL GAS Share of Total %	NATURAL GAS R/P Ratio
U.S.A.	4.4	5.1	9.1	5.6	6.2	12.5
Canada	1.0	1.2	14.3	2.6	2.8	36.2
Total North America	5.4	6.3	9.8	8.2	9.0	15.7
Mexico	6.7	7.1	45.7	2.1	2.4	61.3
Venezuela	3.6	3.7	37.1	1.5	1.7	89.2
Other Latin America	1.1	1.3		1.6	1.8	
Total Latin America	11.4	12.1	35.3	5.2	5.9	67.8
Total Western Europe	3.2	3.5	18.7	4.5	4.9	27.9
Abu Dhabi	4.0	4.5	*	0.6	0.6	93.4
Iran	7.0	7.5	55.3	13.6	15.1	*
Iraq	5.8	6.3	*	0.8	0.9	*
Kuwait	8.8	9.4	*	0.9	1.0	*
Saudi Arabia	22.6	24.6	86.9	3.4	3.8	*
Other Middle East	2.1	2.2		2.6	2.8	
Total Middle East	50.3	54.5	85.1	21.9	24.2	*
Algeria	1.2	1.4	27.4	3.1	3.4	*
Libya	2.8	3.1	54.4	0.6	0.7	*
Nigeria	2.3	2.4	36.9	1.0	1.1	*
Other Africa	1.3	1.5		0.6	0.7	
Total Africa	7.6	8.4	33.2	5.3	5.9	*
Total Asia & Australasia	2.6	2.8	18.0	4.5	4.9	67.4
Total NCW	80.5	87.6	40.0	49.6	54.8	55.1
Centrally-Planned Economies (CPEs)						
China	2.6	2.8	24.6	0.9	0.9	71.9
USSR	8.6	9.3	13.9	39.6	43.8	74.0
Other CPEs	0.3	0.3	15.6	0.5	0.5	14.0
Total CPEs	11.5	12.4	15.5	41.0	45.2	70.5
Total World	92.0	100.0	33.4	90.6	100.0	61.1
of which OPEC	61.0	66.1	68.1	28.8	31.8	*

* Over 100 years

Adapted from (BP 1984)

TABLE 5.2
OPEC RESERVES AND PRODUCTION, 1979*

[redacted]

Country	Reserves in Billion Barrels	1979 Crude Oil Production in Million Barrels Per Day	(Reserves) / (1979 Production) Years
Saudi Arabia	163.4	9.245	48.4
Iraq	31.0	3.435	24.7
Iran	58.0	3.035	52.4
United Arab Emirates	29.4	1.835	43.9
Kuwait	65.4	2.215	80.9
Algeria	8.4	1.025	22.5
Ecuador	1.1	.215	14.0
Gabon	.5	.205	6.7
Indonesia	9.6	1.590	16.5
Libya	23.5	2.065	31.2
Nigeria	17.4	2.305	20.7
Qatar	3.8	.505	20.6
Venezuela	17.9	2.355	20.8

* TAKEN FROM (OTA 1980a)

TABLE 5.3

[redacted]

ULTIMATELY RECOVERABLE WORLD CRUDE OIL RESOURCES ~~**~~, BILLIONS OF BARRELS**
FROM (OTA 1980 a)

	Known	Additional Recovery[1]	Additional Recovery[1] & New Discoveries	Ultimately Recoverable Estimate (†)	Cumulative Production Through 1975	Remaining Resource**
North America*	179.8	43-95	100-200	280-380 (315)	122	160-260
South America	68.4	20-40	52-92	120-160 (174)	41	80-120
Western Europe	24.6	5-10	25-45	50-70 (69)	3	50-70
Eastern Europe/ Soviet Union	102.4	20-40	63-123	165-225 (500)	51	110-170
Africa	75.6	15-30	45-94	120-170 (163)	21	100-150
Middle East	509.9	250-400	350-630	860-1140 (630)	85	780-1060
Asia/Oceanic	50.8	15-25	54-104	105-155 (129)	13	90-140
Unspecified	X	50-90	X	X (20)	X	X
Total**	1000	420-730	700-1300	1700-2300 (2000)	336	1360-1960

** May not add due to rounding

1 In known fields

* (includes Mexico)

Source: Nehring: Giant Oil Fields and World Oil Resources, Rand Corp., June 1978, p. 88.

(†) Figures in Parentheses from [redacted] (Moody & Geiger 1975)

Free World Crude Oil Production, Including Natural Gas Liquids

Thousand b/d

	1973	1976	1977	1978	1979
Free World	48,430	47,655	49,310	49,275	51,500
Non-OPEC Producers	17,120	16,490	17,550	18,815	20,030
United States [1]	10,950	9,735	9,800	10,265	10,205
Canada	2,120	1,585	1,610	1,580	1,785
Mexico	525	895	1,085	1,330	1,610
Norway	30	300	300	390	445
United Kingdom	5	260	800	1,120	1,615
Other	3,490	3,715	3,955	4,130	4,370
OPEC	31,310	31,165	31,760	30,460	31,470
Algeria	1,100	1,085	1,165	1,260	1,275
Ecuador	210	185	185	200	215
Gabon	150	225	220	210	205
Indonesia	1,340	1,515	1,695	1,665	1,630
Iran	5,900	5,930	5,705	5,285	3,045
Iraq	2,020	2,415	2,355	2,565	3,445
Kuwait [2]	2,815	1,960	1,840	1,970	2,340
Libya	2,210	1,975	2,105	2,025	2,105
Neutral Zone [3]	525	465	390	475	565
Nigeria	2,055	2,070	2,085	1,895	2,305
Qatar	570	505	450	490	515
Saudi Arabia [2]	7,425	8,530	9,230	8,315	9,525
United Arab Emirates	1,535	1,935	2,015	1,860	1,865
Abu Dhabi	1,305	1,585	1,665	1,465	1,485
Dubai	230	310	320	375	365
Sharjah	...	40	30	20	15
Venezuela	3,455	2,370	2,320	2,245	2,435

[1] Beginning in 1979 US natural gas liquids production data are being reported by the Department of Energy on a different basis and are not directly comparable to pre-1979 data.

[2] Excluding Neutral Zone production.

[3] Production is shared about equally between Saudi Arabia and Kuwait.

SOURCE: INTERNATIONAL ENERGY STATISTICAL REVIEW, ER IESR 80-009 27 MAY 1980, US CENTRAL INTELLIGENCE AGENCY

TABLE 5.4

TABLE 5.5

FUTURE PETROLEUM PRODUCTION RATES IN INDUSTRIALIZED/DEVELOPED COUNTRIES OUTSIDE THE CENTRALLY PLANNED ECONOMIES MILLION BARRELS/DAY. FROM (OTA 1980a)

	YEAR 1979	1985	1990	1995	2000
UNITED STATES Production arising from:	10.2	7.2-8.6	5.3-7.6	4.3-7.1	4.0-7.0
Primary and secondary recovery from existing 1979 reserves	8.1	4.7	2.7	1.4	0.8
Primary and secondary recovery from addition to reserves	-	0.8-1.5	0.8-2.1	0.7-2.4	0.7-2.5
Natural gas liquids	1.7	1.2-1.5	1.1-1.4	1.1-1.3	1.0-1.25
Production from enhanced recovery techniques	0.4	0.5-0.9	0.7-1.4	1.1-2	1.5-2.5
CANADA	1.8	1.6-1.8	-	-	1-2
NORTH SEA	2.1	2.8-4			1.7-3
OTHER INDUSTRIALIZED COUNTRIES	0.8	0.8			0.8
TOTAL (may not add due to rounding)	14.9	13-15.5			7.5-13

Table 5.6 From (BP 1984)

Natural gas / Consumption million tonnes oil equivalent

† Less than 0.05	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	**1983**	Change 1983 over 1982	1983 Share of total
North America													
USA	562.5	541.4	498.4	508.8	498.0	500.7	516.4	507.1	495.1	459.2	**432.3**	− 5.9%	32.5%
Canada	41.8	42.2	43.1	46.1	45.9	47.3	50.1	49.3	47.8	48.9	**46.7**	− 4.3%	3.5%
Total North America	604.3	583.6	541.5	554.9	543.9	548.0	566.5	556.4	542.9	508.1	**479.0**	− 5.7%	36.0%
Latin America	36.5	37.8	39.2	40.5	39.6	42.3	49.1	53.0	54.4	60.0	**60.7**	+ 1.2%	4.6%
Western Europe													
Austria	3.4	3.7	3.6	4.1	4.2	4.4	4.3	4.2	3.9	3.8	**3.9**	+ 3.7%	0.3%
Belgium & Luxembourg	8.2	9.8	9.6	10.3	10.1	9.9	10.3	10.3	9.5	7.8	**8.2**	+ 4.4%	0.6%
Denmark	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Finland	—	0.4	0.7	0.8	0.7	0.8	0.8	0.8	0.6	0.6	**0.6**	− 6.5%	†
France	15.7	17.2	17.0	19.0	20.4	20.9	23.3	23.6	24.5	24.0	**24.8**	+ 3.3%	1.9%
Greece	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Iceland	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Republic of Ireland	—	—	—	—	—	—	0.3	0.5	0.9	1.4	**1.9**	+32.2%	0.1%
Italy	14.4	15.8	18.0	22.0	21.6	22.5	22.9	22.9	22.8	22.0	**22.6**	+ 2.5%	1.7%
Netherlands	32.2	32.1	33.2	33.0	33.4	32.6	33.1	30.3	30.0	30.4	**32.3**	+ 6.2%	2.4%
Norway	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Portugal	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Spain	1.0	1.3	1.3	1.5	1.4	1.5	1.4	1.8	2.1	2.3	**2.3**	+ 3.0%	0.2%
Sweden	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Switzerland	0.2	0.3	0.5	0.5	0.6	0.7	0.8	0.8	0.8	0.8	**0.9**	+21.3%	0.1%
Turkey	—	—	—	—	—	—	—	—	—	—	**—**	—	—
United Kingdom	26.1	31.8	32.9	34.6	36.9	37.9	41.9	41.4	42.4	42.2	**43.3**	+ 2.6%	3.3%
West Germany	27.0	32.5	34.4	36.3	38.9	41.7	46.2	44.4	41.4	38.0	**38.8**	+ 2.2%	2.9%
Yugoslavia	1.7	2.3	2.2	1.5	1.7	1.7	2.3	3.4	3.7	3.8	**3.9**	+ 2.0%	0.3%
Cyprus/Gibraltar/Malta	—	—	—	—	—	—	—	—	—	—	**—**	—	—
Total Western Europe	129.9	147.2	153.4	163.6	169.9	174.6	187.6	184.4	182.6	177.1	**183.5**	+ 3.6%	13.8%
Middle East	24.1	27.6	26.2	26.9	28.8	30.1	31.0	34.1	35.3	37.8	**38.5**	+ 1.9%	2.9%
Africa	3.2	3.6	4.3	5.1	6.9	11.1	16.5	17.5	19.9	18.0	**17.6**	− 1.9%	1.3%
Japan	5.3	7.0	7.7	9.3	10.9	15.8	20.3	23.4	24.2	24.7	**25.2**	+ 2.0%	1.9%
South East Asia	3.6	4.3	4.1	4.2	4.6	5.9	6.4	7.2	7.4	7.6	**7.8**	+ 2.4%	0.6%
South Asia	8.0	7.9	8.1	8.8	9.4	9.7	6.4	7.3	8.9	11.8	**13.0**	+10.2%	1.0%
Australasia	3.9	4.6	4.9	6.1	7.4	7.8	8.7	9.8	11.6	12.2	**13.4**	+ 9.5%	1.0%
Total NCW	**818.8**	**823.6**	**789.4**	**819.4**	**821.4**	**845.3**	**892.5**	**893.1**	**887.2**	**857.3**	**838.7**	**− 2.2%**	**63.1%**
Centrally-Planned Economies (CPEs)													
China	6.4	7.7	8.7	9.8	10.9	11.7	12.4	11.7	10.4	9.5	**10.7**	+12.6%	0.8%
USSR	198.8	210.8	230.0	253.1	271.2	289.2	307.0	328.0	353.7	380.0	**405.0**	+ 6.6%	30.5%
Others	42.1	46.0	51.3	57.5	58.4	60.0	61.5	64.0	69.4	70.1	**74.5**	+ 6.3%	5.6%
Total CPEs	247.3	264.5	290.0	320.4	340.5	360.9	380.9	403.7	433.5	459.6	**490.2**	+ 6.7%	36.9%
Total World	**1 066.1**	**1 088.1**	**1 079.4**	**1 139.8**	**1 161.9**	**1 206.2**	**1 273.4**	**1 296.8**	**1 320.7**	**1 316.9**	**1 328.9**	**+ 0.9%**	**100.0%**

TABLE 5.7 ESTIMATES OF GAS RESERVES AND ULTIMATE RESOURCES, 1977, ACCORDING TO (CONAES 1980)

REGION	RESERVES		RESOURCES STILL TO BE DISCOVERED.	
	~~$10^9 m^3$~~ $10^{12} m^3$	billion barrels oil equiv.	$10^{12} m^3$	billion bbl oil equiv.
I (NA)	7.76	49	43.5	274
II (SU/EE)	22.6	142	59	372
III (WE/JANZ)	5.1	32	14.5	91
IV (LA)	2.70	17.	15	94
V (Af/SEA)	3.56	22.4	12	76
VI (ME/NAf)	21.2	134	78	491
VII (C/CPA)	0.59	3.7	10	63
Total	63.5	400	232	1462

TABLE 5.8 Coal Resources and Reserves for the Seven IIASA Regions (in 10^9 tce)

Region	Coal Resources			Coal Reserves		
	Hard Coal	Brown Coal	Total	Hard Coal	Brown Coal	Total
I (NA)	1,286	1,400	2,686	122	65	187
II (SU/EE)	4,127	892	5,019	107	41	148
III (WE/JANZ)	683	80	763	117	29	146
IV (LA)	25	9.3	34.3	4.9	5.9	10.8
V (Af/SEA)	179	4.9	184	43	1.9	44.9
VI (ME/NAf)	0.4		0.4	0.2		0.2
VII (C/CPA)	1,427	13.4	1,440	99	n.a.[b]	99
Total[a]	7,727.4	2,399.6	~10,127	493.10	142.8	635.9

[a] Regional figures do not sum to totals because of rounding.

[b] Data not available.

SOURCE: Based on data from World Energy Conference (1978a).

TABLE 5.9 **The distribution of global coal resources in billions of tons of coal equivalent (10^9 tce).**

Greater than 10^{12} tce (1000×10^9 tce)		Between 10^{11} and 10^{12} tce (100 and 1000×10^9 tce)		Between 10^{10} and 10^{11} tce (10 and 100×10^9 tce)		Between 10^9 and 10^{10} tce (1 and 10×10^9 tce)	
USSR	4860	Australia	262	India	57	GDR	9.4
US	2570	FRG	247	South Africa	57	Japan	8.5
China	1438	UK	163	Czechoslovakia	17.5	Colombia	8.3
		Poland	126	Yugoslavia	10.9	Rhodesia	7.1
		Canada	115	Brazil	10	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia	3.7
						Hungary	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2.0
						Romania	1.8
						Bangla Desh	1.6
						Venezuela	1.6
						Peru	1.0

From (Häfele et al 1980)

TABLE 5.10 Estimated Recoverable Fossil Fuel Resources (From Häfele et al 1980)

Type	Amount (TWyr)	Comments
Conventional oil	420	Includes anticipated additions to reserves via secondary recovery, off-shore exploration, and exploitation of smaller fields.
Unconventional oil	420	Heavy oil and tar sands; must be processed before "oil" is recovered.
Shale oil	60	A huge resource, but one whose exploitation has possibly insurmountable environmental problems.
Natural gas	350	Requires heavy investments to deliver to consumers (e.g., new pipelines, liquified natural gas, supertankers).
Coal	2,400	About half in easily recoverable formations; perhaps an additional 1,200 TWyr, beyond the 2,400 TWyr listed, could be obtained from exotic deposits (i.e., permafrost areas).
Total	≐3,650	Less than half is in "cheap to recover" formations or locations.

CORRECTIONS

CHAPTER 6

COAL AND ITS DERIVATIVES

6.1 INTRODUCTION AND OVERVIEW

Coal is the most plentiful of all "conventional"* fossil fuels in the United States and around the world; its distribution is uneven. U.S. coal resources exceed oil resources by about a factor of ten, and U.S. natural gas resources by a less certain but probably comparable factor. Removing it from the ground is, on the whole, not technically difficult; and these several attractions have stimulated the U.S. government and many other public and private organizations to plan large increases in the use of coal during the coming years. The 400-500 billion tons of economically and technologically available reserves in the U.S. would last 600 years at present rate of use, and an estimated 4 trillion tons of ultimate resource would last much longer. The U.S.S.R. and China are comparably rich in coal; Australia, Indonesia, India and other countries have large or at least substantial deposits, so for some countries at least, raw availability is no problem. But for reasons to be given shortly, the actual increases will be more modest than have recently been prophesied.

There are many kinds of coal: low ash (less than 5%, for example) and high ash (20% or more); anthracite (nearly pure carbon), bituminous (with more bound hydrogen), sub-bituminous, lignite; heating values from 25 million BTU/ton (bituminous) to half that value (many lignites); coal suitable for metallurgical use (a premium grade) and coal not so suitable; low sulfur (less than 1%) and high sulfur (up to 7%); coal that cakes when heated in a retort (e.g., to gasify it) and coal that does not.

Many of these differences depend on how coal was formed from its original plant material. Coals in the Eastern United States are relatively old, and came from debris in shallow seas. Therefore they tend to incorporate sulfur once contained in dissolved salts, and to have undergone extensive transformation from the original material; nearly all of it is bituminous, with a little anthracite. Coals in the Western states were more recently formed, mostly in fresh-water swamps; therefore they contain less sulfur, generally more ash (from original mud), and are mainly sub-bituminous or lignite.

Almost all were formed before the present Atlantic Ocean existed, before the age of great dinosaurs, and long before the tectonic plate motion that thrust up the Rocky Mountains, the Alps, and the Himalayas. The coal-fields of Pennsylvania have cousins in Scotland; Chinese coal differs from Indian coal because, as with Eastern and Western coal in the U.S., they were formed continents apart in space and aeons apart in time.

This variety prevents simple categorization, or oversimplistic generalizations about how it can be used. Nevertheless, a great deal of "average" bituminous coal in the U.S. contains about 2.5% sulfur, 5-10% ash; it has no true chemical composition, but can be revealingly categorized as containing one part carbon, 0.8 parts hydrogen, 0.2 parts oxygen (i.e., $C_{1.0}H_{0.8}O_{0.2}$), plus as many as 50 trace elements ranging from relatively benign (such as sodium and chlorine) to not so benign (such as arsenic and mercury).

A "coal molecule," derived chiefly from vegetable material (the structure of 200-million-year-old leaves can often be seen in it) may consist of dozens of six-atom carbon rings, mostly unsaturated (i.e., the carbon atoms are joined by multiple bonds which, on being easily disturbed, become sites for active chemical addition). Prototypical is the benzene ring, C_6H_6, in Figure 6.1, so common a structure that organic chemists replace it with the abbreviation on the right, with hydrogen atoms assumed to occupy the valence sites of the tetravalent carbon not otherwise shown. These rings and other simple structures link in various ways, add polyatomic side chains, sometimes have sulfur or nitrogen in place of carbon, and form "molecules" usually weighing several thousand Daltons. A typical coal molecule could contain any or all of the complex structures shown in Figure 6.2.

Heat, solvents, catalysts and other chemical manipulations can break these molecules into fragments, for example into anthracene and phenol, often leaving free radicals at the severance points. For example, bonds connecting oxygen to other atoms tend to break at temperatures of 300-500°C, yielding simple and fused ring structures. These fragments can re-form in various ways. We already see in this brief vignette the origin of many problems and possibilities about coal: a source of organic material for this and future civilizations, its complex chemistry, and--related as it is to organic structures in living things--its potentially high biologic activity. All these matters are alas imperfectly understood.

Direct combustion of this coal mainly involves problems of preventing excess emission of particulates (mainly from the ash), sulfur oxides, nitrogen oxides, and trace elements. Making synthetic fuels from coal generally involves adding hydrogen to it, invariably from water, and almost invariably by oxidizing some of the excess carbon to obtain the necessary reaction energy. This need for hydrogenation is evident when we note that liquid petroleum hydrocarbons have the approximate C/H ratio corresponding to CH_2, and natural gas is methane (CH_4). If coal in situ had that much hydrogen, it would have been petroleum or natural gas. Hexane is a common light fraction of petroleum, but it and other long-chain hydrocarbons are more rare in coal. Making synthetic fuels from coal also involves removing unwanted trace elements, and generally a complex reforming of organic molecules (phenols, alkanes, etc.) that are also unduly noxious.

All these problems stimulate increasing interest in basic research programs to study coal and what happens to it. Chemists and even physicists become seriously interested as realization of the complexity grows (APS Study Group 1981).

6.2 HOW MUCH COAL WILL BE USED?

Conventional wisdom about the demand for coal fluctuated wildly between the 1960s, when coal was largely neglected in the OECD nations, and the 1970s, when it was seen as an over-simple answer to U.S. energy needs, and the 1980s, when some better perceptions appear.

The World Coal Study (WOCOL)(Wilson 1980) and projections by the International Institute for Applied Systems Analysis (Häfele 1981) represent typical recent work. These are not predictions, but "if-then" scenarios: e.g., if energy demand grows at some particular rate, and if prices and constraints are also set, then the coal (and oil, etc.) demands are figured. Because rates, prices and constraints are not very predictable, the authors usually show several scenarios, along with the defining circumstances. The World Coal Study, figuring that coal use will probably increase somewhere between 3.2 and 5.0%/year in the OECD countries as a whole, shows total OECD requirements growing from 990 million metric tons coal equivalent (mtce, e.g., all coal figured on an energy basis, at about 25 million BTU/ton), or 24.8 quads, to between 2000 ~~or~~ and 3025 mtce (50, ~~or~~ 76 quads) in year 2000. U.S. domestic requirements on this basis would grow from 509 mtce (12.8 quads) in 1977, to between 655 ~~or~~ and 725 mtce (16.4 ~~or~~, 18.2 quads) in 1985, and between 1075 ~~or~~ and 1700 mtce (27, ~~or~~ 42.5 quads) in year 2000.* The IIASA "high energy" scenario is rather similar, but their "low energy" scenario has only 2/3 - 3/4 as rapid coal growth.

The CONAES (1980) study shows many scenarios for the U.S., which are worth examining, especially in comparison with others. Total U.S. production in 1977 was 16.4 quads, of which actual domestic use came to 13 quads, corresponding to WOCOL figures. Table 6.1 shows data from several sources, with the year (in parentheses) in which it was made. The numbers without parentheses under various years 1985-2010 are the domestic coal projections, and the numbers in parentheses next to some of them--e.g., 20 (70)-- indicate the total domestic energy demand--e.g., 20 quads of coal out of 70 quads total energy demand.

All the studies show an absolute increase in coal use, and an even larger increase in the energy fraction supplied by coal, in contrast to trends prior to 1970. The CONAES Supply-Delivery Panel, considering mainly the possibilities of supply irrespective of demand, exhibit a range of numbers higher than most others, especially at later times if large amounts are to be supplied for synthetic fuels, probably as a result of strong government intervention.

The CONAES "study" scenarios attempted to relate coal and total energy demand to various national moods and futures, ranging from energy-frugal, low-growth (I_2) to energy-intensive, high growth (IV_3); almost all numbers exceeding 30 quads coal/year reflected growth of synfuels industries, e.g., 26 quads out of 60 in (III_3, 2010). The Energy Information Agency took a similar view about using much coal for synfuels in its 1978 projections.

As each year passes, the conventional wisdom changes, in general toward lower energy use. Already in 1981, the lower CONAES scenarios looked much more believable than the high ones. Why is this so? One obvious reason is the vast increase in oil prices, partly foreseen but largely ignored except a posteriori--the consequent rise in all other energy prices, and the also consequent increased effort devoted to more effective energy use. But for coal, the situation is more complicated.

First, examine the opportunities for increased use of coal, in the next decade or so. About 70 million tons (1.8 quads) went into industrial boilers in 1978; complete conversion of industry to coal where it is theoretically possible would open up a market of 500 million tons/year additional (12.5 quads/yr). But present industrial plant designs, environmental constraints and other considerations probably limit the practical possibilities to 10 - 30% of the theoretical total. Nevertheless some conversion is possible, especially with fluidized bed combustors (see Section 6.4). About 100 million tons go to making coke; increases in the those quantitites are likely to be quite modest, tied as they are to steel production and other activities not expected to grow rapidly; some are expected to shrink. Electric utilities use the bulk of the coal--about 480 million tons/yr in 1980--and major increases must come there.

The total name-plate capacity of all new coal-burning electric power plants, plus expansion of present plants, planned in 1981 to be in operation by 1986, amounted to about 130,000 electric megawatts. The average size is 400-500 MWe, but some are considerably smaller intermediate load units, so the total overall capacity is likely to be about 50%. Figuring a generous 37% overall net efficiency (allowing for scrubbers and stack gas reheat) and 25 million ~~BTU~~ Btu/ton fuel, we arrive at an extra demand of 224 million tons/year, and less if any present coal-burning plants are shut down in the meantime. Conversions (or re-conversions) from oil to coal of present plants is small (a few thousand megawatts) and is expected to remain small, because stack gas scrubbers required by present regulations cannot usually be fitted. Also, many utilities have sold their quondam coal-yards and cannot get them back. Thus, the yearly increase in coal use comes to 3-40 million tons, but not more; the 1985 total coal use is liable not to exceed 900 or 1000 million tons, before considering further limits imposed by environmental or other restrictions so far unmentioned.

Superficially, these numbers (e.g., 20 - 25 quads) seem to agree with the upper values mentioned in Project Independence 1974 (Table 6.1), but it is fortuitous. If oil prices had not risen to $35/barrel in 1980 (about $20 in 1974 dollars), present coal use would not have risen nearly so fast. Large increases in domestic oil production were forecast, making a total of domestic plus imported oil of 38-47 quads/yr (19-23 million barrels/day), numbers now seen as hopelessly overestimated, probably at any price. The M.I.T. 1974 study was similarly off the mark. So were most other studies made, even up to now.

From whence arose the large forecasts and (as we now recognize) excessive euphoria about the problems of coal? Many causes exist, of which a principal one is the relative neglect of coal technology (as compared to nuclear technology, for example) through the 1950s and 1960s. Thorough understanding of the problems and development of a major coal technology requires 20 years or so; the budget for the U.S. Office of Coal Research through the 1960s was about $10 million/yr, enough to permit a claim of active involvement, but too small either to attract enough first-rank talent or to support major programs. The rapidly increasing attention paid to coal research and technology, starting in the early 1970s, will pay off in available industrial technologies in the late 1980s or early 1990s. An energy review panel of the President's Office of Science and Technology was unable in 1972 or 1973 to obtain from the Office of Coal Research much useful information, and the coal technology part had to be prepared by others.

These misperceptions appear clearly in the Federal Energy

Administration's <u>Project Independence 1974</u> study, wherein simple supply took precedence over most other considerations, and especially in the principal working document on coal prepared for the FEA by Thompson-Ramo Wooldridge (TRW), a 4-cm-thick report that was notable for its omissions and inclusions:

- No discussion of new technology; for example, nothing on long-wall mining (see below).
- No environmental or health-impact information, except for one page on disturbed land. Air pollution is quoted as being a key constraint, with no elaboration on that statement.
- No consideration of long-range effects (e.g., acid sulfates).
- No mention of coal transportation or coal end-use.
- No analysis or comment about effects on mining communities.
- Long lists of equipment and manpower requirements for various coal-mining regions of the U.S., based on business-as-usual or accelerated production, obtained principally by multiplying 1974 use tables by assumed growth factors.

The euphoria came from a long process of selective inattention, of which the M.I.T., TRW, FEA and other reports are passing but trenchant examples. The attitudes led to assumptions of coal at $9/ton or less in future years almost everywhere (FEA 1974); but the price had already exceeded that in many U.S. locations, even then. New England paid about $40/ton in 1981 (about $25 in 1975 dollars) for coal in bulk.

Great increases were expected: 714 million tons/yr from new mines by 1985. Where it was to come from is revealing: 224 from Wyoming alone (i.e., one-third of the entire present U.S. production), 89 from Montana, 24 from Colorado, 21 from New Mexico, etc.--that is, most of it from the West.

These matters could be dismissed as history, except that plenty of information was available in the early 1970s, and criticisms such as that of the preceding paragraphs existed then; but those criticisms were mainly and selectively ignored. That legacy of oversimplification lingers on, but in more sophisticated ways, and the realization helps to avoid future difficulties.

These public assessments (or partial mis-assessments) were apparently preceded by others, done more quietly, in the early-to-mid-1960s. Leasing Federal coal lands was relatively cheap, especially through the early 1970s. Figure 6.3, from a Congressional Office of Technology Assessment Memorandum (OTA 1981), shows the number of federal coal acres under lease in the period 1950-1980. Large companies increased their holdings dramatically through the 1960s in anticipation of later action, when leases were particularly cheap and easy to get, and the process was virtually complete by 1970. In another report, the OTA (1979) concluded that coal production could be increased to about 2 billion tons/yr in the U.S. by the year 2000, but only at large costs to the public and to the industry itself. The assessment of this chapter supports that opinion.

6.3 COAL MINING, TRANSPORTATION AND CLEANING

Table 6.2 shows where U.S. coal is found, mined and consumed. Figure 6.4 shows these regions graphically, where the division between East~~ern~~ and West~~ern~~, with ~~and~~ their different coal types can easily be seen. About one-quarter of the Eastern coal reserves and one-half of the Western can be surface-mined. Surface mining is almost always cheaper than deep mining; some of the Western coal beds are 30 m thick. Those facts, plus generally low sulfur content make Western coal very attractive, at least from those points of view.

In 1920 there were about 800,000 coal miners in the U.S. who mined 650 million tons of coal. In 1968, about 140,000 mined 500 million tons, a factor of about four increase in productivity. Part of this increase arose from technical improvements in deep mines, and part arose from an increase in surface mining, from a negligible fraction in 1920 to about 50% of all coal mined in 1968. The fraction rose to 65% in the early 1980s, and is likely to level off there, partly for political reasons; regulations requiring virtually all new coal-burning utilities to install stack-gas sulfur oxide scrubbers irrespective of the sulfur content of the coal--of which more later--reduces the attractiveness of strip-mined low-sulfur Western coal, and effectively keeps Western coal out of many Eastern markets.

The 1969-1977 period was one of changing conditions for coal mining. The Federal Coal Mine Health and Safety Act of 1969, when it went into effect on July 1, 1969, caused many deep mines to close,* in order to meet the new dust standards of 2 mg/m^3 or less, and other criteria. Also, many land reclamation regulations, culminating in the Federal Surface Mining Control and Reclamation Act of 1977, brought surface mining under much more strict control. These regulations, much needed and long overdue, not only improved mining conditions and environmental quality considerably, but also lowered the mine productivity so that the 140,000 miners of the late 1960s almost doubled by 1980. Productivity dropped from 35 to 25 tons per worker-day in surface mines during that period, and from 16 to 9 in deep mines.* So many new and inexperienced workers, coupled with inadequate mine training programs, adversely affected accident rates temporarily, but much improvement is possible; the safety record of some mines owned by steel companies is an order of magnitude better than that of a few large independent ones.

6.3.1. Surface Mining

Surface mining, or strip mining, has three recognizably different modes, of which two are shown in Figure 6.5.

Open pit mining is used on more-or-less level ground. For large areas, thick seams and high production rates, drag-lines shown figuratively in Figures 6.5 a) and b) can reach out 100 m or more, and pick up 70 tons or more per bite of the shovel. Present reclamation regulations encourage and usually require segregation of topsoil and other strata, so that the land can be restored; Figure 6.5 b) shows stylistically a mode of operation practiced for years in Germany and now in the U.S.: the material from each fresh cut is used to repair the previous one, layer by layer.

On steeper ground, as in West Virginia, Kentucky and Tennessee, the strata often run horizontally for many miles like layers in an eroded layer cake, and every few hundred meters in elevation a coal layer may be found. These can be contour mined, as in Figures 6.5 c), d), and e). Coal seams only 0.3 m thick can be profitably mined this way, and 20:1 overburden/coal thickness is not too much. Rather than dumping the spoil over the bank as in Figure 6.5 d), present custom shifts toward the reclamation scheme shown in 6.5 e).

The third remaining method is principally an extension of contour mining. When the hill has been notched back in Figure 6.5 d) to the limit of economic feasibility, much coal still remains further under the hill. Then, if the strata are even enough, large augers bore as far as 100 m further in, removing yet more. However, such holes are virtually impossible to back-fill, and remain a source of oxidation, pollution and water seepage.

6.3.2. Deep Mining

Coal seams thicker than about 1.3 m can usually be mined by digging conventional shafts and tunnels, and thinner seams sometimes by variations of the auger techniques just described.

The hiterto conventional room-and-pillar technique, where the coal seam is excavated as miniature streets in a city, with the interior blocks left to support the roof, only yields 50-60% of the coal. Sometimes, some of the pillars can be mined at the end of the operation, leaving the strata to collapse behind. Machinery developed and deployed principally since 1970 can cut coal from the face of the seam, convey it from the face, and load it onto a conveyor, in one continuous operation.

Introduction of new underground coal mining methods were hampered prior to the early 1970s by the depressed state of the industry, and the general lack of attention mentioned earlier. Underground coal mining is an unpleasant occupation at best, and hazardous besides; in times of expansion and new posperity for mine operators and coal miners, more capital-intensive and man-frugal technologies find acceptance. One technique borrowed from Europe is long-wall mining, shown in Figure 6.6. Two parallel passages ("drifts") are driven in, perhaps 50 m apart, and an initial cross-connection is made. Then a cutter and a whole series of hydraulic jacks are installed across this corridor. The cutter then travels across the face of the seam, the mined coal travels by conveyor belt to the side tunnels, where another conveyor takes it toward the mine-mouth. After a cut is completed, the cutter moves back to its starting position, and the whole assembly--cutter, hydraulic jack and all--is moved toward the face. The jacks keep the roof up in the mining area, the cutter makes its next pass, and the overlying strata collapse in the mined-out area behind the jacks. This is capital intensive, but productivity per underground miner can be ten times or more as high as room-and-pillar methods.

This trend toward fully automated mines will surely continue.

6.3.3. Transportation

In the United States, about 65% of coal is transported by rail, 10% by barges on waterways, and 13% by truck, this last and most expensive mode being generally for much shorter distances, say up to 30 miles.

Truck traffic grows rapidly, but for short haul; gross weight restrictions ~~limits~~ of 35-40 t~~ons gross weight~~ limit the load to 30 tons at most, much less than can be carried much cheaper in a rail hopper car. Highway damage by one such heavy truck is equivalent to that from thousands of automobiles, hence the weight limits and concern. Truck-hauling is the most energy-intensive of all the common modes, and its market share is sustained because of easy access to small mines and small users, and routing flexibility.

Coal by rail increasingly moves by unit trains--typically a string of 100 hopper cars, each holding 100 tons, dedicated with their diesel locomotives to running continuously from mines or major coal-gathering points to large power plants or other major users. One such unit train, carrying 10,000 tons, will supply a 1000 MWe power plant for about one day. Some of the railroads in the U.S. South and Midwest are fairly well equipped for this heavy continuous high speed traffic, but other regions are not, especially the Northeast. The problems of the U.S. railroads, including the public Conrail and the still-private lines, are well known, and the tale of their past neglect is too long and complicated to recall here. But rail, especially for Western coal, is likely to remain the dominant transportation mode.

That last conclusion is selectively and somewhat speculatively tempered when we consider the case for coal slurry pipelines. The Congressional Office of Technology Assessment gives a good account (OTA 1978) which illuminates the complexities that typify so many of these energy-related risks.

Transporting coal by slurry requires first crushing it, typically to the size of rice grains or smaller, an operation which is also desirable if the coal is to be cleaned (see the next section). Thus more sophisticated uses of coal (reduced emission of pollutants, coal liquefaction and gasification, etc.) and transport by slurry pipeline often offer mutual support.

The pipeline requires approximately one ton of water per ton of coal, depending somewhat on the moisture in the coal itself, and the velocity in the pipeline is 1-2 m/s, maintained by booster pumps every 100 km or so. Thus, a pipe of moderate dimater can carry much coal. The only slurry pipeline operating in the U.S. in the mid-1980s extends from the Four Corners region of Arizona to the Nevada-California-Arizona junction, 400 km; it is 45 cm diameter, and has carried almost 5 million tons/yr since 1972.

A smaller 170-km pipeline across Ohio was closed after competing railroads introduced trains and secured rate structure from the Interstate Commerce Commission. Several much larger and linger pipelines were planned in the early 1980s, for example to carry 15 million tons/yr from Wyoming to the Gulf of Mexico, a distance of about 2000 km; but oil price reductions soon after, plus opposition by railroads, make early implementation of many of them unlikely.

Coal slurry pipelines can transport coal more cheaply than any other mode, under certain combinations of circumstances, the principal ones of which are:

--Large coal shipments from large sources to large, concentrated, secure markets.

--Long distances.

--Low real interest rates (because of the initial construction cost).

--Sufficient water at low cost.

--Low cost of electric power for pumping (compared to cost of diesel fuel for trains).

--Inadequate or inefficient railroads.

--Absence of a parallel navigable waterway.

The requirements of sufficient water and no navigable waterways may seem contradictory, but that is not necessarily true: the principal U.S. inland waterways are the Mississippi, Ohio and Tennessee Rivers, which leaves opportunities for pipelines even in the Eastern U.S., for example from Kentucky to the Virginia coast or to Florida. The Office of Technology Assessment concludes that sufficient water could be available even in Wyoming for the maximum credible pipeline traffic (125 million tons/yr); 3% of the available runoff would be required. However, water availability in the Western U.S. is bound up in legal precedents and prior allocations (mainly for agriculture) which have in fact overcommitted the Colorado River and others in the region. Thus, providing the water for pipelines in the relatively arid Western states, a significant but not prohibitively large amount, will require complicated economic and political negotiation.

At a flow rate of one ton of water per ton of coal, dewatering the coal at the terminal end is no severe problem, but cleaning it prior to discharge is more difficult. The water dissolves some noncarbon materials contained in the coal, the most toxic of which are liable to be metallic salts, particularly antimony and arsenic. Also, corrosion inhibitors added to protect the pipe, and coagulating agents used during dewatering, complicate the disposal problem.

The biggest single impediment to more slurry pipelines is obtaining right-of-way. Railroads would be expected to oppose pipelines crossing their track; also, states through which pipelines would pass (but neither originate nor terminate) find little direct advantage in permitting their presence. Eventually, new federal and state laws will probably be required, granting power of eminent domain to coal slurry pipeline enterprises, and at the same time imposing various restrictions and requirements on their activities. However, once pipelines were built, they would enjoy a considerable advantage over railroads. The pipeline is a dedicated full-operation facility; unlike railroads, it is not required to maintain uneconomic branch lines. Thus, the railroads stand to lose some of their core business, in what could be described as unfair competition; but that imbalance could be corrected by compensatory taxation.

The environmental choice between pipelines and increased rail traffic primarily involves water use and pipeline construction activities, against the various disadvantages of increased rail traffic. All other environmental impacts seem relatively small. It is worth noting that environmental impact statements are generally not required for new facilities, in this case pipelines.

Contrary to some popular misconceptions, the energy required to run a coal slurry pipeline usually exceeds that used in barge or even rail transport, per ton of coal moved. However, this energy cost is usually a small fraction of the energy in the coal; the pipeline's principal advantage is the advantage of all pipelines--automatic operation, simple control, low maintenance, high volume.

6.3.4. Cleaning

Increasing demand since the 1960s for cleaner use of coal led to new regulations, tax incentives and technology in the 1970s to clean up combustion effluents. Many of the same results could be obtained by cleaning the coal first, but equivalent action came only several years later. One reason was that the coal users, principally electric utilities, were publicly visible, could pass on costs to the electric consumers, and were technologically and managerically more advanced tham most coal producers in the early 1970s. Also, until that time, coal producers thought they had to compete with cheap oil, and did not favor activities that would raise coal costs.

Those circumstances changed in the late 1970s; tax and investment incentives are available for cleaning the coal prior to combustion, as well as after. The technology is not particularly difficult. In many coals, especially high-sulfur ones, half the sulfur is not bound into the coal molecules, but comes via pyrite inclusions, both in the coal and in the ash. The pyrites and ash are generally both heavier and harder than the coal. Thus, typically the coal is crushed, and sizing screens sort out large lumps from small.

Almost half the coal cleaning in the U.S. proceeds by way of jigs, in which the coal and refuse rest on a screen, then are levitated by pulsed water jets from below. The lighter coal tends to rise to the top, and the refuse tends to sink. Both this and an air-operated jig were first invented more than a century ago.

Flotation in heavy liquids, often in a cone cyclone to augment gravity by centrifugal forces, separates heavy from light particles more precisely. The liquid, usually a suspension of finely ground magnetite in water, can easily be adjusted to be intermediate between that of the coal and the refuse.

Inefficient crushing can produce up to 25% of fine coal particles too small to be cleaned or even retained by these techniques. Better crushers produce less unwanted fines, but need will persist for a way to catch and clean them. Among various techniques, froth flotation is a favorite; oil added to the dry fines sticks to the coal preferentially; then, when the mixture is placed in water in a froth flotation tank, the wet refuse sinks, and air bubbles stick to the coal and carry it out the top.

Another technique, in the early experimental stage in 1980, involves passing the crushed coal plus pryritic inclusions on a conveyor through a strong magnetic field. The pyrites, being weakly magnetic, are held up and the coal falls through a screen. The pyrites fall out later into a separate place as the conveyor leaves the high-field region. Here we see a synergistic technological benefit. Superconducting magnets, operating with only a refrigeration energy loss, might make the scheme practical; normally conducting magnet coils, with their high electric energy losses, could never be used. Experiments along this line proceed at the Oak Ridge National Laboratory.

In 1980, about 25% of all U.S. coal was pre-cleaned; the fraction rises, at modest investment cost. Depending on the coal, size of operation, and the degree of cleaning required, coal cleaning equipment costs between \$3000 and \$30,000 per ton per hour of coal capacity (EPRI 1979a). That comes to \$4-40 per thermal kilowatt, a relative bargain compared to most post-combustion cleanup installations.

6.4 TECHNOLOGY FOR BURNING COAL

Coal dust, or grain elevator dust, or a handful of flour, when thrown into the air, can explode, a continual hazard in coal mines, grain elevators, and flour mills. Blown in through a nozzle, coal dust will burn like a gas.

6.4.1. Conventional Powdered Coal Combustors

Thus arose the common present generation of large tangentially fired boilers--called tangential because the coal and air are blown in that way to set up circumfrential internal circulation and proper mixing. The hot gas heats water and steam in large arrays of tubes at the top of the boiler. The installations, per unit of power, are larger than equivalent oil or gas-fired ones, a fact which hinders conversion of oil or gas systems to coal, and which was overlooked in many estimates made in the early-to-mid 1970s.

The advantages of these powdered-coal burners are low cost and a well-developed technology. The main disadvantage is lack of pollution control. Seventy percent of the ash goes up the stack, where it must be recovered by electrostatic precipitators or large bag filters: the fine, almost invisible part of this ash--smaller than three microns, say--constitutes a small fraction of the weight but most of the particles, and has most of the surface area. It is harder to catch than the larger particles, and biologically more dangerous because it is too small to be filtered out on the way to people's lungs. Furthermore, it adsorbs sulfur oxides and other effluents from the burning, especially because of its large surface area per unit mass, and aggravates the environmental and health consequences. These disadvantages, little anticipated prior to 1970, now weigh heavily against these conventional combustors and cause large post-cleanup costs. Section 6.7 contains more information about particulate emission and cleanup efficiencies.

6.4.2. Fluidized-Bed Combustors

Imagine a vertical pipe, several times longer than its diameter, with a fine screen at the bottom, filled one-tenth full of sand. Blow air in at the bottom gently, and it only percolates without disturbing anything. Too much air blows the sand out the top. At intermediate air flows, the sand becomes levitated in the stream, well mixed and turbulent, a fluidized bed, a phenomenon discovered by Fritz Winkler in Germany in the 1920s as he attempted to gasify coal, then exploited by the oil refining industry, and now re-adopted by the coal burners. Figure 6.7 shows the basic components. The bed is mostly ash, with a little coal added more or less continuously. The advantages are:

- Low combustion temperature, typically 850°C, too low to form nitrogen oxides from air and atmospheric nitrogen (however, nitrogen contained in the coal still forms oxides). The temperature is also too low to melt the ash, which is not the case with tangentially fired boilers.
- Low vapor pressure of alkali metal sulfates, chlorides, etc., enabling most of these potentially polluting constituents to remain in the bed.
- The opportunity to add crushed limestone to the bed, to absorb sulfur oxides (forming calcium sulfite) and permitting much of the sulfur oxides to be removed with the solid ash particles, in a dry form.
- Intimate contact with steam-raising pipes, which can be immersed in the fluidized bed, or above it, or (usually) both.

o More compact than tangentially fired boilers, hence possibly less expensive.

The disadvantages are:

o Uneven mixing, a design problem which surely will be overcome.

o Severe abrasion and corrosion of internal parts, especially the steam-raising pipes. Ceramic and refractory materials can be used in many places, but metals are essential in many places also.

o Carry-over of fine ash and unburned carbon, usually solved by recirculation of larger particles from the mechanical separator (see Figure 6.7) and fabric (baghouse) filters.

The Office of Coal Research provided modest but important developmental support in the late 1960s, ~~late~~ overdue, but in time for the Foster-Wheeler Corporation to start a small power plant in 1976 and later a larger and more publicized system to produce 100,000 lb/hr of heating steam for Georgetown University in Washington, D.C. The Electric Power Research Institute cooperates with the Tennessee Valley Authority to install a 200 MWe demonstration power plant in Kentucky, whose operation will be studied closely. The Babcock and Wilcox Company provided the equipment for this installation; they and their international subsidiary plus other organizations have also operated a demonstration plant successfully in Scotland (IRD 1980).

Unit size is liable to remain not large--say 200 MWe (thermal)--because of problems of uniform feed and mixing; but this can be an advantage because units can be ganged to run in parallel and turned on and off slowly to match slow changes in demand.

Fluidized-bed combustors will surely run first at atmospheric pressure, thus avoiding the need for locking coal-feed systems and many other complications. However, research continues on pressurized fluidized-bed systems, because of potential advantages:

- o Smaller.
- o Higher efficiency, by running the combustion gas directly through a gas turbine, then using the exhaust to make steam for a steam turbine.

The second potential advantage brings further complications: erosion and corrosion of turbine blades by material carried from ~~over~~ the fluidized bed. It has been proposed to solve this by passing the hot gas through a granular filter bed inserted between the mechanical separator and the gas turbine.

But meanwhile, atmospheric fluidized-bed combustion appears very promising, and may be relatively attractive in cases where oil- or gas-fired boilers must switch to coal.

6.5 FUELS DERIVED FROM COAL

An excellent and readable review of coal science and research opportunities is given by M. L. Gobarty et al (1979) of Exxon Research and Engineering Company. Almost all large petroleum and coal companies now engage in research and development work related to topics discussed here.

Since 1800, coke-making has produced so-called town gas, a mixture of hydrogen, methane, carbon monoxide and other less-desirable products, along with various liquid and solid organic substances derived from the breakup of coal molecules. Water added to the process converted more of the carbon to CO_2 and produced more hydrogenated fractions--water gas. All this went out of fashion with the advent of natural gas--methane, CH_4--and in any event the CO, H_2S and other constituents would be environmentally unacceptable today.

As described in the introduction to this chapter, coal chemistry involves the breakup of coal molecules and, for fuels, often the addition of hydrogen to the carbon-rich substance, because liquid and gaseous fuels are usually easier to transport, meter and use than solid ones. The reaction

$$2C + 2H_2O \rightarrow CO_2 + CH_4 \tag{1}$$

is simplistically appealing, especially since the total heat of reaction is small. Unfortunately the reaction dislikes going that way, but rather in stages:

Process	Heat Input Required	
Gasification		
$2C + 2H_2O \rightarrow 2CO + 2H_2$	+ 62.76 kcal/mole at 1250°K	(2)
Shift Reaction		
$CO + H_2O \rightarrow CO_2 + H_2$	- 9.83 kcal/mole at 600°K	(3)
Methanation		
$3H_2 + CO \rightarrow CH_4 + H_2O$	- 49.27 kcal/mole at 650°K	(4)

The sum of these yields reaction (1) with a net endothermic heat of 3.66 kcal/mole. We see here the problem: the highly endothermic carbon-steam reaction proceeds only at high temperature, and is responsible for the large thermal inputs characteristic of all gasification schemes.

Hydrogen is needed for liquefication schemes also, though not in such large quantity; reaction (2) is the only way to do it from carbon, so the energy losses apply to liquefication also. Chemists search for catalysts that will make reactions like (1) proceed more easily, to produce either usable gases or liquids directly from coal, but the sulfur and nitrogen compounds, trace elements and ash in real coal deactivate most catalysts rapidly.

The chemical facts of life described in the introduction and the preceding paragraphs constrain many schemes for producing clean fuels from coal to operation at temperatures typically of 1000°C and pressures of 4000 kPa (600 psi) to obtain reasonable reaction rates in reactors that are economically small. Such pressures and temperatures combined would be no problem for modern technology, were it not for the requirements to feed coal and remove ash through pressure locks, and to deal with gases containing tars and other materials. To do all this reliably in an environment of chemically active materials is difficult.

The energy losses described in relation to reactions (2) - (4) limit most of these processes to a maximum efficiency of about 65-70%; that much can appear in the product, the rest being dissipated in the irreversible chemical processes, particularly for producing hydrogen by gasification. The economic and environmental consequences of this 50% energy loss per unit of clean energy are large.

6.5.1. Pyrolysis

This generally means destructive distillation. The principal advantage is simplicity: operation at 500-700°C and relatively low pressure. The major products are some volatile liquids and gases, plus more solid carbonaceous material called char. Most of the liquids are heavy (i.e., large molecules, and hydrogen-poor), which could easily be predicted from the general properties of coal. The liquids contain many biologically active fractions, and would require much upgrading by hydrogenation to be useful in normal commerce. Also, any pyrolysis scheme must be coupled with some way to use the char, which contains ash and many trace elements.

Pyrolysis is not now much in favor, compared to processes now to be described.

6.5.2. Gasification

Figure 6.8 shows two of the three major classes of gasifiers, schematically.* All operate with maximum temperatures 1100-1400°C, as predicted, and high pressure. They are fixed bed (the Lurgi process) and entrained flow (Koppers-Totzek), named after the developers. The other important type, the fluidized-bed gasifier, is similar in principle to Figure 6.7.

The Lurgi process is now in use in Europe, the U.S. and elsewhere. In its most common form, the combustion zone is at 1100°C, hot enough to burn some of the coal but not hot enough to melt the ash; the gasification zone is at 750°C and the top at (say) 350°C. The reactions (2) and (3) described above proceed, but methanation must generally take place in a later catalytic stage. A modification of this device is the slagging Lurgi, at higher temperature; the ash melts and re-solidifies on its way out; it may be more efficient and compact, and yield a better quality gas with less steam consumption.

The fluidized-bed gasifier is similar in principle to Figure 6.7, but with steam injection, usually no steam-raising pipes, and an output to the gas treatment equipment. With coal, it must operate in the range 850 - 1100°C to avoid melting ash.

The entrained flow scheme avoids the problem of some coal tending to cake (fuse into large lumps) at these temperatures, by working with powdered coal and having it entrained in the air (or oxygen) and steam through the entire cycle. Thus it runs typically at higher temperature, 1300°C.

The gas quality depends on whether air (cheap) or osygen (more expensive) are used. With air, the nitrogen is of course carried over, and furthermore, some nitrogen oxides will be produced (but not much at the lower operating temperatures). The atmosphere in the top of the gasifier is a reducing one, so the sulfur appears as hydrogen sulfide (H_2S), not SO_2. Almost as toxic as hydrogen cyanide (HCN) is H_2S; this is not well known since its smell tends to limit exposure. This disadvantage is more than counterbalanced by the ease with which H_2S can be removed and converted to elemental sulfur, a desirable form for disposal (or use in advantageously close industries).

If air is used in the gasifiers, the product consists of a mixture of CO, H_2, CH_4, N_2, H_2S, H_2O and some NO_x, plus other small additions. Scrubbing the gas and drying it leaves only the first four components, which chiefly because of the large N_2 component has low energy density, about 150-200 BTU/ft^3. Nevertheless, this synthesis gas is very suitable for industrial use, especially if burned in combined-cycle electric generating plants, driving a gas turbine and then raising steam for a subsequent steam turbine, as described in the fluidized bed discussion. This scheme, which promises 37-39% overall efficiency from coal to electricity is in an advanced developmental stage. In operation of 100-200 MWe units, the Lurgi system is the first to be used this way.

More oxygen and less nitrogen produces intermediate-grade gas, at higher cost, say at $5 per million ~~BTU~~ ($10^9$ joules), equivalent in cost to coal at $120/ton but with the advantage of being much cleaner. But natural gas was still cheaper in 1984. Using pure oxygen produces a gas of CO, H_2 and CH_4 which then can be methanated by reaction (4) to produce virtually pure methane, the same as natural gas.

in 1982, ~~At present (1981)~~, the Southern California Edison Company, Texaco Corp. and other companies cooperated to construct a 100 MWe combined cycle installation. A Lurgi gasifier to produce 125 million cubic feet per day of methane (equivalent to 40,000 barrels/day of oil) is planned to be built in North Dakota.

So that these simple descriptions do not leave a false sense of engineering simplicity, Figure 6.9 shows in slightly more detail, a multi-function energy plant* being designed in the early 1980s, planned for operation in southeast New England in the late 1980s. Its input would be 3.8 million tons of coal per year, the output would be 600 MW of electric power, 2500 tons of methanol per day, plus medium BTU gas and recoverable waste heat for an adjacent industrial park.

The coal arrives at the top left in the figure (probably by barge rather than rail), is ground and fed as a slurry into the pressurized gasifier shown cross-hatched in the upper middle, along with oxygen from an air liquefaction plant (not shown). The excess reaction heat raises steam for sale here and at other places shown in the diagram. Two streams emerge from the gasifier. One goes to the upper left through purifiers to the combined gas turbine-steam cycle electric generating plant. The second stream flows through various purification and methanation stages at lower left, passes through an H_2S stripper, CO_2 absorber and other purification stages, and emerges as methane and hydrogen at lower right, on its way to the methanol plant. The sulfur appears in elemental form, typically 150 tons per day from 1.3% S coal from southern Appalachia. Only the major components are shown even here, and each is itself a complicated device. The estimated cost of the plant was $2.3 billion in 1980.

6.5.3. Liquefaction

The fuel in most critical supply is petroleum, so present "synfuels" programs often refer in fact to liquefaction.

The only scheme in significant commercial use in 1981 is the relatively inefficient Fischer-Tropsch scheme, developed in Germany and used there during WWII, and now extensively by the South African Coal, Oil and Gas Corporation ("SASOL"). The coal is gasified to produce CO and H_2 by any scheme, for example the Lurgi method. The H_2 could even come from natural gas, if it should be available in excess. The CO and H_2 are then combined over an alkalized iron catalyst to produce liquids. South Africa expects to supply about half its petroleum needs in the mid-1980s with about $7 billion of such installations.

Some hot liquids derived from the coal liquefaction process can "dissolve" the coal itself, by which is meant breaking enough of the coal bonds in the "molecules" so that the whole mix becomes liquified. Thus arises the possibility of several direct liquefaction processes, which have the advantages of relatively mild conditions, high percentage conversion and higher efficiency. But the liquid, with entrained ash and other unpleasant qualities, is hard to work with.

The simplest process, solvent-refined coal I (SRC-I) by Gulf Mineral Resources Company, does not in fact produce a liquid, but rather a clean solid fuel which melts at about 180°C. A demonstration plant using 6000 tons/day of coal will cost about $1.3 billion, including its hydro-generation plant. At an equivalent output of 17,000 barrels of petroleum per day, this comes to $77,000 investment per daily barrel of capacity, a very high cost, expected to be reduced later.

The SRC-II scheme is similar, but produces liquids, and plans are underway to build a similar-size demonstration unit.

The Exxon donor solvent scheme depends on adding hydrogen to coal-solvent mixtures, heating it to 450-500°C, liquefying it and fractionating the product. The heavy fractions go into a gasifier (as in coal gasification) to produce hydrogen and other products. After recharging with excess hydrogen some of the liquid recycles as the donor solvent. A 250 ton/day plant operates at Baystown, Texas.

6.6 SOME REFLECTIONS ON THE SYNFUEL PROGRAM, AND ON COSTS

From the early 1970s to the early 1980s, estimates of synfuels costs have risen by a factor of almost ten, most of which is not attributable to inflation, but rather to misunderstanding the complexities. Mel Horwitch (1980) describes the synfuels program since the early 1960s in three stages. The first, funded at low levels principally by the Office of Coal Research jointly with industrial companies and associations, was one of limited activity but considerable optimism. For example, the Consolidation Coal Company, in conjunction with the OCR, in their joint "Project Gasoline," imagined gasoline from coal at 10 or 11¢/gallon. Oil and gas companies bought into the coal business (e.g., Consolidation Coal bought by Continental Oil), perhaps in expectation of cheap synfuels by inexpensive processes from cheap ($5/ton) coal, and perhaps as a quiet hedge against future oil shortages predicted even then by some people, but publicly ignored. In 1966, according to Horwitch, an officer of the National Coal Association called for coal and oil interests to combat government-funded nuclear energy research. In Horwitch's second stage, 1970-1976, many fuel-from-coal projects started; oil companies attempted to devise integrative projects; the Federal government still underwrote most of it, increasing its contribution from 4% of energy R&D in 1963 to 14% of a much bigger pie in 1974. Various consortiums started (e.g., Coalcon, begun in 1975 by a consortium of Union Carbide, Aero-Jet Corp., ERDA and others; also, a scheme to mine Navajo coal in the Arizona-New Mexico-Utah-Colorado "Four Corners" region, gasify it on-site and put it into existing pipelines). Most of these activities had collapsed in disarray by 1976, through organizational and technical difficulties, neglect of environmental problems or local opposition, and so forth.

Does the program take off again (Horwitch's third stage)? We have seen, and will see in succeeding sections, how the plans had been built on unrecognized mis-assessments. Dealing with coal (or oil shale, for that matter) seemed fairly straightforward; coal, chemical reaction columns and so forth seemed to be familiar things. But the real composition, the real nature of the products, the real social and environmental consequences had almost all been neglected, especially by industrial and academic participants who had spent too little time in important parts of the real world.

This persistent optimism led to many projections that synfuels would cost about the same as, or a little more than, the cost of petroleum, whatever the price of petroleum might have been at the time. Natural and even commendable enthusiasm led participants to seek and expect success in the short or medium term.

In mid-1973, estimates of synfuel costs ran $5-10 per barrel, compared with the OPEC price then of about $3/barrel.* In 1980, the Oak Ridge National Laboratory estimated $40-60/barrel of liquid, in very capital-intensive plants. Thus, for example, a 50,000 bpd plant would cost $40,000 per daily barrel of output, i.e., $2 billion, the same as the cost of a 200,000 barrel/day oil refinery. For 2 million barrels per day, the capitalization cost would be $80 billion, a number quoted by the U.S. Administration in 1980.

In early 1981, OPEC crude oil sold for $35-40/barrel. Stobaugh and Yergin (1979) figured at a time when OPEC oil was selling at $15/barrel that the total hidden costs of importing more oil (which would cause OPEC prices to rise still more, to $21/bbl) would be large. It would increase the world price, reduce U.S. GNP, and reduce U.S. security. A hidden incremental cost somewhere between $18 and $70/ barrel could be associated with imported oil, which made it something to stop importing or tax heavily. With continuing rising prices, the argument remains valid in concept, although the exact amount of hidden cost can be much debated--from $10/bbl to very large amounts, with conclusions based more on social perception than anything else.

This line of reasoning suggests that synfuels would be nationally attractive at $50/bbl, and perhaps even more, justified by national security, foreign trade balance and similar considerations. As the demonstration plants start to run, the originally too-low estimates become much firmer at the presently predicted costs of (say) $60/bbl. These are high numbers, but perhaps where reality lies, eventually. However, the large plans of 1979-1980 have been substantially deferred because of ~~more slowly rising~~ slowly declining petroleum prices in the early 1980s, and reduced federal support.

6.7 ADVERSE ENVIRONMENTAL IMPACTS--LISTS AND COMMENTS

The principal benefits of coal--energy for electric power plants and industrial processes, metallurgical ore reduction, source of chemical raw materials, domestic and commercial heat in many parts of the world--have been adequately publicized elsewhere. Despite increasing attention, the adverse environmental impacts, considered in their broadest sense, have not.

Listing the major parts of the fuel cycle permits making a mental check-list:

a) Associated with mining, transportation, etc.

- (i) Occupational hazards of deep mining, chiefly dusts, cave-ins, and other accidents.
- (ii) Occupational hazards of surface mining (generally milder than in deep mines).
- (iii) Deep mine acid drainage, rupture of overlying strata, and surface settling.
- (iv) Surface mine acid drainage, soil washing, etc.
- (v) Downstream effects from (iii) and (iv).
- (vi) Loss of land values.
- (vii) Boom town and associated effects.
- (viii) Transportation accidents and other problems.

b) Associated with processing and conversion

- (i) Occupational hazards, chiefly exposure to fumes, particulates, contaminated liquids, and accidents.
- (ii) Contaminated water, and often insufficient water, especially in the Western U.S.
- (iii) Ash, slag, and other solids.
- (iv) Release of gases and liquids to the uncontrolled environment.

c) Associated with the conversion product

- (i) Conventionally toxic fractions.
- (ii) Mutagenic, teratogenic and carcinogenic fractions.

d) Associated with combustion products

(i) Solid slag and ash.

(ii) Liquid waste water.

(iii) Sludge.

(iv) Gaseous emissions: SO_2 and NO_x.

(v) Particulate and trace element emission.

(vi) Unburned organic materials.

(run ?) They ~~These~~ are of different importance, and all do not occur simultaneously; many represent trade-offs.

Little integrated thinking has gone into handling these problems. The history of environmental improvement has generally been one of add-ons, often agreed to reluctantly, often the substitution of one problem for another, of selective and even callous inattention.*

From such a long list, only a few examples can be selected here. Some supposed ameliatory actions represent little more than a transfer of problems from one sector to another. Waste water, sludge, and other effluents come out of conventional coal-burning plants and synfuels plants, and must be disposed of in any event.

More holistic thinking increases, but slowly. In August 1980 the U.S. Department of Energy published an "Environmental Development Plan: Coal Liquefaction" Report DOE/EDP 0044 (72 pp.), with substantial methodology and procedure. It was general enough to (1) give the feeling that DOE was starting to think in major categories, (2) allow ignoring many specific issues, hence stimulating selective attitudes of "out of sight, out of mind." Even so, it was a sign of improvement.

Here are several broad topics which illustrate complexity typical of all the rest.

6.7.1. Control of Sulfur Emissions

Sulfur emissions, as SO_2, H_2S or other less common forms have long been regarded as undesirable and hazardous. Some medical data were available by 1970. At that time, it was thought that the SO_2 ~~as emitted~~ itself was the principal environemtnal and health hazard, but work then and since increasingly points to acid sulfates. These form by oxidation of SO_2 to SO_3, followed by hydration to droplets of sulfuric acid, H_2SO_4; ~~but~~ fine particulates in the air (often the condensed ash from coal burning) adsorb the SO_2 or SO_3, plus water vapor, and provide a good catalytic surface on which the reactions can proceed. Thus form various acid sulfates, also acid rain, as described in Chapter 3.

The air quality laws in the early and mid-1970s limited SO_2 concentration (80 $\mu g/m^3$) with no regulation on acid sulfates at all. Thus arose the idea of tall stacks to disperse the SO_2 and keep the level locally and afar at less than the legal limit.

In the late 1970s, new regulations came to control the sulfur emissions themselves from new installations, at present to a maximum of 1.2 lb (0.55 kg) of SO_2 per million ~~BTU~~ Btu in all fixed installations of more than a certain minimum size (thus excluding all household and many small commercial enterprises from such controls).* This corresponds to about 1% sulfur content by weight, in high-grade coal. As stated earlier, the average sulfur content of U.S. coal is about 2.5%, and up to half of that can often be separated prior to combustion. ~~However, present~~ regulations also state that all new ~~large~~ plants must have stack-gas sulfur removal installations ~~that remove 70-90%~~ of the sulfur, regardless of the initial sulfur content of U.S. coal is about 2.5%, and up to half of ~~that can often~~ be separated prior to combustion. However, present regulations also state that all new large plants must have stack-gas sulfur removal installations which remove 70-90% of the sulfur, regardless of the initial sulfur content, unless that content is so low as to exclude almost all coal. The effect of that regulation is to make Eastern U.S. high-sulfur coal attractive. If the effluents must be scrubbed anyway and the final emission contains less than 1.2 lb/10^6 BTU, why pay more to ship low sulfur coal from the Western U.S.? Thus does political expediency often dominate.

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The form of sulfur removal much favored by the U.S. Environmental Protection Agency is wet-limestone scrubbing, wherein the stack gases encounter baffles through which falls a calcium carbonate slurry. The products are calcium sulfite, unreacted limestone, particulates from the transported ash, some generally undesirable trace compounds, in a sludge. This sludge is difficult to dewater, is thixotropic (physically unstable), occurs in enormous amounts (10% or more of the weight of coal), forms scale in the scrubber unit, and may cost as much as $100/ton to dispose of in landfill sites that are acceptable by 1980-era standards. Attempts have been made to convert the $CaSO_3$ to $CaSO_4$ and use it as gypsum (for wall-board, etc.) but the inclusion of undesirable constituents generally makes it unattractive compared with pure gypsum which can be mined for a few dollars per ton.

These unsatisfactory circumstances increase the attractiveness of fluidized-bed combustion, which yields a dry ash, and also the attractiveness of second or third generation schemes of stack gas cleanup. Amongst the latter are several that use regenerable absorbers: for example, a sodium-base alkali absorbs SO_2 from the trace gas; the liquid is reacted with lime to precipitate $CaSO_3$ or $CaSO_4$, and the sodium-base alkali is regenerated for recycling. A main advantage is elimination of scaling in the scrubber, but the process is more complicated (EPRI 1979b).

Other schemes are under development or trial installation. Most of them depend on passing the stack-gas through falling columns of absorbing liquid; this cools the gas, which must often be reheated to restore its buoyancy and lift it from the stack in a proper plume.

Some imagine that recaptured SO_2 or sulfur can be sold at a profit, or converted to sulfuric acid and sold, and so forth. These materials have low value per ton, hence can be manufactured and sold profitably only if a ready and preferably local market exists. In addition, the potential 50 million tons of sulfuric acid available this way is a great deal to sell, or even dispose of.

One technological or regulatory patch follows another, regional problems remain, the reduction from emissions equivalent to 2.5% sulfur to those equivalent to 1% sulfur accomplish moderate improvement at best; the acid rain problem persists. A better and more integrated technology has been needed for years, from the ground up.

6.7.2. Particulates

The New Source Performance Standards presently (1982) prescribed by the U.S. Environmental Protection Agency require particulate emissions from all coal-burning installations producing more than 10^8 BTU/hr (about 4 tons of coal/hr) not to exceed 0.03 lb/10^6 BTU. For bituminous coal with 8% ash, heating value of 24 x 10^6 BTU/ton, and a boiler that produces 30% bottom ash and 70% fly ash (all typical numbers), the fly ash removal fraction must be 99.4%. This sounds impressive and can be readily achieved, but there is more to the story.

McElroy, Carr, Ensor and Markowski (1982) discuss the size distribution and other properties of these fly ash particles, and part of this section summarizes part of their work. Under the electron microscope, the particles appear roughly spheroidal, many are hollow, and the walls themselves often have many small cavities, like swiss cheese. They look very much like some vesicular lavas in miniature.

Almost all the mass is contained in the "large" particles--for example, larger than 2-3 microns. When they are not removed, the exhuast plume from the smokestack is obviously dirty. These large particles are also the easiest to remove; the largest will fall out in centrifugal cyclone separators, but now electrostatic precipitators usually remove 99% or more of the total.

These precipitators, placed in the exhaust stack, consist of many parallel plates mounted edge-on to the gas stream, alternately charged positively and negatively. The voltage is adjusted to give a corona electric discharge in the region, akin to what is sometimes seen on high-voltage electric transmission lines and insulators. The current and power are small; electrons emitted into the space attach themselves to the fly ash particles, which then are attracted to the collector electrodes. Periodically, the collected fly ash falls to the bottom of the precipitator, where it is collected mechanically for eventual disposal. This collected ash has some of the properties of Portland cement, and can be used as an extender for it; however, the total amount of this ash produced in the U.S. (about 50 million tons annually) far exceeds the demand.

The most troublesome particles are those below (say) 3 microns in size; the smaller ones, invisible except as a general haze, can penetrate the lungs of people and animals and damage them. These small particles, though they contain little of the mass, have most of the surface area and therefore become selectively loaded with pollutants from the gas stream.

Electrostatic precipitators generally do not collect these very small particles as well as they do the larger ones. Furthermore, SO_2 tends to promote beneficial corona emission of electrons in the precipitator; thus, low sulfur coal makes electrostatic precipitators work less well.

McElroy et al discuss some of these matters. Figure 6.10 shows the typical bimodal differential size distribution at the inlet to an electrostatic precipitator, measured by an impactor and/or an electric aerosol analyzer. The submicrometer mode, despite its small mass, contains almost all the particles and most of the surface area.

Two main strategies are on hand to reduce the emission of these particularly dangerous, small particles to the atmosphere: producing fewer of them in the first place, or capturing them more efficiently. Some evidence exists that these smallest particles form at least in part from vaporized ash; thus, higher combustion temperature should produce more small particles and low temperature should produce fewer. Nitrogen oxide formation in the flame also follows the same trend, so NO_x and submicrometer particulates should be correlated. McElroy et al show this is so by comparing formation of both in six different boilers. They show that the submicrometer particles have enriched concentrations of the most vaporized trace elements, with respect to the concentration in large particles. For example, for 0.1 μ particles, arsenic and zinc appear eight times enriched, mercury six times, and so forth.

Baghouses collect both large and small particles with high efficiency, and many new coal-burning plants install these instead of precipitators. Typically, the exhaust gas from the boiler passes through a heat exchanger to pre-heat combustion air, then into the many bags of the baghouse. Each acts like a vacuum-cleaner bag, is typically made of fabric or glass-fiber coated with a high-temperature anti-abrasive material (e.g., teflon-B), is about 30 cm diameter, and 10 meters long, connected at the top to the incoming gas stream, and at the bottom to a closed hopper. The ash can be removed periodically from the bags, for example by taking them off-stream and reversing the air flow through them for a short while. The bags collapse, then fly ash dust falls into the hopper, where it can be removed through a valve. This requirement for occasional off-line service plus other considerations of reliability lead to installation with (say) ten baghouses in parallel, each containing several thousand bags.

Figure 6.11 shows a comparison of collection efficiency between a precipitator on a large boiler and a baghouse on a small one. The superiority of the baghouse is obvious, and should be independent of size.

Electrostatic precipitators are usually cheaper than baghouses, \$40/kWe versus \$80/kWe, for example. Technology of both collection schemes improves with time, but the baghouses have shown the ability to limit fly ash emission to much better than the EPA standard, say to 0.01 lb/10^6 BTU. Btu
Baghouses have been in use in other industries for many years; their relatively recent appearance in the very large power plant market stimulates improvements in their design and construction, and the price may fall relative to precipitators.

Sulfur oxides, nitrogen oxides and submicrometer particulates are all inhibited by low-temperature combustion in fluidized beds. The arguments for their more rapid development tend to reinforce.

6.7.3. Underground vs. Surface Mining

Large Shovels and drag lines for surface mining were mainly post-WWII developments; until then, most coal came from deep mines. Safety in those deep mines has improved during the past several decades by an order of magnitude, so that in 1980 the fatality rate was about 0.3 deaths per million tons of mined coal. Even so, coal mining remains an unhealthy and hazardous occupation. A legacy of the lax dust control before 1970 is the continuing payment of more than $1 billion per year to underground miners certified as having "black lung" disease, a catch-all definition for various conditions which can range from mildly discomforting to progressively, inexorably and tortuously fatal.

Additionally, deep mining causes land settling (as in many suburbs of Pittsburg) and rupture of strata above the mine. Exhausted mines can be neither completely back-filled nor sealed from outside air. Thus air and water enter, sometimes through aquifers in the broken strata, and create the conditions for acid mine drainage (principally from oxidation of the sulfur) which, invisible in its formation, can appear many miles away, virtually unstoppable.

Modern Strip mining techniques permit economical removing of up to 20 feet of overburden for each foot of coal seam thickness. Therefore, wide 100-foot trenches in Ohio, Wyoming, Montana and elsewhere are common. Surface mining is usually cheaper than deep mining; the coal in a 30-meter-thick Western seam is worth $10 million/ha, after it is delivered in Chicago. The occupational hazards are less. Thus strip mining came into fashion, as described earlier, but brought large problems of visible land destruction, lack of restoration, and even fierce opposition to full reclamation. After all, it was argued, proper restoration might cost $10,000 or more per hectare, for land that might sell for only $1000/ha afterward. That the coal might have been sold for a million dollars was sometimes declared irrelevant. The passage of the Mine Safety and Health Act of 1969 stimulated shifts to surface mines.

However, the visible surface damage, the prompt despoilation of many Appalachian streams by acid drainage, and evident official and business unenthusiasm for land reclamation all led to popular movements in the Appalachian region in the early 1970s for more strict controls, and even for banning all strip mining (especially by armchair environmentalists who had no understanding of deep mining).

Counteracting this trend, the simplistic enthusiasm for coal in 1974 and soon afterward led to much-increased strip mining in Montana, Wyoming and other Western states, to complaints about difficulties of land reclamation there, and even to reassurances from Washington, D.C., that some regions should be considered as "sacrifice areas." This generated little enthusiasm in Western states.

The mid-1970s saw increased understanding of the cost of repairing strip-mined land, especially in the West. With scant rainfall there (on the order of 30 cm/yr or less), many regions lose their moisture entirely by evaporation with no downward percolation; then a sturdy but ecologically delicate crust develops, with successive layers sometimes measured in millimeters rather than centimeters or more. Once disturbed, the underlying soil blows or washes away; a new vegetative crust capable of surviving without attention in the semi-arid region is difficult to establish.

In relatively flat, well-watered land, strip mines can be fully restored. In the scheme of Figure 6.5b, whole farms and villages in the Rhine-Westphalia region of Germany have been so treated for more than a decade, to remove thick deposits of sub-bituminous "brown coal" lying 300 meters deep, with reconstruction of the land, surface deposits of new silt, and replanting with new agricultural and forest crops.

6.7.4. Organic Pollutants from Coal Conversion

Toxicological problems associated with coal conversion and with oil shale are enormously important. Coal tars and soot were recognized carcinogens in the 1700s in England. High temperature operations with coal produce literally thousands of different polycyclic aromatic hydrocarbons (PAH), pehnols and other substances not even encountered in conventional chemistry. Many organizations and agencies now collaborate to identify these biologically active materials--for example, the Department of Energy, the Environmental Protection Agency, the American Petroleum Institute, and the Electric Power Research Institute. Recent examples from just one place and time--the Oak Ridge National Laboratory in the late 1970s--testify to the amount of work. ORNL Review (1980) contains a good summary; see especially "Toward Non-Toxic Coal Technologies," pp. 75-81. Vastly more detailed is Braunstein, Copenhaver and Pfuderer (1977), 1100 pages. Note also Salk and De Cicco (1978), and ORNL-5361 (1978), which contains much more background information.

Chapter 5 of Braunstein et al (1977) lists hundreds of different PAH compounds detected in distillates from typical (West Virginia) coals, some in trace amounts, some constituting several percent. Their tables 4.56 through 4.61 (pp. 4-112 through 4-119) show PAH concentrations in coal-derived liquids ranging from a few hundred to several thousand parts per million. Many of these are directly toxic, mutagenic, teratogenic (i.e., cause birth defects) and/or carcinogenic. They clump together, attach themselves to fine particulates, and enter the lungs of people and other animals. Benzo(a)pyrene is one well-publicized carcinogenic PAH, whose potency can apparently be increased still further through epoxidation by ozone (Pitts et al 1980). So do pollutants often reinforce each other (for example, with automotive emissions, forming peroxyacetyl nitrate (PAN), a major constituent of smog).

Most carcinogens seem also to be mutagenic; thus the rapid Ames test (observing genetic reversions in modified Salmonella bacterial cultures) and similar procedures help in preliminary sorting. However, longer term tests on more complex organisms must follow, and hitherto unfamiliar byproducts bring unwelcome surprises. For example, the azaarines are not usually found in conventional petroleum chemistry, but do occur in coal conversion; the impurities normally present in one of them (acridine) produces extra compound eyes in crickets (Walton 1981).

Coals and oil processed at high temperature produce more biologically active molecules. Free radicals form at the sites were the molecules separate; though these sites might be terminated with added hydrogen, the molecules are still unstable. They tend to polymerize at the active sites, yielding process liquids whose viscosity increases with time. This behavior can be expected from the simple chemical considerations described earlier in the chapter.

These dangerous substances need not cause occupational or public misery. They can be hydrogenated, their molecules opened or straightened by chemical refining techniques, but at a cost yet to be fully determined. As a class, the coal and oil-shale derived liquids are more hazardous than the petroleum-derived ones. If the difference is an order of magnitude, then the refineries must be that much more leakproof, and treatment of coal-derived solid wastes, waste water and gaseous effluents must be similarly upgraded.

6.7.5. Effects on Public Health

No one imagines the public health effects to be beneficial, but measuring the influence of specific pollutants turns out to be extraordinarily difficult, confused by effects of mobile populations; different living habits caused by economic, ethnic and dietary habits; different indoor and outdoor microclimates; different measurement techniques; effects that develop only after many years; and above all, smoking. Indeed, effects often cannot be ascribed to individual pollutants anyway; they act synergistically, as already described. Acid sulfates and toxic metals invade the lungs on the backs of 1 μm particulates.

Epidemiological studies of the late 1960s and early 1970s show that more data are needed, but all seem to indicate that surely something real is happening (Lave and

Seskin 1977). The Harvard School of Public Health follows cohorts of school children in Watertown, Massachusetts, documenting not only health, but many other variables. Perhaps more definitive data will come from studies like that. Anecdotal experiences abound, some of them very real: the 1952 London, England, smog killed about 4000 people, and led to passage of much stricter laws limiting particulate emission (but not SO_x except incidentally). Both the public health and the sky in London are much improved.

These uncertainties, the difficulties of resolving them, and the miserably inadequate attention given to supporting the effort, are well described by James Wittenberger (in Landsberg 1979).

Even with all these uncertainties, rough limits can probably be put on the damage. With almost uncontrolled emission of acid sulfates and sub-micron particles typical of the early 1970s, the deaths per gigawatt-year (i.e., a 1000 MWe plant running for one year) seemed to be somewhere between 10 and 100, conceivably as high as 200, from air quality degradation alone. Even if the lower number is true, the deaths per year would be about 4500, now being reduced by gradual compliance with new source performance standards and other measures. The morbidity figures too are uncertain, but hospital admissions during times of polluted air, plus the existence of several million people in the U.S. suffering from asthma and emphysema, aggravated during these times, attest to a widespread problem.

The combination of increasing awareness of the environmental effects--health, ecological damage, long-term waste disposal--coupled with a seemingly permanent shift toward fossil fuels with much greater pollution potential then hitherto, can provide the fuel for great public fights, reminiscent of and probably liable to surpass in vehemence the arguments about nuclear power.

FOOTNOTES - CHAPTER 6

6.1 i.e., excluding the total contained in all oil shales and tar sands.

6.5 WOCOL data from their Table 2.3, p. 98.

6.11 For example, every one in East Tennessee, at least temporarily, I have been told.

6.12 CONAES (1980) p. 189.

6.28 Courtesy of Oak Ridge National Laboratory Review, Winter, 1980, p.54.

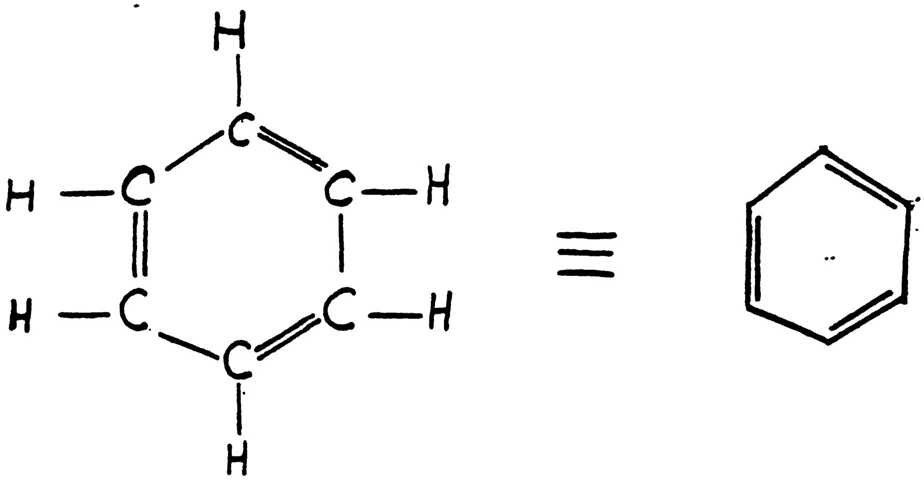
6.30 Courtesy EG&G Synfuels, Inc., 20 Willow Street, Wellesley, Massachusetts. The project was indefinitely postponed by late 1981, partly because of curtailment of federal support for synfuels development.

6.34 A wryly amusing story accompanies these numbers. In October-November, 1973, I prepared an analysis "How Much Domestic Syncrude Is Enough?", pointing out that as OPEC was watching these U.S. activities closely, and as it raised prices beyond the then-prevailing \$3-3.50, the question would arise about how much U.S. domestic petroleum would then cost (\$6.50-\$7.00), how much more syncrude would cost, and how much syncrude capacity the U.S. might plan for. A large available capacity to produce the syncrude at some particular price would tend to put a limit on OPEC increases. Too little syncrude capacity (say 1,000,000 bpd) would have no leverage on OPEC; too much brings the hazard of letting the U.S. build it all, then having OPEC drop the price below the the economic operating costs of the plants, in effect pulling out the rug. Thus the question came: How much capacity? At what price could syncrude be produced?

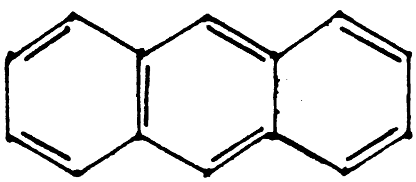
After analysis, I concluded inter alia in early November 1973 that an increase ~~a cost~~ of \$7/barrel (mid-1973 dollars) was reasonable to produce syncrude of usable but not outstanding quality, and distributed the analysis privately to the U.S. Government and some close colleagues. On December 23, 1973, the price of OPEC crude was set at \$10/barrel, roughly a \$7 increment, a number stated by the Shah of Iran as the cost of producing syncrude, according to his advice.

6.36 A good example appeared in the November 9, 1980, Boston Globe. On one page, staff writer William Davis, in an article entitled "Coal Heat--A Cheery Alternative," praises a book Coal Comfort which describes how to heat your house with a coal stove, with no mention of environmental controls or effluents. Another page contains the report of five miners found dead in a methane gas explosion in a Westmoreland Coal Company mine, "bringing to 29 the number of West Virginia miners killed this year, and to 26 the number who have died across the nation in the past six weeks."

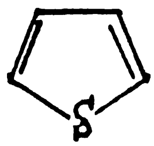
6.37 The so-called New Source Performance Standards (NSPS), implementing the Clean Air Act Amendments of 1977. Also, 0.5-0.6 lb NO_x per 10^6 BTU depending on circumstances, and other restrictions on other pollutants.



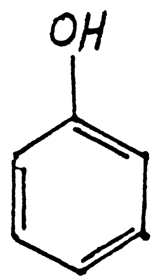
Benzene, C_6H_6



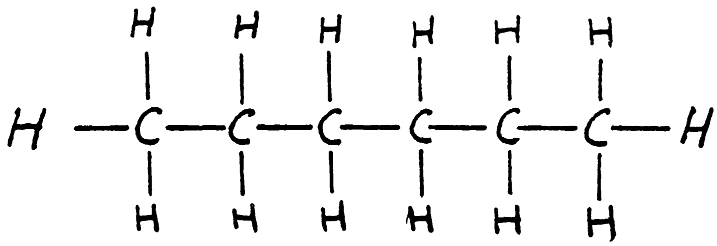
Anthracene $C_{14}H_{10}$



Thiophene

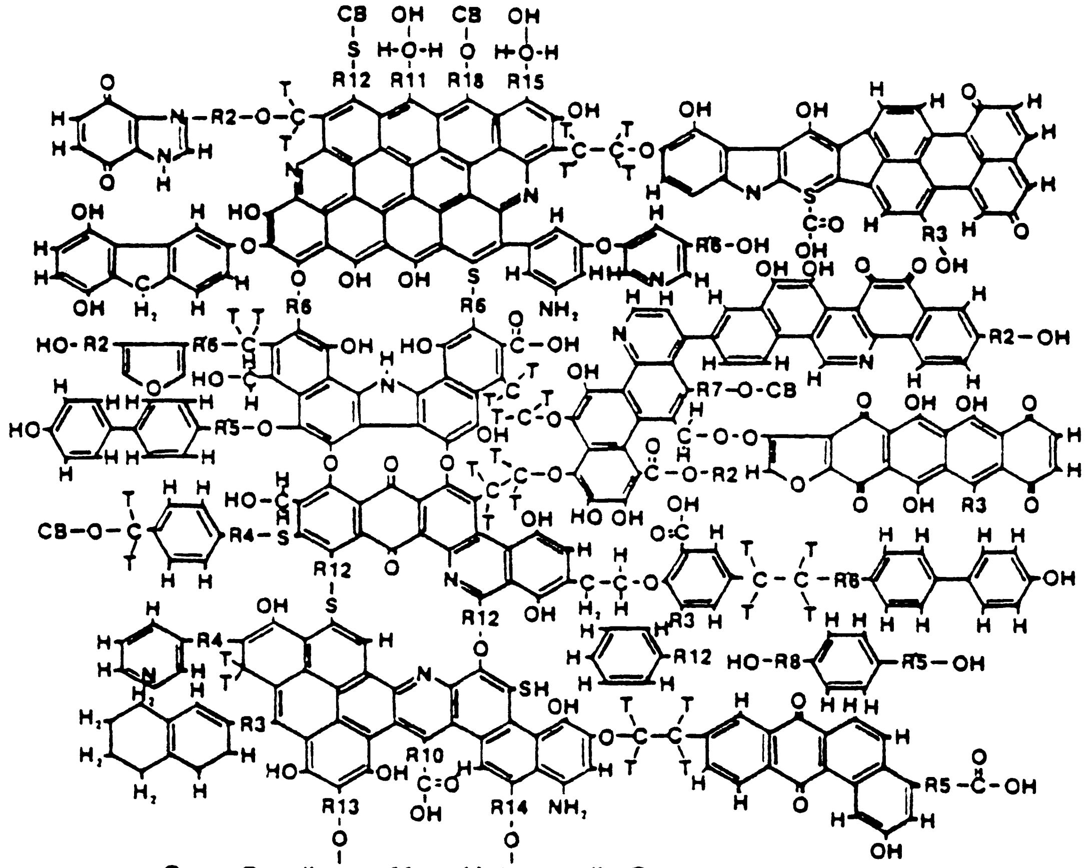


Phenol



Hexane C_6H_{14}

Figure 6.1 Some simple organic molecules.



Cross Bonding to More Heterocyclic Groups

Figure. 6.2 A coal molecule may be this complicated. For ~~the~~ chemical enthusiasts, the symbols are: R°N = alicyclic rings of N carbons; RN = alkyl sidechain of N carbons; CB = cross-bonding by O or S to new heterocyclic groups with sidechains; T = tetrahedral 3-D C-C bonds and C-S bonds. From Stanley Kasper "Coal Conversion Chemistry - see it in common terms," Industrial Research & Development, Jan 1981 p. 165.

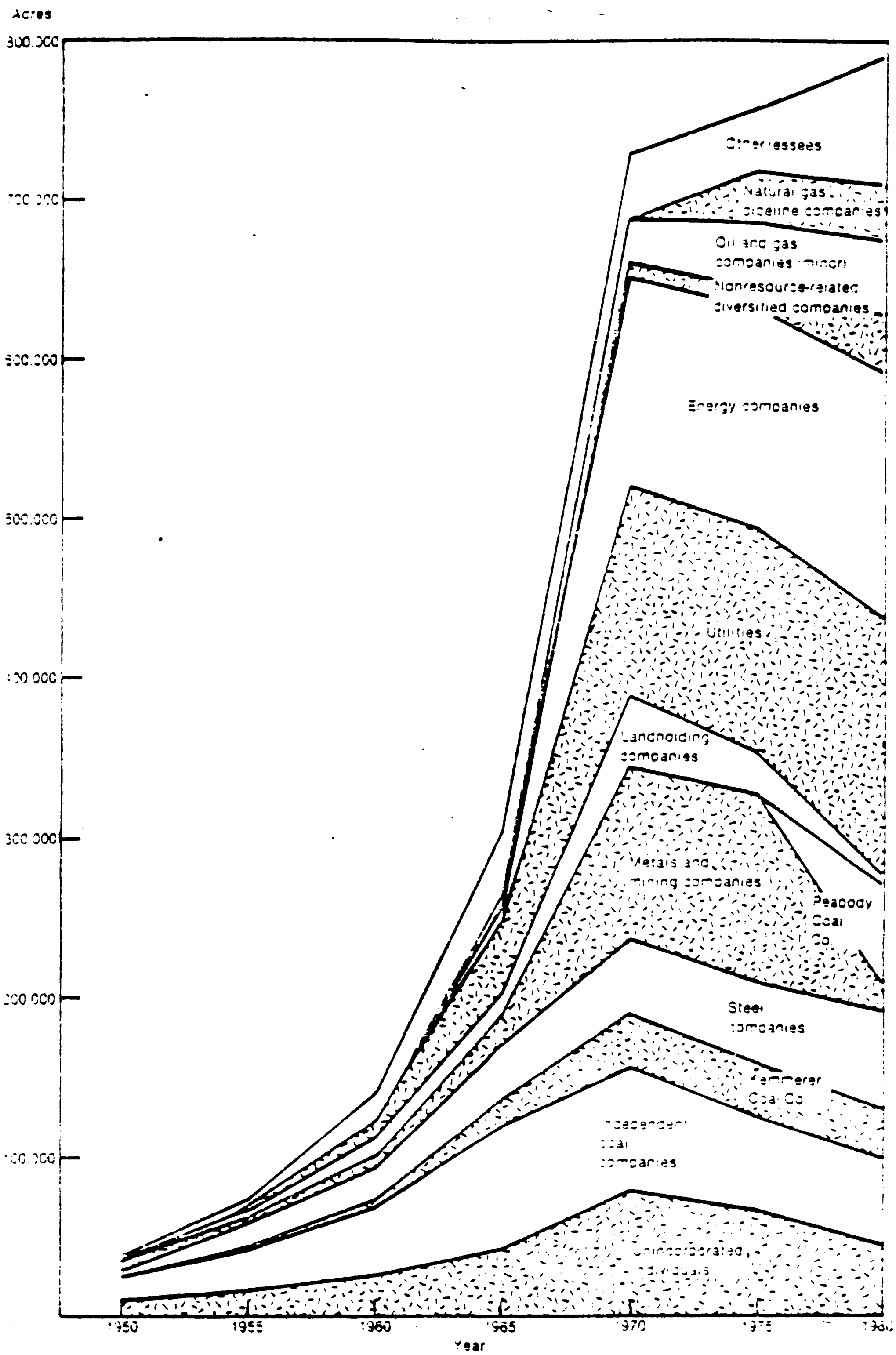


Figure 6.3 Number of Federal Coal Acres Under Lease by Business Activity Category, 1950-80.
Source: Office of Technology Assessment.

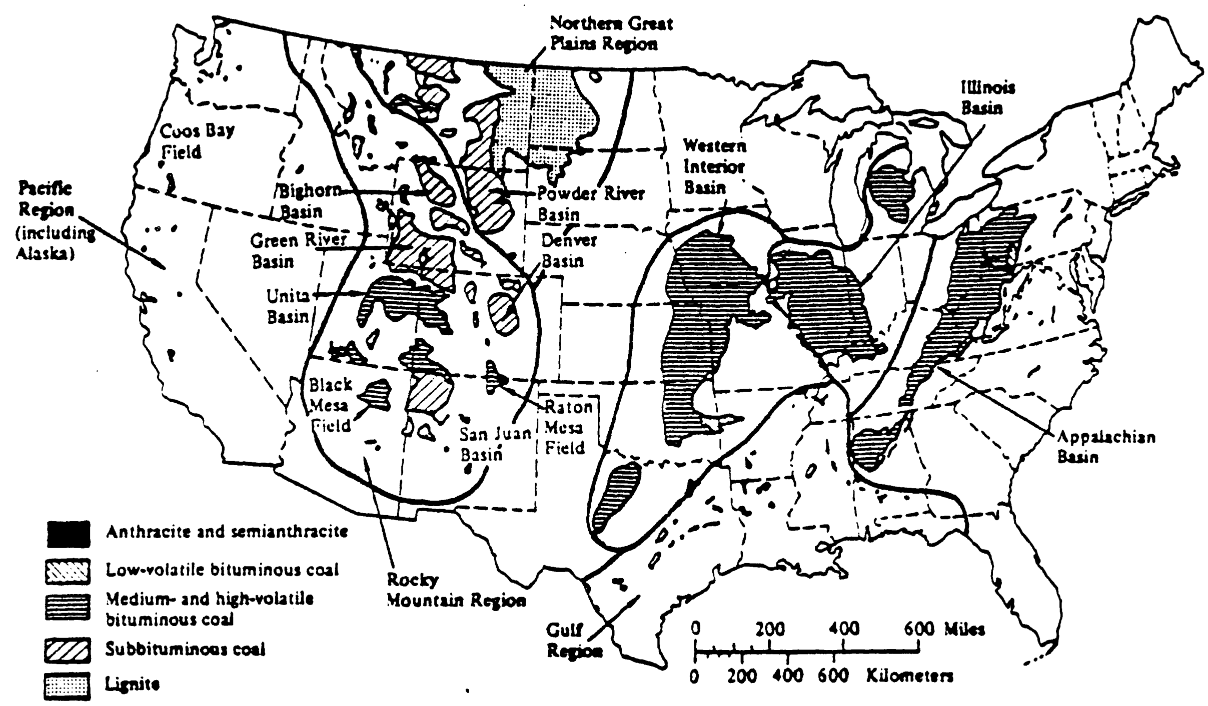
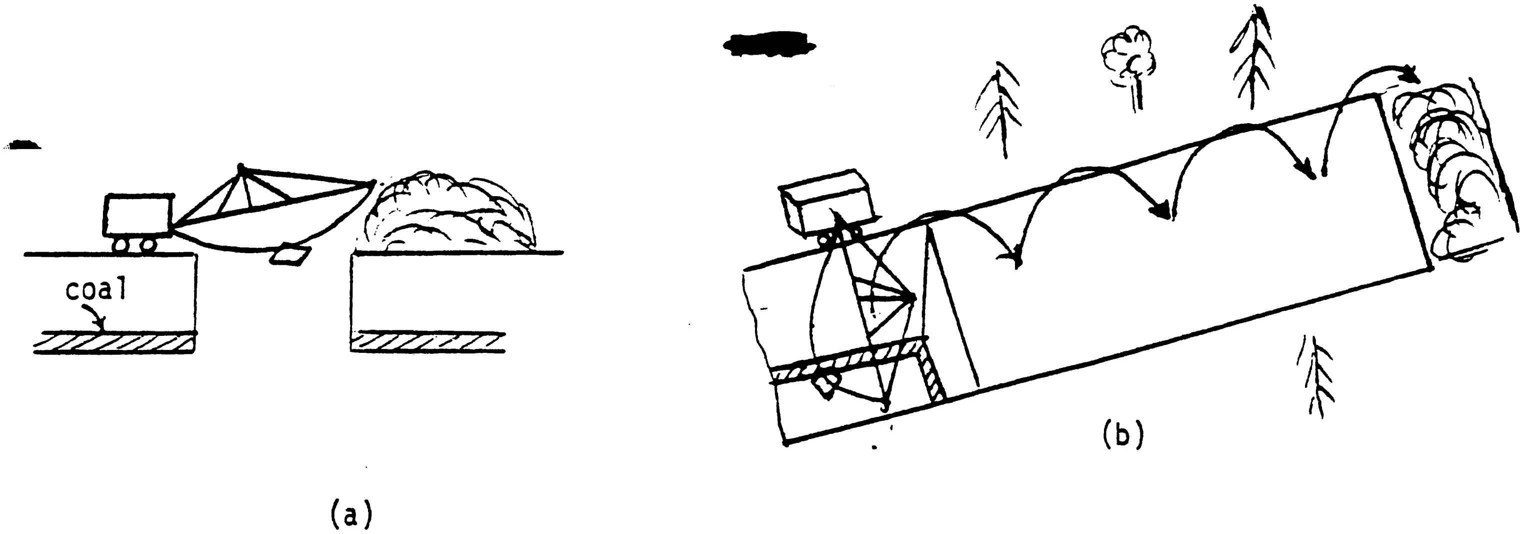
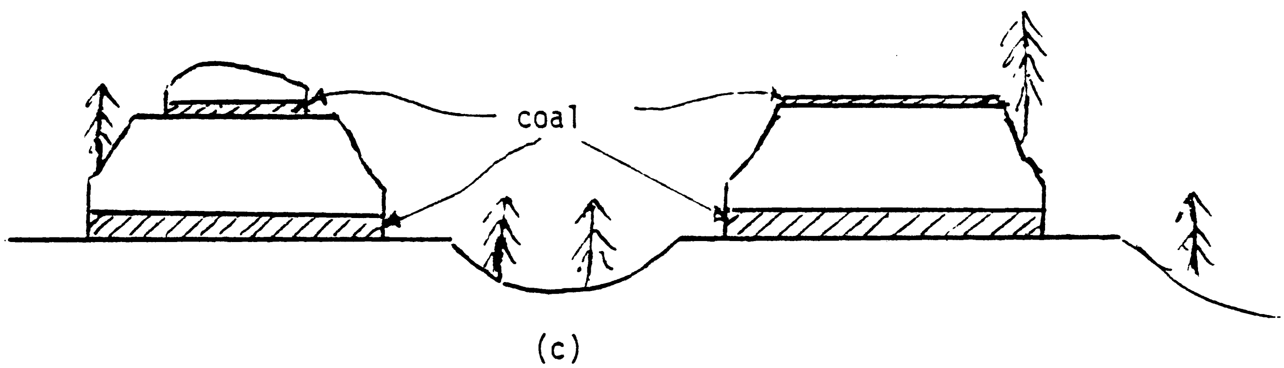


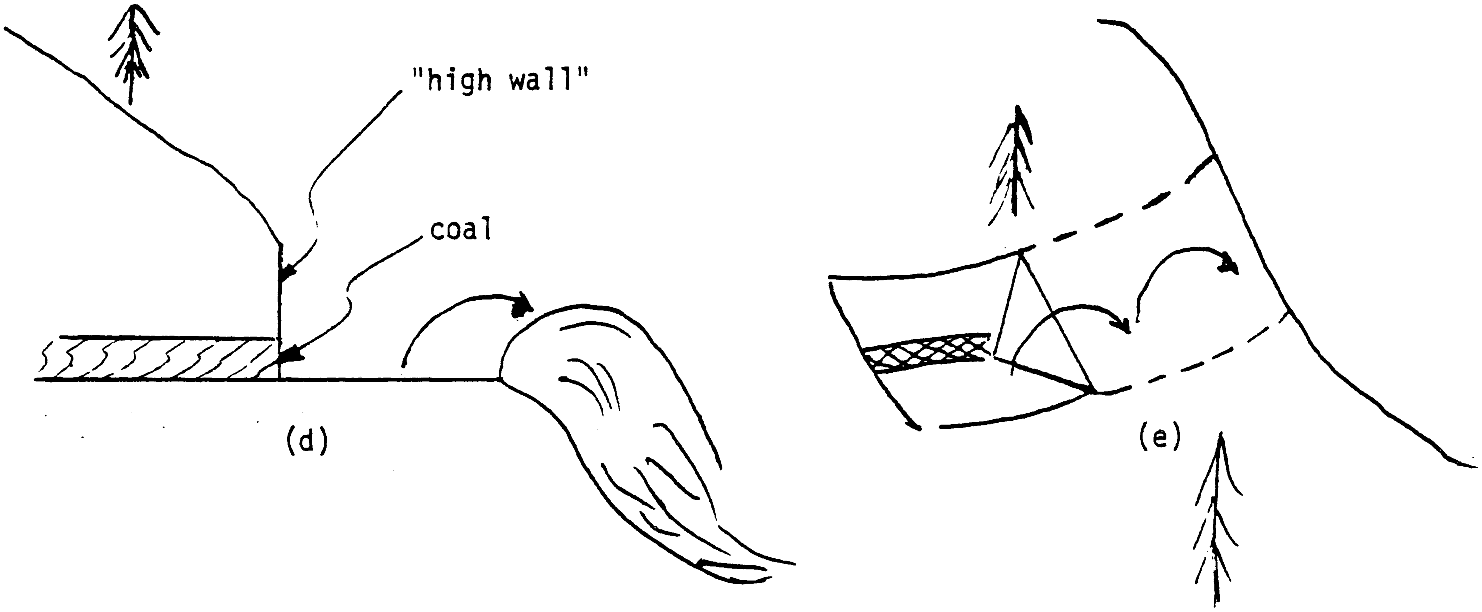
Figure 6.4 Coal fields of the coterminous United States. Source: Energy in Transition, 1985-2010, p. 154.



Open Pit

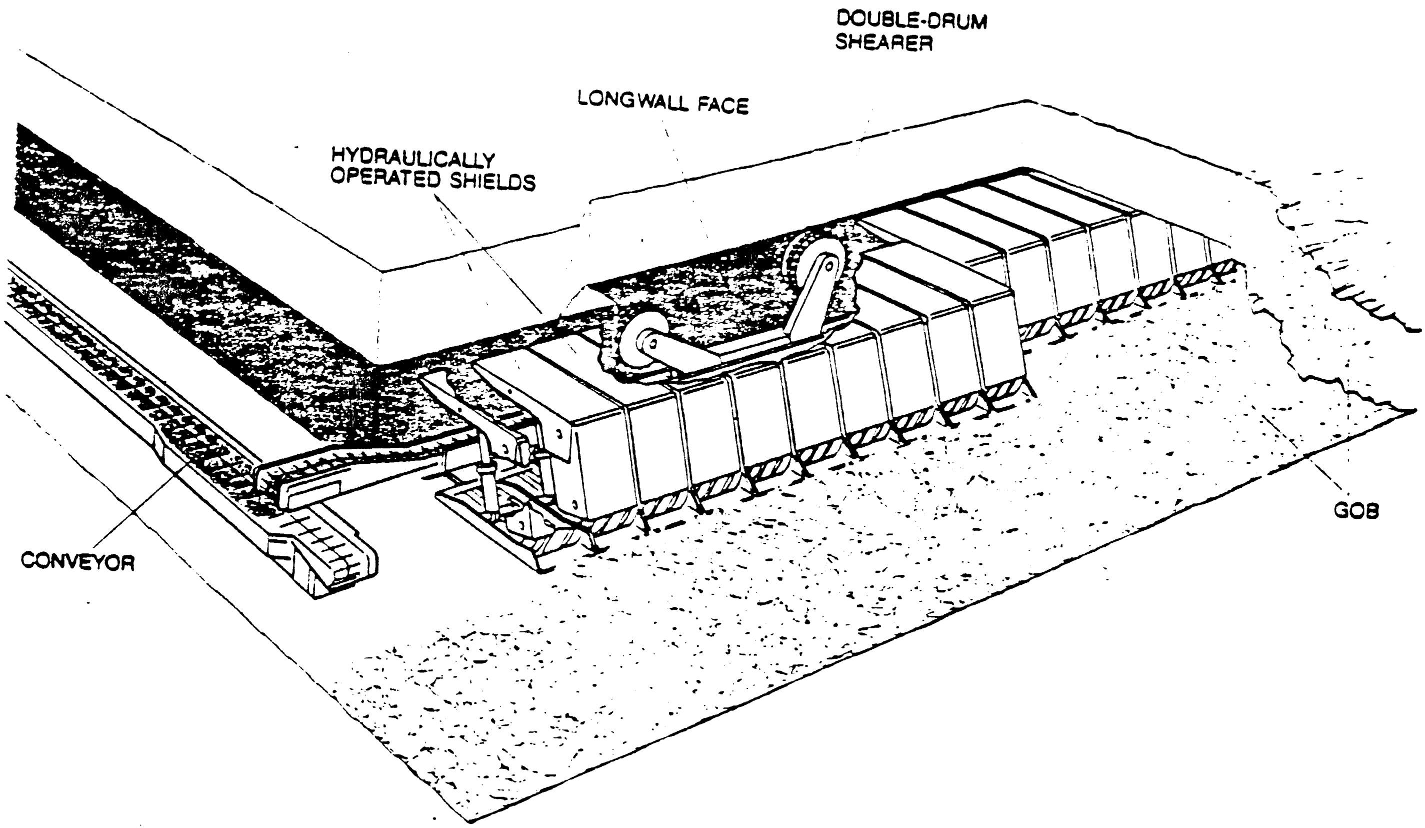


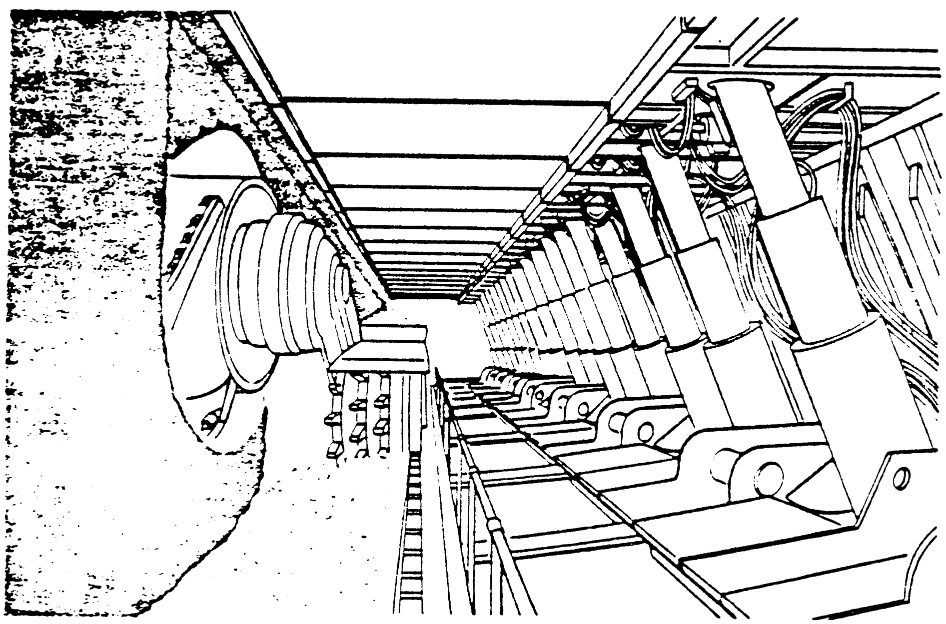
Contour-Mined Hills



Contour Mining, Detail

Figure 6.5 Methods of Strip Mining





LONGWALL MINING, which has been common in British and European mines for many years, exploits a continuous mining machine that either planes or shears coal from one face of a block 500 feet wide and up to a mile long. The machine shown is a double-drum shearer. The cutting machine makes continuous passes across the entire face. The mine layout no longer follows a room-and-pillar pattern (except for entryways surrounding the longwall panels). Instead the roof adjacent to the longwall is supported by hydraulic props that move forward as the face is advanced. The roof behind the props is allowed to collapse, leaving rubble called gob. When a panel has been mined out, the cutter and supports are moved to the next panel.

FIG 6.6 Longwall mining. From Robert R. Marovelli and John M. Karhnak "The Mechanization of Mining, Sci. Amer. Vol 247 pp 91-102 September 1982

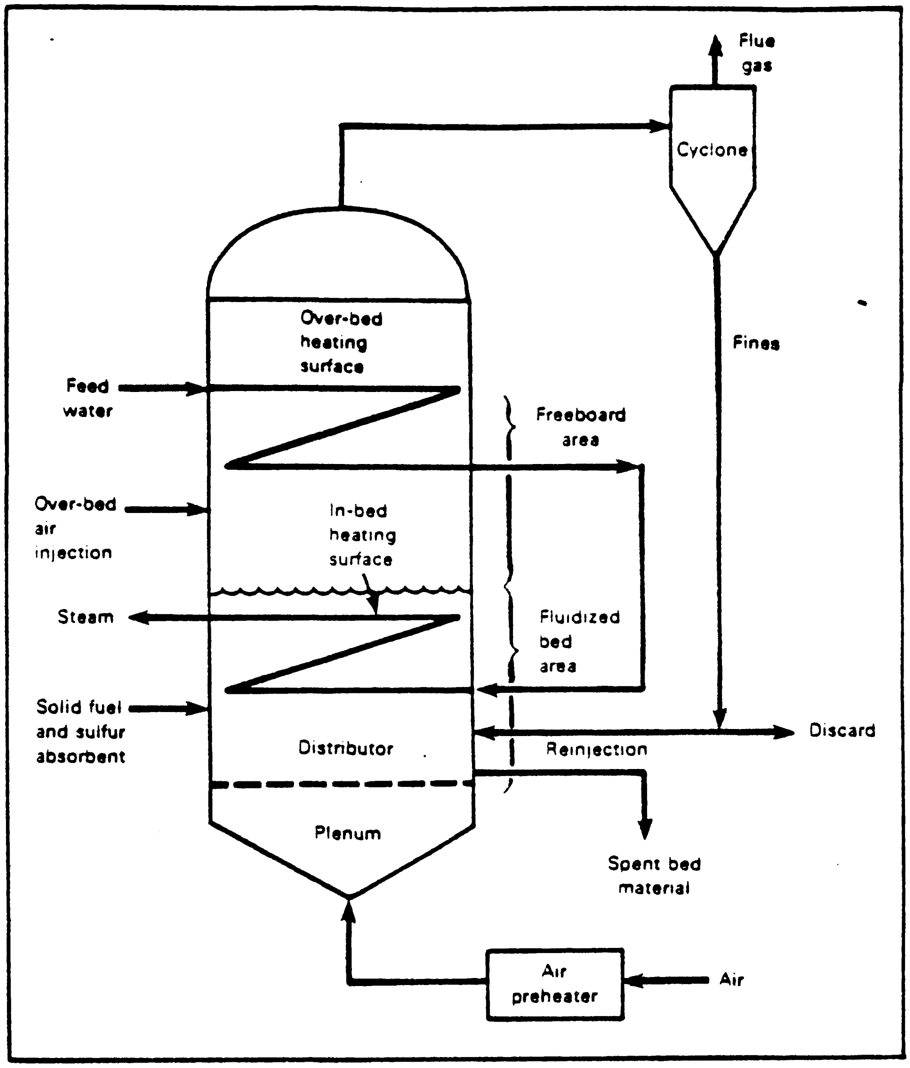
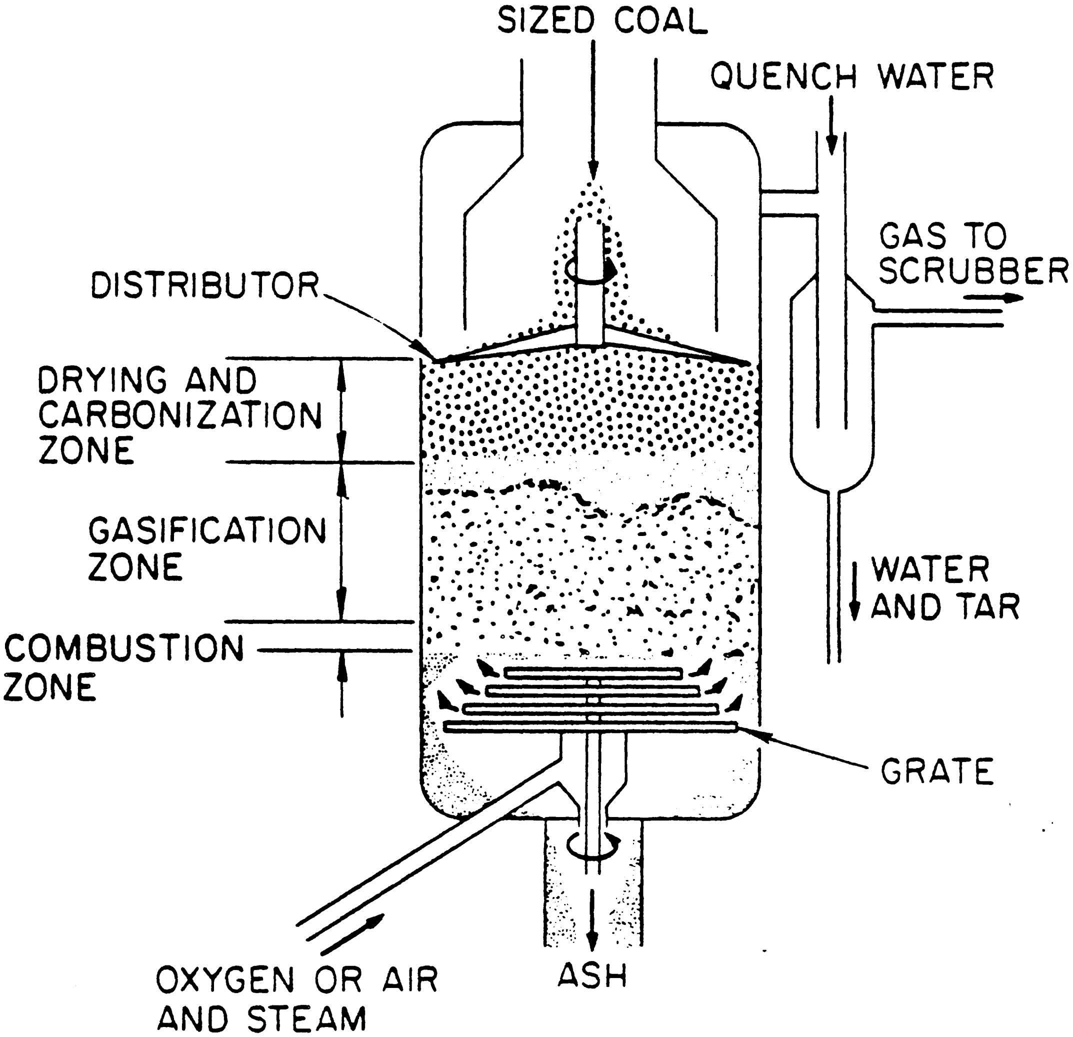


Figure 6.7. Basic components of a fluidized bed combustion boiler. In practice, the flue gases would pass through an economizer and a baghouse filter, after leaving the mechanical ~~separator~~ cyclone separator. From Energy Technologies and the Environment, U.S. Dep't of Energy (1981)

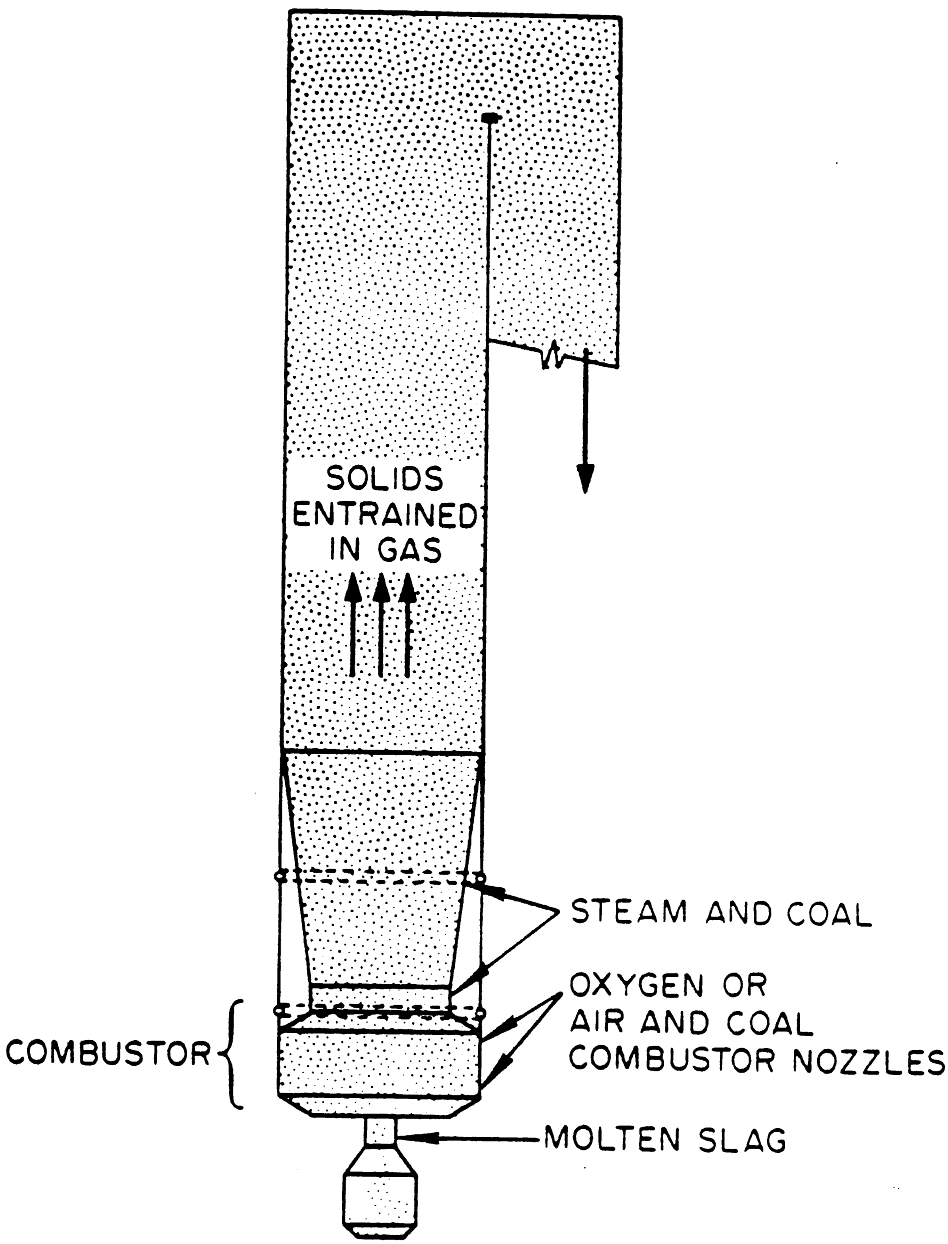
Fig. 6.8a [redacted]

ORNL-DWG 80-8379



~~Fig 6.8(a)~~
Fig 6.8(b)

ORNL-DWG 80-8378



New England Energy Park Process Diagram

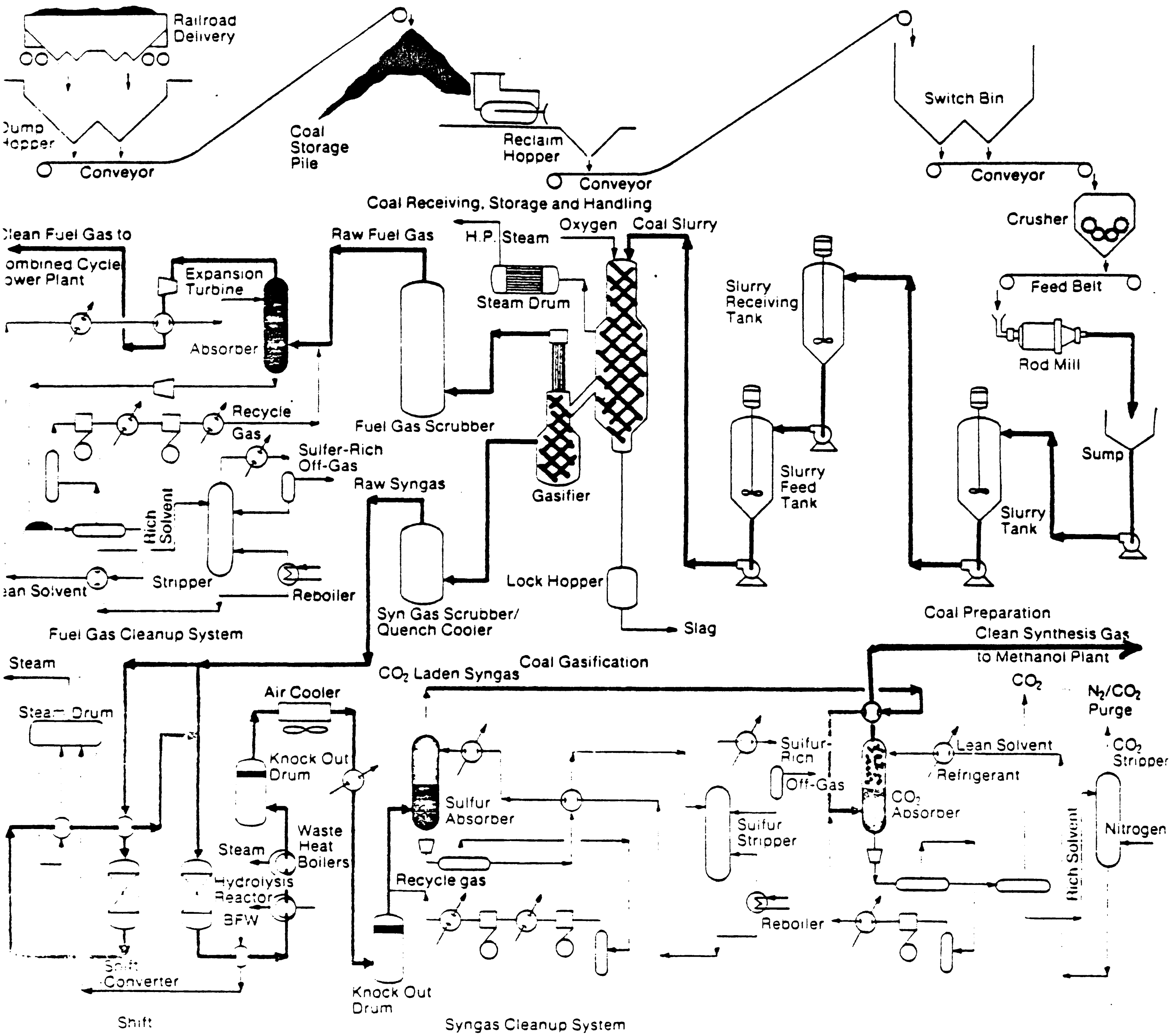


FIGURE 6.9

For additional information contact:
EG&G Synfuels, Inc. 20 William Street Wellesley, Massachusetts

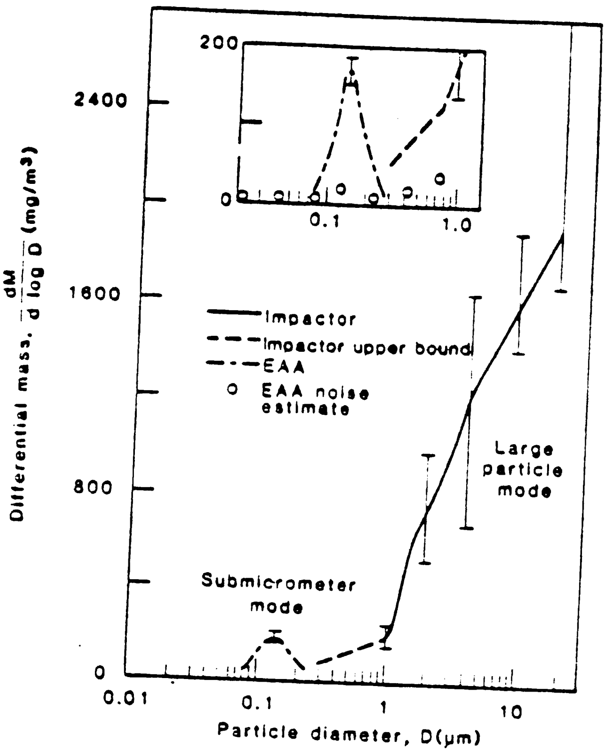


Figure 6.10 Typical bimodal differential size distribution of fly ash particles at the boiler outlet of a coal-burning power plant. The submicrometer mode contains 1.5 % of the total mass. EAA is an electric aerosol analyzer. From McElroy et al, loc. cit.

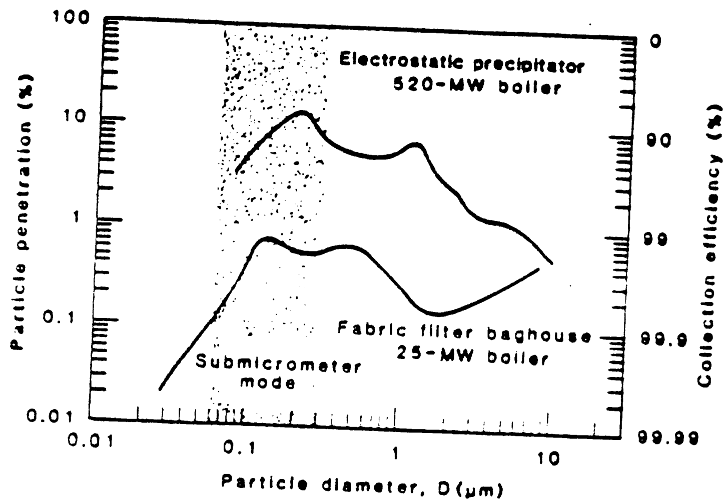


Figure 6.11. Particle size-dependent efficiency comparison between a fabric filter baghouse and an electrostatic precipitator. From McElroy et al, loc. cit.

Table 6.1 Some Domestic Coal Demands for the U.S., quads.

SOURCE	1985	1990	2000	2010
WOCOL (1979)	16.4 18.2		27 42.5	
EIA[a] (1978)		31.2	46.9	65.2
CONAES (1979)[b]				
Supply-Delivery Panel:				
Business as Usual		25	34	42
Enhanced Supply		26.6	37.2	49.5
National Committment		32.5	75	100
Study Scenarios:				
I_2 (2%/yr GNP growth)		20 (70)		15 (64)
I_3 (3%/yr GNP growth)		27 (85)		25 (85)
II_2 (2%/yr GNP growth)		25 (76)		22 (83)
II_3 (3%/yr GNP growth)		31 (89)		38 (115)
III_2 (2%/yr GNP growth)		25 (85)		38 (102)
III_3 (3%/yr GNP growth)		32 (101)		60 (140)
IV_2 (2%/yr GNP growth)		29 (99)		57 (140)
IV_3 (3%/yr GNP growth)		35 (113)		73 (188)
PIB (1974) $7 oil[c]	17.7-19.9 (109)			
PIB (1974) $11 oil	20.7-22.9 (104)			
M.I.T. (1974) $11 oil [d] 16.94 in 1980 (83-97)				
National Energy Plan (1977) Department of Energy	23 31	27 ?		

Notes for Table 6.1

(a) Energy Information Administration

(b) CONAES and EIA data taken from CONAES Tables 11.16 P. 563 and Tables 11.17-11.24 PP. 571-578.

(c) Project Independence Blueprint Summary, Federal Energy Administration, November 1974, Table I-21.

(d) Adapted by FEA from Energy Self-Sufficiency: An Economic Viewpoint, Technology Review, May, 1974.

Census Region[b]	Recoverable Reserves[c]	Annual Production[d]	Annual Consumption[e]
New England	0	0	0.1
Middle Atlantic	6.3	13.4	12.8
East North Central	21.9	19.0	30.4
West North Central	5.1	2.6	8.9
South Atlantic	9.4	22.1	15.5
East South Central	6.9	25.5	11.8
West South Central	1.3	2.7	2.6
Mountain	47.5	13.8	7.1
Pacific	1.7	0.7	1.2

Table 6.2 1976 Recoverable Reserves, Production, and Consumption of U.S. Coal, by Census Region (percent of total tons). Source: ~~Energy in Transition 1985-2000, p. 159.~~ (CONAES 1980) p. 159.

Gorbaty

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CHAPTER 7

CORRECTIONS NOTED

NUCLEAR POWER

7.1 INTRODUCTION

Because nuclear power has stimulated so many conflicting views, so much social debate and political controversy, any significant discussion of it must include some examination of those matters. Thus this chapter augments technical presentations with commentary, even more than do most of the other chapters. Personal views and opinions always lurk behind such commentary, no matter how the writer might disclaim bias; the very choice of material steers attitudes this way or that. The best that can be done is to present what seem to be reasonable and important issues as honestly and evenly as possible, so that the reader feels substantially assisted in understanding the issues, and not intellectually manipulated or proselytized.

Figure 7.1 helps to put much of the material of this chapter in context. It is a flow diagram of a fuel cycle for nuclear power from so-called light water reactors (LWR), the kind most commonly in service or contemplated in the near future. Some parts of it are not yet technologically resolved or socially and politically accepted, and choosing this one instead of another implies no special prior endorsement. Its purpose here is to help focus attention on important issues.

Uranium is mined, and converted to U_3O_8 ("yellow cake"). It contains 0.71% U-235 that is directly fissionable by slow neutrons, and 99.3% U-238 that is not fissionable that way (but can be turned into plutonium, to be discussed later). The LWRs cannot run on natural uranium -- the neutron losses are too high -- so the U-235 isotopes must be enriched to about 3%. Most enrichment processes to date require the uranium in gas phase; the only uranium compound suitable for this is uranium hexafluoride (UF_6), hence its prominence in the diagram.

After enrichment, the pellets of UO_2, a highly stable refractory ceramic, about 1 cm in size, are inserted into thin-wall zircalloy tubes (fuel rods), the rods are assembled into bundles, and constitute the nuclear fuel for the reactors. After an appropriate residence time in the operating reactor (typically three years), these fuel bundles are removed and put into water-filled storage pools at the reactor site.

At the moment (1984), that is virtually the end of the story in the U.S.; what to do about the spent fuel has been a volatile topic for years, and will be taken up later. As the reactor operates, 1-2% of the U-238 (the major species present) absorbs fission neutrons, to form U-239, which converts by β-decay successively to Np-239, then Pu-239. This Pu-239 is fissionable by fast or slow neutrons (as is U-235); it decays by α-emission to U-235, with a half-life of about 25,000 years. Figure 7.1 shows this plutonium being separated, and both the recovered uranium and the plutonium being re-used as LWR fuel, thus augmenting the initial uranium supply.

Important topics arise everywhere on the flow diagram, and off it too; some are:

- o Uranium resources (thorium also, which is fertile in the same sense as U-238);

- o Uranium mining and milling;
- o Enrichment technologies;
- o Nuclear reactor technology -- LWR's, natural uranium reactors, breeder reactors, big reactors, small reactors, etc.
- o Fuel reprocessing, necessary for breeder reactors;
- o Nuclear waste disposal;
- o Power plant siting;
- o Costs (vis-a-vis what?);
- o Accidents -- how big, how frequent, due to what?
- o Other environmental consequences;
- o The degree of connection between peaceful and warful atoms;
- o Centralized vis-a-vis decentralized systems;
- o Large unit sizes vis-a-vis small ones;
- o High technology as socially desirable or not;
- o Nuclear power as a target of social criticism;
- o Nuclear power as an inherent evil, vis-a-vis nuclear power as a conditionally good gift of creation.

These topics range from high technology to high theology; the last ones, seemingly bizarre and out of place in a technological assessment, turn out to be not only germane, but surpassingly important, root causes of much of the difficulty.

Most of those topics, plus intercalated comments, appear in what follows, approximately in that order.

The dramatic decline of the U.S. Nuclear sector -- especially manufacturing, where no new domestic plants have been ordered since 1978 -- can be traced to some of the problems lurking in that list, and to other causes to be described later.

7.2 URANIUM AND THORIUM: RESOURCES, SOME PROPERTIES AND SOME IMPLICATIONS

Both elements can be made to fission, or converted to fissionable material. For reasons to be made clear a little later, uranium is the most important.

Figure 7.2 helps to make clear some of the discussion of this and later sections. It shows the yield of neutrons from fission of the three fissionable elements U-235, U-233 and Pu-239. For high energy neutrons, e.g., 2 x 10^6 ev, fresh from a fission event, Pu-239 ~~fission~~ gives the highest ~~fission~~ yield; thus it is the fuel for fast breeder reactors, of which more later. For neutrons at "thermal" energies, e.g., 0.03-0.1 ev., U-233 is best, but for non-breeding reactors, any one of them will suffice.

A good number to remember is that one gram of uranium, completely fissioned, delivers almost exactly one megawatt-day of energy. Thus it is easy to calculate that a 1,000 MWe nuclear-electric plant, operating at its normal 32% net thermal efficiency for 70% of each year (i.e., 0.7 capacity factor), must use up 800 kg of fissionable material per year. Were it all to come from U-235, the reactor would require 114 tons of natural uranium per year. The proper calculation is more complicated. Not all the U-235 in the reactor is fissioned, but some of the Pu-239 formed during the operation does fission, and the two effects almost offset each other in LWR's now in use. However, U-235 is left behind in the enrichment process, and we shall assume a requirement of 180 tons/year of uranium, a number to be justified later.

Consider now the known uranium reserves and probable resources. The CONAES report listed in 1979 known U.S. reserves of 920,000 tons, plus a probable additional 1,505,000, for a total of 2.4 million tons available at near-present prices, i.e., corresponding to ore with about 0.2% by weight uranium or more. About 55 GWe of nuclear capacity was installed in the U. S. in 1982, and even if the number should rise to 150 GWe by the year 2000, the known and probable reserves would last 67 years.

Other estimates of U.S. probable reserves at present prices range from 1.5 to 8 million tons. Even "present prices" is an imprecise term, as the price of yellow-cake (U_3O_8) rose from $18/kg in the early 1970's to $88/kg in the late 1970's, then declined to $50 by early 1982 as future expectations in the U.S. nuclear sector withered.

Considering the fact that almost all U.S. uranium deposits have been discovered as outcrops, it seems likely that significantly more uranium exists of the quality already discovered, but few incentives exist at the moment to look for it. But even 5 million tons of uranium contains about 3000 quads of energy in its U-235, comparable to the energy in 120 billion tons or (500 billion barrels) of oil. This is the same order of magnitude as oil resources or known U.S. coal reserves -- enough for a substantial contribution to medium-term energy needs, but no solution for the very long term.

A roughly similar statement can be made about expected global requirements for uranium and its expected availability, from Australia, South Africa, Gabon, the USSR and elsewhere, and thus arose the often made but incorrect claim that nuclear power can be no long-term solution for global energy, because the uranium resources are insufficient.

That claim is wrong, because the nuclear chemistry of uranium (and Thorium) permit very different fuel cycles, possibilities with no parallel in chemical fuels. The neutron yield per fission of U-235 by thermal (i.e., ≈ 300 - 1000°K) neutrons slightly exceeds 2; see Fig. 7.2. Thus in principle in a perfect system, one neutron could be dedicated to being adsorbed in U-238 to produce Pu-239, and the other fission neutron to inducing fission of a Pu-239 atom, again yielding a little more than two neutrons. Thus we discover the breeder reactor, which in principle could extract the potential nuclear energy from all the uranium, not just the 0.71% U-235 ~~forma~~tion. But complications arise:

- Neutrons are lost by absorption in structural material (despite use of materials with low neutron-absorption) and even in the light water by neutron absorption in protium to make deuterium. Pu-238 absorbs neutrons to make fissionable Pu-239, but that in turn can absorb neutrons to make Pu-240, which does not easily fission (but undergoes very slow spontaneous fission, too slow to affect conditions in the reactor, but introduces other interesting complications to be addressed later). Some neutrons also diffuse out of the reactor's active region in the surrounding structure and shielding material. The excess neutrons by fission of U-235 ~~on~~ or Pu-239 in thermal LWR's are insufficient to over~~s~~come these losses (but U-233 could in principle be used in a thermal breeder).

- High energy relatively unmoderated neutrons, desirable for breeder reactors (see Fig. 7.2 again) require the reactor to be designed to maintain this high neutron energy, which introduces additional complications.

The reactors themselves will be briefly described in a later section. Suppose for the moment that all this is possible; how would the resources appear then?

Suppose the world's total present technological energy production -- about 10 TW-yr/yr -- were produced by fission; that would require 3700 tons of uranium/year. Already the conservative 2.4 million tons of U.S. uranium would last the whole world 650 years, but that is only the beginning. The continental crusts of the earth contain 2.2×10^{-6} weight percent uranium, or about 6×10^{10} tons in the upper 100 meters alone, enough to last 1.6×10^{7} years, in which time natural geologic processes will have, on the average, turned over the earth's crust more than that. Thus the world could subsist indefinitely by mining outcrops, or very low-grade ores.

Furthermore, mining such low-grade ore would be economically and technically feasible; because all the uranium energy is extracted, rather than just 1%, the raw fuel cost would be very low, even at $5000/kg of extracted uranium.

All these statistics are well known both to proponents and opponents of nuclear power. Whatever problems exist for nuclear power, availability of the basic energy resource is not one of them.

It is possible but now now sure that enough uranium can be obtained at intermediate costs to fuel LWR's (or somewhat more efficient converter reactors) for a very long time, without the need for breeders. The source is sea-water: even at the meager concentration of 3.3×10^{-9} parts by weight uranium, this comes to more than 4 billion tons of uranium, enough to last a 10-TW nuclear world 1.2×10^{6} years. Although the concentration is low, having the uranium in solution is a great advantage. Even so, economic extraction would be difficult, and the most likely prospects at present are for absorption -- possibily on hydrated titanium oxide films or (more likely) on ion exchange resins, followed by elution recovery and further concentration, on large passive surfaces placed in warm ocean waters (to speed the absorption), where natural currents provide part of the flow. The Gulf Stream past the S.E. United States and the Kuroshio extension between Okinawa and Kyushu, and currents near Somalia look interesting. Prospects are very uncertain, but some workers in the U.S. (Driscoll and Best 1981) and

Japan (Yamawaki 1982) estimate uranium might be producible this way for $400-$500/kg. That is noncompetitive now and for several decades at least, but could have important effects -- mostly beneficial -- on future prospects, as will be described later.

Conventional mining of uranium-bearing sandstone, in the U.S. mainly on the Colorado Plateau, proceeds via ore crushing, extraction of the uranium by acid leaching (for low-lime-content ores) or alkaline leaching (for high-lime ores). The remaining solids and slurry mill tailings constitute the major long-term environmental hazard. The Generic Environmental Impact Statement on this topic (U.S. NRC 1980) estimates that a mill producing 520 tons of uranium/year and rejecting 560,000 tons of tailings per year (left uncovered above ground) increases the risk of a person nearby dying from radiation-induced cancer by 0.13% (mostly from radon inhalation), increases the risk of death from all cancers by 0.001%, and increases the risk of occupational cancer death by 2.8%. Covering the tailings piles would substantially reduce these figures, which are already low compared with hazards from coal mining (for instance).

Thorium is judged to be about four times as abundant in the Earth's crust than uranium. It consists of just one isotope, Th-232, which is not fissionable; but, like U-238, it can absorb one neutron to form fissionable U-233. Thus the possibility exists of fission power, even breeder reactors, operating on a Th-232 —— U-233 cycle. See Fig. 7.2 yet again.

Besides the apparent necessity of fuel reprocessing (to extract or recycle U-233) other difficulties arise; for example, U-232 also appears; both it and its daughters are radioactive and their presence complicates the fuel cycle. However, the thermal fission yield from U-233 exceeds that of U-235 or Pu-239, so the possibility of thermal breeder reactors remains alive.

This whole account so far touches on only two extremes: LWRs with no recycled plutonium, and breeder reactors; the uranium resource picture came out dramatically differently. A whole spectrum of reactor concepts lies between, ranging from LWRs with no recycle (nominally requiring 5300 tons U_3O_8 per 30 year life) to LWRs with U and Pu recycle (the full cycle shown in Fig. 7.1, 3000 tons U_3O_8), heavy water-moderated reactors ("CANDU" reactors, 1200-4300 tons U_3O_8, depending on recycle or not), and so forth. Their attraction depends on many things in addition to uranium price and availability: development cost, production cost, optimal size, safety, proliferation resistance of the fuel cycle, for example. See the CONAES report, Chapter 5, especially pages 226 et seq. for examples of different uranium requirements for the same total electric power supply, using different reactor types introduced at particular future dates.

7.3 URANIUM ENRICHMENT

Breeder reactors and some non-breeders will run on natural (or even depleted) uranium, but most require uranium enriched in its U-235 isotope, usually to about 3%, a factor of about four.

Gaseous diffusion of UF_6 through a permeable barrier has been the dominant method up to 1980. Fig. 7.3 shows the generic idea. The enrichment per stage is very small, so hundreds, even thousands of stages form an enrichment cascade, with more stages in parallel at the higher-volume lower end and fewer at the lower-volume higher-enrichment end. The enriched output of each stage goes up in the figure to become the input of the next. Except at the very bottom of the cascade, the depleted stream from each stage is far from useless, being about as much enriched as the input to a lower stage. Thus the depleted streams flow down and join lower-enriched inputs, as shown. Not shown here are the barriers in each stage separating input from enriched output, pumps at every stage, valves, heaters (UF_6 has unworkably low vapor pressure at room temperature), and other components.

The high pressure drop across the many membranes makes gaseous diffusion enrichment very energy-intensive, requiring about 5% of the electric energy generated in LWRs by the enriched uranium, constituting by far the largest energy input to the front end (i.e., pre-reactor end) of the fuel cycle.

Gas centrifuges have been developed (again with UF_6) that require only one-twentieth the power per unit of enrichment, and may be the method of choice in future. The stream flows of Fig. 7.3 apply here also: the U-235 enriched stream leaves on-axis, and the heavier depleted stream leaves at the periphery. The U.S. is adding a centrifuge plant to augment its large but aging gaseous diffusion facilities (built in the 1940's and 1950's); a European consortium (Urenco) operates another, and a third exists in Japan.

The capacity of these enrichment plants is measured in Separative Work Units ("SWUs") per year, which have the dimension of mass flow rate (e.g., kg/year). The lower the U-235 fraction in the rejected tails, the greater is the separative work required. Thus for example, we have from the CONAES report, the following table of the SWU's required to produce one kilogram of 3% enriched uranium. If, for example, the tails assay is to be 0.25%, then 30 tons of 3% enriched fuel require 179 tons of natural uranium (justifying the 180 ton figure cited in the introduction of the chapter), at an energy cost of 114,000 SWUs.

	Tails Assay (percent U-235)		
	0.20	0.25	0.30
Natural U, kg	5.479	5.965	6.569
SWU's	4.306	3.811	3.425

The U.S. gas diffusion capacity is about 18 million SWUs/year, when all of it runs well, sufficient for U.S. domestic and various foreign commitments. Planned additions in the U.S. and abroad, mainly by centrifuges, will handle expected demands into the 1990's, particularly in view of reduced U.S. expectations.

All those schemes can be used to produce highly-enriched U-235 for weapons. It requires about the same number of SWUs to take a kilogram of U-235 from natural uranium to 3% enriched as it does to take it from 3% to 90%: the enrichment is more, but the material to be handled is much less. Thus either gas diffusion plants or centrifuges can be used to make weapons-grade U-235 (e.g. 90% enriched). Gaseous diffusion plants are large, very expensive, energy intensive, and cannot be hidden from satellite observation, thus they are unattractive to nations that aspire to clandestine nuclear weapons. Centrifuges are not so proliferation-resistant; the installations are smaller, and the same centrifuge cascade can be re-used to batch-process uranium to successively higher enrichment. It is believed that would-be proliferations are presently limited to aluminum alloy technologies similar to those applied to advanced commercial aircraft; the higher performance materials used by the U.S. are classified. Nevertheless, a modestly-performing centrifuge string is probably within the capability of many countries at intermediate stages of technological development; the amount of U-235 is not great: 10 kg of U-235 will make a bomb, but 1000 kg. of it (in the enriched fuel) is needed each year for each 1000 MWe reactor.

A third method -- laser isotope separation (LIS) -- may become dominant in the future. It works by virtue of the fact that the mass difference between U-235 and U-238 makes the optical absorption spectra of the two atoms, and of compounds containing them, very slightly different. In the method presently being developed in the U.S., a stream of atomic uranium vapor is illuminated by an intense monochromatic laser flash, which is absorbed by U-235, but not by U-238. These electronically excited U-235 atoms can then be ionized by a second selected beam, and swept electrically to collector plates, while the unaffected U-238 streams through unchanged to a different location. The advantages are (probably) less required energy than even in the centrifuge process, plus the ability to remove almost all of the U-235 from a natural uranium feed stream. Thus tails assays of 0.05% seem quite feasible, and the present 0.2% or 0.25% assay tails presently in storage could even be further stripped.

A similar scheme, using UF_6 vapor and selective laser wavelengths to optically excite it then dissociate it, was studied, and terminated in 1982.

This LIS scheme in principle requires no great space or power, and has conjured up visions of clandestine enrichment plants in national or even terrorist basements. Such national technological proliferation will not come quickly, and for terrorists probably never, because LIS is scientifically and technologically very demanding: the spectral differences are tiny, there are thousands of spectral lines, of which only a few are suitable, uranium vapor is very hard to work with, atomic densities and laser intensities must be carefully controlled, and so forth. However, the technology will almost surely eventually diffuse around the world, thus making possible new national enrichment plans. All this reinforces the urgency of working during the intervening years to reduce the global tensions that stimulate national desires to build nuclear weapons.

7.4 THE REACTORS

This section describes briefly the main features of several types of nuclear reactor: (a) LWRs, the most common kind in service, of which there are two principal ~~kinds~~ types; (b) heavy-water moderated natural uranium reactors ("CANDU"); (c) gas cooled reactors; (d) liquid metal fast breeder reactors; (e) some trends and variations, including smaller reactors.

The first nuclear power reactors were large by 1960 standards, 100 to 200 MWe. But both the electric utilities and the manufacturers noted the evidence of 7% growth/year in electric power continuously over seven decades, similarly noted that components twice as large cost less than twice as much, and also realized that some control and auxiliary components were more or less independent of reactor size. Thus a firm belief in economy of scale set in, leading to nuclear reactor systems of 1100 MWe capacity today. However, the electric sector did not grow so fast in the U.S. or Western Europe, the cost of all nuclear systems (and non-nuclear ones too) increased during the 1970's in ways not at all foreseen in the 1960's, and when such large installations do not run, they greatly disturb the electric utility company, both operationally and financially. Therefore it is time to exhume the topic of smaller power reactors.

(a) Light Water Reactors

Figure 7.4 shows somewhat schematically the layout of a LWR electric power plant, in this case a pressurized water reactor (PWR). First, one can ask, why the water, other than to remove the heat from the nuclear fuel and deliver it to the steam turbines? The water, H_2O, efficiently reduces the energy of the newly-born fission neutrons (at, say 2 Mev) toward thermal energies, chiefly by virtue of the large protium (H) content, which has good momentum and energy exchange with the equal-mass neutrons. The neutrons deliver their energy to the water, and are virtually thermalized at the water temperature before causing another uranium fission. The rising fission cross-sections of U-235 and Pu-239 with decreasing neutron energy leads to an inherent safety feature of "thermal" reactors like these, to be discussed again shortly. Note however in ~~pass,~~ passing, that nearly all the fission energy (about 85%) appears with the fission-fragments which stay inside the fuel pellets.

Consider now the system as a whole. It consists of a reactor pressure vessel, several primary heat exchangers that take heat from the water that has circulated through the core and make steam in a separate circuit to operate the turbines. The steam turbines are conventional except designed to run at slightly lower temperature and pressure than for coal-fired plants (because the reactor operating temperature and pressure, limited by stress and other considerations, is slightly below the steam temperatures attainable with modern fossil-fuel plants). After leaving the low pressure end of the turbine, steam saturated at about 50°C is condensed and delivers its remaining heat of condensation to the condenser cooling water and hence to either a cooling tower or a large cool reservoir (for example, the ocean). Overall efficiency of conversion from nuclear heat to electricity is about 32%. Thus for an 1100 Mwe plant, about 2340 Mw of waste heat appears in the cooling water; a modern 1100 Mwe fossil-fuel plant with net efficiency of 38% (about 40% prior to stack gas cleanup) will discharge about 1200 Mw (thermal) into its cooling system, and about 500 Mw up the stack or into its stack gas cleanup system.

In this PWR, the primary reactor cooling water circulates under pressure from the reactor vessel to the steam generators, never boils, and in principle goes nowhere else. In the alternative design, boiling water reactors (BWR), the reactor cooling water boils at its top, then passes under pressure to drive the steam turbines; there is only one water circuit. The turbines must be specially designed to run with saturated steam.

Figure 7.5 shows the nuclear-specific parts of a PWR more realistically, inside the secondary containment structure that characterizes nuclear power plants, and Figure 7.6 shows the items inside it in more detail, for a PWR. The main parts are the reactor vessel itself (of which more anon), and large pipes (70 cm diameter, for example) that take the primary water to the steam-raising heat exchangers, of which there are at least two, and in the most common design (Westinghouse, Framatone, etc.) four. Pumps in the "cold" legs (which are not cold at all, but less than 50°C cooler than in the "hot" legs) recirculate the water. A pressurizer in the circuit has in its upper part steam, whose pressure is controlled by an internal heater, to control the pressure in the entire system. Not shown are many smaller but essential things: an auxiliary cooling system, to circulate water to cool the shut-down reactor in case the main system is not generating; an emergency core cooling system, that sprays water into the reactor pressure vessel in case of loss of water in the main cooling system.

The pressure vessel itself, its core of fuel, control rods, etc., is shown in Fig. 7.7, again for a PWR. The reactor vessel, typically 12 meters high and 4-5 meters in diameter, with walls 20 cm thick, requires very advanced construction techniques to build. The main cylinder is made up from several ring sections individually forged, then stacked end-to-end and welded. To avoid weakening it near the core where radiation damage to the metal is greatest, all inlets and outlets are located above or below. Pressure inside the vessel and throughout the primary circuit of Fig. 7.5 is about 14-17 MPa (2000-2400 psi), to prevent boiling. A BWR pressure vessel differs from Fig. 7.7 in having a steam separator at the top ahead of the outlet pipes; it operates at slightly lower temperature and pressure, but the overall system efficiency is about the same, partly because of the absence of heat exchangers and primary circulation pumps.

The core may contain several hundred fuel assemblies, each with up to 200 fuel rods (making some 40,000 rods total); at full power, the average heat flux from the rods to the cooling water is about 60 W/cm^2.

A 1000 Mwe LWR contains about 100 tons of 3%-enriched U_3O_8, and in typical operation, the reactor pressure vessel is opened once a year (sometimes 18 months) and one-third of the fuel is replaced. Thus each fuel rod lives in the reactor for about three years, and the fuel burnup is about 3% of the uranium, i.e., about 30 megawatt-days (thermal) per kg of fuel (possibly to be raised to 35-40 mwd/kg as designs and operating experience improve). Thus some 3 tons of uranium disappear per year, about 150 kg of unfissioned plutonium appears in the spent fuel, almost all the remaining mass appears as fission fragments, and about 1 kg of mass was turned into energy via $E = mc^2$.

The many control rods (containing neutron-absorbing cadmium or boron) control the power. The reactors are inherently safe against large nuclear excursions (i.e., explosive-type events) because of their inherent design: the fission yield decreases with increasing neutron energy, as described earlier in this chapter. If it heated up greatly, or even (and especially) if all the neutron-moderating water were to disappear, the reactor would go sub-critical and shut itself down. Another safety feature is the fact that not all fission neutrons appear promptly after a fission event. The few delayed (by many seconds) neutrons permit precise control of the reactor power level with the control rods, and a comfortably long response time of the whole system. However, thermal power excursions could occur if the control rods were withdrawn too far too suddenly.*

In summary, the principal advantages of LWRs are:

- o Most construction and operating experience -- about 300 reactor-years in the U.S., in 1982. Their reliability is comparable to that of coal-burning plants (see Sec. 7.6).
- o Inherently safe against many types of thermal excursions and transients.
- o Ordinary water is inexpensive.
- o Economically competitive (though very capital-intensive, a disadvantage at times of high interest rates).
- o Numerous sources of technology.

Some principal disadvantages are:

- o Neutron absorption (p+n→d) makes them uranium-fuel-inefficient.
- o Requires enriched uranium.
- o Limited thermal efficiency.
- o Nonconventional steam turbine technology.
- o Large volume of pressurized water, an incipient accident hazard (see the discussion of the Three Mile Island accident, later).
- o Requires heavy industry to support its technology.

(b) Heavy-water moderated Reactors (HWRs)

A natural uranium-light water matrix captures too many neutrons in the protium to make possible a power reactor. The Canadian CANDU reactors overcome this difficulty, and also avoid using a large pressure vessel operating at high temperature, by using heavy water (D_2O) as both moderator and fuel coolant in separate circuits, but at the cost of some compensating complications.

Canada was the first country to focus its attention on civilian nuclear power. Faced at the end of WWII with heavy-water production facilities, plentiful uranium resources, no enrichment plants, and an embryonic nuclear establishment, Canada turned in this direction, with much of the research and development stimulus supplied by W. Bennett Lewis.

Fig. 7.8 shows the reactor core, which differs greatly from that of an LWR. Observe first the large tank, called a calendria (7.5 m diameter, 6 m long in the 500 MWe Pickering reactors). It has some 390 zircalloy tubes running between its ends. The tank contains the D_2O moderator at 90°C, near atmospheric pressure. Concentrically through each of the tubes runs a zircalloy pressure tube 10.3 cm diameter at reactor operating temperature, thermally isolated from the calandria tubes; they are shown protruding from the ends of the calandria in the figure. These 390 pressure tubes hold the fuel bundles, and are cooled by D_2O entering from feeders at one end, and leaving via feeders at the other. This collected D_2O circulates through a heat exchanger to raise steam for the turbines, as in a PWR. The heavy water moderator in the calandria goes nowhere, except possibly into the lower dump tank in case of particular emergencies.

The reactor is fueled on-line, as follows. The normally sealed ends of any selected pressure tube can be entered by a special fueling machine (not shown), that works at both ends simultaneously. Each fuel bundle consists of about 30 fuel pins and is only 50 cm long, so each pressure tube holds 12 bundles end-to-end. The machine inserts a fresh bundle at one end, and removes a spent one from the other. In normal operation, several bundles are replaced each day.

The CANDU reactors operate at slightly lower outlet temperature than PWRs (290°C compared to about 320°C) and have lower net efficiency (29%). Despite this, their uranium utilization is more efficient, partly because there are no enrichment tails to discard, and partly because all such natural uranium-D_2O reactors produce Pu-239 more prolifically, and burn more of it up. Total fuel burnup is about 10 MW-days/kg. Calculations show that the CANDU reactor would use uranium even more efficiently (without Pu recycle) if it were enriched to about 1.1%.

The main advantages of the CANDU reactors have been described; its on-line servicing has permitted operation at greater than 93% capacity factor. Main disadvantages are: D_2O is a poor and expensive moderator, so CANDU requires a much more spaced-out core; it uses a saturated steam system; it has a positive temperature coefficient of reactivity, an in-principle unsafety feature.

(c) Gas-cooled Reactors

Graphite is an excellent neutron moderator, was used in the first and many subsequent reactors, and figures in several modern designs. It provides safe and immobile thermal inertia and will structurally support itself and a load of nuclear fuel. Both CO_2 (in the United Kingdom and France) and helium (in the U.S. and Germany) cool the assembly; this permits: higher operating temperature than in LWRs; superheated steam; and conversion efficiency of 38% or more, comparable to that of modern coal-burning plants.

The large core size of these reactors has stimulated development of pre-stressed concrete pressure vessels. They have walls 5 m thick (for example), reinforced not only with normal steel reinforcement in the concrete, but also pre-stressed circumferential and axial steel cables. This type of construction, commonly used on prefabricated bridge and building sections, utilizes the good compressive strength of concrete and the tensile strength of the steel.

The first gas-cooled power reactors put in service in the United Kingdom and France had natural uranium metal fuel encased in magnesium alloy and cooled by CO_2 ("Magnox" reactors). They performed satisfactorily in their time, but the fuel limited the operating temperature and efficiency was low. In service now are Advanced Gas Reactors (AGR) with enriched UO_2 fuel pellets in stainless steel tubes, allowing a reactor outlet temperature of 675°C, and an electric conversion efficiency near 40%. The gas circulators and steam generators reside inside the prestressed concrete pressure vessel, and the British AGR can be fueled on-line.

Only one gas-cooled power reactor operates in the U.S. (Fort Saint Vrain, near Denver) cooled by helium. Fig. 7.9 shows a sketch of a conceptual larger gas-cooled reactor.

The German "pebble-bed" helium-cooled reactor, under development since the early 1960s, received increasing attention in the early 1980s, both in Europe and the U.S. Figure 7.10 shows a small experimental model, with the steam generator and circulation pump all inside the pressure vessel. The fuel is contained in the centers of graphite balls 6 cm diameter, which are dropped in from the top, to fill the core region. The reactor is fueled on-line and has these further advantages: high operating temperature (850°C); capable of withstanding substantial temperature rise without damage, hence virtually immune to loss-of-coolant-type accidents; small size (50 MWth in the prototype shown, perhaps 300 MWth in some applications) hence suitable for industrial use ~~applications~~ as well as small electric grid additions. It appears to be a close approximation to a "walk-away" safe reactor.

Principal advantages of these gas-cooled reactors are: high efficiency; good reliability in Europe; large thermal capacity of the core; apparently good inherent safety. A main impediment to their deployment is that LWRs, developed in part as a consequence of earlier U.S. application of smaller LWRs to navy ships, took over the market ahead of gas-cooled reactors, and now enjoy a commercial lead world-wide. One can speculate that if comparable effort had been put into developing gas-cooled commercial reactors instead of water-cooled ones, the situation might be quite different now.

(d) Breeder Reactors

In an LWR, each fission of a U-235 atom leads to formation of about 0.55 Pu239 atoms, giving a so-called conversion ratio of 0.55. CANDUs and HTGRs have somewhat higher conversion ratio, say 0.7. If the conversion ratio can be coaxed above 1.0, the reactor is in principle a breeder reactor, and will be in fact if the plutonium (or U-233, etc.) is recovered, reprocessed and reinserted as fresh fuel without deleterious loss.

Some proposals have been made, and experimental work done on thermal breeder reactors, but the technical prospects are not bright. The TH232-U233 system offers marginal excess, utilizable only if the neutron parasitic capture is very small. Thus it has been proposed to use a mixed LiF-BeF_2 molten salt moderator-cooler in which the thorium and uranium fluorides are mixed also. The critical and sub-critical parts of the reactor would be determined by wide and narrow regions of the molten salt loop. The advantages would be significant: low pressure, high temperature, a fairly unreactive salt, plentiful thorium supply, etc. But the problems of on-line purification of the salt (to remove fission products, proactinium, etc.), chemical compatibility with the contained materials, etc., made the prognosis gloomy. However, a 7.5 MW(th) molten salt non-breeder was run for several years successfully.

The major present scheme involves the U238-Pu239 cycle (see Fig. 7.2 again); the neutrons cannot be permitted to thermalize, so a non- (or weakly-) moderating coolant must be found that is compatible with containment materials and has other desirable properties. Liquid sodium, despite disadvantages of high reactivity with oxygen or water and of opacity, is the material of choice. It has low melting point, boiling point higher than the maximum reactor temperature, excellent heat transfer properties, does not react with stainless steel or various other construction metals.

Thus we have the Liquid Metal Fast Breeder Reactor (LMFBR), whose present need has been much debated, and whose prospects in the next several decades are uncertain. The U.S. nuclear program, laid out in the 1960's, envisaged something like 1000 GWe of nuclear power by about the year 2000; if that were to be the case, breeder reactors would surely be required by the 1980's, and plans were laid accordingly, including the much-debated Clinch River Breeder Reactor Project, terminated in 1983 after a decade of confusion. Detailed reasons for the delay changed with time, but most centered on whether or when it would be needed, and whether the difficulties attending its widespread introduction (with large-scale fuel reprocessing, the need to guard plutonium, etc.) would outweigh its advantages. The main unique advantage of breeder reactors is the small uranium supply needed to run ~~it~~ them, signifying a measure of energy independence for any country that has few indigenous energy resources but does possess (or have reliable access to) fuel reprocessing facilities. Thus breeder reactors are being vigorously developed in France (particularly), Japan, the United Kingdom and Germany for those reasons. The USSR also has a large program, with a 350 MWe developmental reactor in operation.

The U.S. has spent more money and effort on its breeder program than any other country, but because of the uncertainties mentioned above and corresponding political and administrative policy indecision and changes, has relatively little to show for it. Some claim that a breeder reactor will be cheaper than an LWR, because of low pressure except in the steam system; that appears unlikely. What is very likely is that relatively low uranium prices continuing until the year 2000, projected fuel reprocessing prices of $500/kg, and reawakened interest in better converter reactors than present LWRs combine to delay the large-scale introduction of breeder reactors at least until early in the next century. An early global consensus to avert a global CO_2 buildup would create strong pressures for accelerated development of breeder reactors, but so would it for other non-fossil strategies, and the post-2000 date appears to remain secure.

Consider now the configuration of liquid metal fast breeder reactors. The sodium flowing through the core becomes radioactive, so cannot be used directly to raise steam for the turbines because a heat exchanger leak would present intolerable chemical and radioactive contamination problems. Thus in every design, the primary reactor coolant passes through a primary heat exchanger to heat sodium in an intermediate loop, which in turn passes through a secondary heat exchanger to make steam.

Liquid metal fast breeders come in two main configurations: loop and pot. In the loop-type, presently favored in the U.S., the reactor vessel, sodium pumps and the two heat exchangers all stand separately and are connected by insulated pipes, conceptually in the style of (say) PWRs, but at low pressure.

In the pot-type, favored in France, the reactor, primary sodium pumps, intermediate heat exchangers and fuel-handling machine are all put in a large pot filled with liquid sodium, covered with inert gas. This is possible because the sodium is at approximately atmospheric pressure. Each type has advantages: for the loop-type, easier access to individual components and no need to make a very large pot and its cover; for the pot-type, few joints and surfaces to leak externally, probably easier fuel-handling (which must be done removely under inert atmosphere in any case).

Fig. 7.11 shows the French Phénix and SuperPhénix reactors, as far as the intermediate heat exchangers; the steam-raising parts are separately mounted. Phénix, 250 MWe, has operated since 1974; and SuperPhénix, designed for 1200 MWe, is at Creys-Malville, midway between Lyon and Genève, under Franch leadership with German, Italian and British participation, In SuperPhénix:

The roof slab is 25 m diameter, weighs 800 te.

Each stainless steel vessel (3) weighs 350 te.

The two rotating plugs weigh 640 and 290 te.

This SuperPhénix assembly as shown, plus the steam-raising heat exchangers and other equipment reside in a large cylindrical reactor containment building, 64 m diameter and 84 m high. It is a very large device.

Cores of breeder reactors differ from conventional LWR cores, which have the same fuel mixture throughout. The LMFBR core (with Pu-239 as the principal fissile ingredient) is surrounded by a natural (or U235-depleted) uranium blanket, in which the Pu is bred by neutron capture. The core is compact, to allow little neutron slowing down between fissions. Stainless steel fuel rods contain the fuel.

Fast breeder reactors have special qualities. Because the fission cross section rises with increasing neutron energy (i.e., with less moderation), special care must be taken about the possibility of reactivity increases that could occur in case of sodium voids (i.e., if it boiled) or loss of coolant. LWR cores are designed for near-maximum reactivity in their normal configuration; therefore if the core disassembles in an accident and then re-assembles in some new way (e.g., partly collapsed) its reactivity is less and it is sub-critical; not so with fast breeders, and "core-catchers" have been proposed for the bottom of LMFBRs to distribute any collapsed core in an assured sub-critical shape.* Another design problem with all large high temperature devices designed for high heat transfer is that of thermal stress, for example in SuperPhénix between the "hot" sodium moving from the top of the blanket to the heat exchanger, and the "cold" sodium returning at the bottom; the divider is double-walled, compared to the simpler single-wall arrangement in Phénix.

The dismal vacillation of the U.S. breeder program deserves further comment. The situation at the end of the Carter Administration is summarized well by the U.S. General Accounting Office (USGAO 1980), and what follows is taken verbatim from it.

> For more than three years the Administration and the Congress have been unable to agree on the future role ... The issue boils down to whether the U.S. wishes to rely on nuclear power as a long- or short-term energy supply source.
>
> If a long-term future for nuclear power is desired or even if ... a nuclear option is to be maintained, constructing and operating a fast breeder demonstration plant is needed. On the other hand, if nuclear power is seen as having only a short-term role, the need to continue the breeder program is eliminated.
>
> The LMFBR program was accorded top priority until 1977 when the current administration significantly stretched out ... commercialization ... to about the year 2020. The new policy was founded on

- concern (about Pu239 and weapons proliferation);
- projections (for reduced electric energy growth and increased uranium resources, and that LMFBRs would not be economically competitive for a long time);
- questions about LMFBR safety;
- belief that the CRBR was too small, too costly, technically obsolete.

GAO believes this policy is based on uncertain data and not supported by the evidence:

- The (delayed LMFBR) strategy will not necessarily enable this country to achieve its non-proliferation goals.
- Uranium supply projections are uncertain.
- Unanticipated events, such as the loss of Persian Gulf oil or future constraints on coal supply could increase future demand for nuclear energy ...
- The ultimate economics of the LMFBR are hard to project.
- The LMFBR is no more or less safe than the current generation of LWRs.

  (With the 1980 policies), the U. S. May not even be able to meet (a 2020) date. The LMFBR program
- lacks a clear mission and focus resulting in a considerable waste of time and money.

o does not assure that the requisite institutional conditions for commercialization ... will be in place.

. . . .

After three decades and several billion dollars of research and development on this energy system, DOE officials were unable to provide GAO with an approved and generally accepted plan on how to secure the LMFBR option by the year 2020 even though they recognize the need to have such a plan.

. . . .

The Congress has continued funding the Clinch River Plant every year since 1977, despite the administration's repeated attempts to kill it. Even with continued funding, however, no (construction) work has begun ... the Nuclear Regulatory Commission licensing staff that is necessary (for the CRBR project) has been dispersed ... The 1981 budget requests that the NRC's LMFBR safety research program be terminated, a move that, according to the Commission would cost the LMFBR program about 10 years of development time if work is ever resumed.

(The GAO report at this point also deplores the termination of a smaller gas-cooled fast breeder reactor program.)

. . . .

If this country ... even chooses only to preserve a future energy supply option for possible use if other energy technologies cannot carry the load, the information gathered by GAO supports the position that fast breeder technology should move forward to the construction and operation of a LMFBR demonstration ... the Congress appears to have chosen this path ... it should be noted that constructing a LMFBR (demonstration) plant ... should not be viewed as an irrevocable commitment to commercial deployment ... these can and should be two distinct phases.

... the administration has chosen a different path ... if the program is to move forward, GAO believes ... that the only real alternative is for the Congress to shoulder the burden.

. . . .

GAO recommends that (the Congress) require DOE to demonstrate the viability of the LMFBR technology by mandating the construction of a breeder reactor facility. However, in making this recommendation, GAO wants to emphasize that it is not necessarily advocating the completion of the Clinch River project as the only means of moving the program forward ...

On the other hand, if the Congress cannot reach a resolution on whether to preserve the breeder option or if it does not wish to do so, GAO recommends that it consider terminating the breeder program ... GAO points out, however, that if the program is terminated it could cost many years of developmental time if the Congress later chooses to re-start it. If this should occur, the only available alternative may be to purchase breeder reactors from some advanced, foreign nation.

So the impasse continued until election day, 4 November 1980. The new Reagan administration, committed generally to stimulating decisions via market forces, but also generally favorable to nuclear power (the U.S. Federal nuclear R&D program has never been determined by market forces) might take any of several paths vis-a-vis the LMFBR issue, and the time appeared ripe for a fresh broad and constructive debate, unencumbered by the necessity to defend past positions.* But, as it turned out, the decision had already been made by election day, to push strongly for government support of nuclear power, especially to build the Clinch River Breeder Reactor as its design then stood, all in the midst of simultaneous administration actions to dismantle DOE and remand many of its other activities to the custody of the marketplace. This was greeted joyously by most of the nuclear sector, but since then its longer-term difficulties have become more apparent, even to formerly uncritical supporters, and Congressional support for the CRBR finally collapsed.

(e) Trends and Variations

Both the CONAES study (mentioned earlier) and the International Fuel Cycle Evaluation Project 1977-79 ("INFCE," to study problems of proliferation resistance of reactors and their fuel cycles) looked for more assuredly proliferation-resistant systems than LWRs, and eventual LMFBRs. None seemed both appreciably better and still technically and economically attractive. So that problem remains much as before, but better illuminated than before. However, the few years since then have brought some new ideas, and modifications of earlier views. Three important issues are standardization, smaller reactors, and safer reactors.

Regarding standardization, the U.S. has the largest variety of systems, because of the existence of several suppliers (Westinghouse, Combustion Engineering, General Electric, and Babcock and Wilcox in 1981, of which the first two may persevere in the business), the fragmented electric utility industry, the multiplicity of architect-engineer corporations (who design ~~and~~ plant using components supplied by vendors, then put the plant together), state jurisdictions, and other factors. The process of building a nuclear power plant sometimes seems like deciding to build an aircraft carrier, starting at and with the MIT sailing pavilion dock.

Many other countries with smaller nuclear programs have more standardized ones. Canada has four identical 515 MWe CANDUs with four more to come, and four 740 MWe CANDUs with four more to come, all for Ontario Hydro, a Crown Corporation (similar to the Tennessee Valley Authority in the U.S., but responsible to the Province rather than to the Federal Government). France, with its highly organized program of making its electric sector mainly nuclear, has eleven 920 MW reactors (by Framatome) in service and more coming. The USSR and its neighbors have in operation or under construction about forty VVER 440 MWe PWR reactors.

Some have argued that standardization of current designs is premature (Thomas and Surrey 1981), citing the need for improvement of present reactors, unpredictability about size, economic cost, changing national standards, etc. On the other hand, the Congressional Office of Technology Assessment addresses these very questions and recommends a carefully thoughtout degree of standardization (OTA 1981); they seem to have the better of the argument, as they make these points:

- Although standardization is no cure-all, it can reduce diversity advantageously, in that: designers and safety experts could better focus on perfecting existing designs, the licensing process could be stabilized (with pre-approved designs and only site-specific features to be specially licensed in each case); evaluating and implementing safety modifications for operating plants could be improved.

- Uniform reporting practices and industry-wide participation in reviews of operating experience could be beneficial.

A national safety goal for nuclear power plants would be easier to adopt and turn into practice.

In the early and middle 1980s, with no new U.S. orders for nuclear plants, the issue may seem, so to speak, academic. But judicious standardization could greatly assist in restoring confidence in nuclear systems, and lower the cost, partly by reducing the ever-lengthening time between commitment and operation (see Sec. 7.8 for more on this last point).

Regarding smaller reactors, interest rekindled in the early 1980s, partly because (a) the slower electric power growth meant that overcapacity (e.g., from installing one large reactor) would take longer to absorb; (b) even if large reactors cost less per kilowatt, the capital was not available for many large investments; (c) when a large reactor runs well, it can be a great benefit, but when it does not, it is a heavy burden; (d) smaller reactors might be factory built, with the advantages of standardization and better quality control, and shipped via barges to water-side sites; (d) shorter construction time;

(e) smaller reactors could be used for other purposes -- industrial or even district heat; (f) smaller reactors could be more easily ad~~o~~apted to the needs of smaller electric grids in presently-industrializing countries, and shipped to them by major industrial suppliers (more on this point will appear in a later section); (g) they can, in principle, be built to be safer, e.g., with the heat after shutdown produced by radioactivity removable by completely passive means.

To be sure, smaller size comes at a cost: higher per kilowatt except for the benefits of factory construction; a smaller core, hence higher neutron leakage and somewhat less fuel burnup.

A prime candidate is the pebble-bed gas-cooled reactor, discussed earlier. In addition, here is a brief list of manufacturers who claimed in 1980-81 to be interested and/or active, taken mostly from a report (Egan 1981).

o In France, the Commisariat à l'Energie Atomique (CEA) announced plans to begin developing small reactors for export. Technicatome (a subsidiary of CEA and Electricité de France) propose 300 MWe and 125 MWe models, largely prefabricated. Alsthom-Atlantique, with much experience in naval nuclear propulsion, offers to build 250 MWth or 420 MWth PWR reactor systems complete, with 300°C output steam raisers, refueling system, etc., all factory-built and housed in a containment "egg," suitable for barge transport and final installation; these reactors would weigh 1850 te and 2780 te and deliver 73 or 125 MWe, respectively, at 29% net efficiency.

- In West Germany, Kraftwerk Union announced in 1980 its intention to develop a 200 MW crossbreed LWR -- a boiling water core, with live steam circulating naturally without pumps, to raise turbine steam in a separate heat exchanger.
- In the United Kingdom, Rolls Royce Limited (a conglomerate consisting of Rolls Royce and Associates, Babcock International, Foster Wheeler, and Vickers) in 1978 announced plans to develop a 200-300 MWe prelicensed, standardized, prefabricated PWR, that would be barge-mounted for export. But economic difficulties caused RRL in 1981 to postpone its decision about whether to proceed.
- In Japan, the Agency of Natural Resources and Energy, an agency of the Ministry of International Trade and Industry (MITI) announced in 1981 that it would undertake development of LWRs in the 50-300 MWe range for electric power and other purposes, prefabricated, etc. Also the Hitachi Company, which now makes BWRs for domestic use, stated in 1981 that it was developing a 200 MWe BWR for export. Japan has much expertise in barge technology; the Ishikawajima Harima Company towed a 56,000 te pulp plant to the Jari

plantation in Brasil, in 1978.

- In the USSR, the 440 MWe VVER reactor is available for export, but in sections for site assembly. The USSR is also developing 500 MW th reactors for district heating.
- In the U.S. interest has been weak, but in 1982 started to grow again, especially in the Department of Energy, but the situation remains unclear (1984).
- In Canada, AECL offers a 2 MW thermal reactor for heating single large buildings ~~for~~ for process heat for intermediate-size industries. It is a non-pressurized pool-type device, selling for less than $1,000,000 in 1981.
- In India, the 220 MWe CANDU-type reactors are made domestically and could, in collaboration with Canada, be offered for sale elsewhere, especially to industrializing countries where the extensive Indian experience with incorporating small reactors into power grids could be helpful.
- In Sweden, Asea-Atom proposes to build very small reactors for either district heating or larger ones for electric power, claimed to be ultra-safe against large disruptions. The larger ones could still fall into the category of "small," but they would have to be assembled on site. In any event, their design is so interesting as to warrant a separate discussion, as follows.

The principle behind the Area-Atom designs is that catastrophic accidents, caused by equipment failure, operator failure, or malevolent action in warfare or by saboteurs must be absolutely prevented by inherent equipment design, irrespective of very low (or even vanishingly small according to some estimates) probability of such events. This means: no valves, controls or other devices needed for safe reactor shutdown in the circuit -- they might malfunction or be caused to malfunction; enough residual cooling capacity built in to handle the residual heat generation (about 7% of full thermal power at the moment of shutdown, decreasing to about 0.1% after 24 hours) for several days at least; the possibility of leaving the reactor completely unattended in any operating condition, with assurance that it would shut down safely without operator intervention.

The simplest Asea-Atom design to accomplish all this is incorporated in the "SECURE" district heating reactor, shown very schematically in Fig. 7.12. It is designed to deliver 200 MWth of 120°C outlet water to an intermediate water-to-water heat exchanger, with 13 te of 2.7% enriched fuel, 27 MW days/kg burnup. The containment would be a prestressed concrete reactor vessel (PCRV) as discussed earlier in regard to high temperature gas-cooled reactors. The PCRV would be buried in the ground, and it is assumed that this structure could not fail suddenly or catastrophically (all engineering experience supports this assumption).

The large volume of water inside is ~~to~~ of two kinds; they are connected at the bottom of the reactor (by a matrix of tubes, to prevent turbulence) and at the top by an inert gas seal. The outer water contains enough boron so that if it enters the reactor, the reactor shuts down. The inner volume contains water with much lower and controlled boron concentration, by which the reactor power is controlled (rather than by boron-containing control rods, for example).

Why do the two volumes not mix inadvertently? The primary circulating pump and the consequent pressure drop through the reactor core establishes a static pressure difference sufficient to maintain the difference in upper water levels, and the gas cannot escape through the upper end, nor can water enter. The power is reduced normally by adding small amounts of boric acid solution, as shown, or increased normally by withdrawing some of the borated reactor water and adding pure water.

What if something goes wrong? Suppose the primary pump fails. The differential water pressure disappears, and the borated outer water enters to shut the reactor down. What if the reactor power becomes excessive? The venturi constriction in the outlet pipe causes cavitation and a reduced flow, whereupon again the borated outer water enters from below.

Once the reactor is shut down and the gas has escaped from the upper lock, the reactor core is cooled by simple thermo-syphon action, and the after-heat [redacted] can be removed by a secondary cooling circuit (under normal circumstances) or the water can be allowed slowly to evaporate, with fresh water poured in from the top (if the auxiliary system is inoperative). The reactor is started up by injecting pure water, injecting gas into the upper lock, and controlling the pump speed, all in a carefully programmed way.

Figure 7.13 shows how Asea-Atom proposes to extend this concept to an electric power-producer, in their example, 500 MWe maximum, 294°C reactor outlet temperature. The principal difference is that the differential pressure formerly supplied by the air column is now supplied by the density difference between the heavy cold (50°C) borated outer water and the lighter hot reactor water in the riser. This difference, about 40,000 Pa (6 psi) is again balanced by the reactor core pressure drop and maintained by the primary circulation pump. There is no gas volume. Now the large hot-cold difference requires that the two parts be insulated from each other, for which it is proposed to use multiple layers of what could be described as stainless steel mesh, designed to prevent thermally-driven transport through it.

Operation is much the same as for the simpler SECURE system, except here hot-cold temperature sensors at the upper and lower interfaces control the fluid levels.

If anything goes wrong, the system shuts down automatically, and the large volume of cold water inside the very large PCRV (walls 8 m thick) will remove residual heat during the first week of shutdown. No secondary containment structure is needed (it is claimed) so even the overhead servicing crane can be partly disassembled and removed, thus preventing any access, even by saboteurs.

No doubt this and many other new design proposals put forward elsewhere will have their own peculiar problems. For example, in the Asea-Atom electric power design, there are two circulating pumps and steam generators; what about thermal stress, in case one pump fails and the other does not, then pumps cold water into its steam generator? Nevertheless, many new ideas are being suggested, and the prospects for improvement look good, if industries and governments are awake to the possibilities.

7.5 REACTOR OPERATIONAL ACCIDENTS

Material at the end of Section 7.4 leads naturally to this one, and the topic will be re-visited later as well. Both technical and perceptual aspects complicate it, the latter often dominating. Facts and perceptions sometimes disagree. In briefest summary, performance up to 1982 has shown that the reactors are for the most part well built and safely operated, which is not to say that they have no troubles -- some serious. As evidence, even today in the wake of the Three-Mile-Island accident, and other malfunctions, the number of public deaths and injuries per unit of energy produced lies far below those assignable ~~for~~ to some other major energy sources, and may even be zero. Some benefits of standardization, and the possibility of making large-accident-proof reactors were mentioned before, and several other topics will be brought up here, particularly how accident probabilities and sequences are estimated when in fact no such accidents have occurred, man-machine mismatches (for example in reactor control rooms), and some other assessment difficulties.

Consider first the best-known and much debated Reactor Safety Study (USNRC 1975) ~~-- the "Rasmussen Report"--~~ describing methods of analysis of probabilities of various accidents that might befall light water reactors, in particular for a typical PWR and a typical BWR. Such probabilistic risk analyses are essential stages in the designs of many things that are supposed to fail so seldom (or never) that testing to failure just cannot apply. Neither would such sparse failure statistics shed much light on what might happen in the future. Bridges, airplanes, ground control radars for airports are good examples; so are nuclear reactors.

Figure 7.14 shows how a major part of the Reactor Safety Study was organized. Some initiating accident (a pipe break, for example) was imagined to occur; depending on the condition of the reactor and the proper or improper actions that took place subsequently, various events might occur, leading (or not leading) to the release of radioactive material, and other consequences. Into the calculations go design data, failure rates of components (for example, an auxiliary pump not working when called upon), inventories of radioactive material and their various release rates as functions of temperature and time, etc.

Figure 7.15 carries this concept further, and shows an "event tree," in which an event, or a sequence of them are deemed to have happened or not, or components that have or have not functioned. Some initiating event is assumed to occur, here a pipe break with probability P_A. Was the electric power system working or not at the time? The probability that it was not is P_B, and the probability that electric power was available is $1 - P_B$. Because each failure probability (P_B, etc.) is small, $1 - P_B \approx 1$ and so the upper "succeeds" paths are usually assigned unit probability, with negligible errors: we are interested in the system failures. Thus the sequence continues through all the systems called into play. The best outcome is the top line: the pipe breaks, but everything works as it should; the probability is (relatively) high, but the external consequence is small. The worst outcome, with low probability, is that everything fails, the sequence at the bottom. These "on-off" type ~~fault~~ trees do not include partial malfunctions, for example a reactor core damaged but not melted down, as was the case at TMI-2; but more detailed analyses can include them.

Figure 7.16 shows the other main analytic mode, the "fault tree" analysis. It works in the opposite way to an event tree; in this case, suppose the probability of some end result is to be estimated; in this case, it is the failure to maintain water in the reactor vessel after the Brown's Ferry accident (burning of control cables and loss of function) in 1975. It proceeds by Boolean algebra, via "and" and "or" gates. Here, as it happens, they are all "and" gates (the domed junctions), and the probabilities are multiplicative. That is, where two inputs arrive from below, both must be failures at the next higher stage for the failure to have propagated. Such calculations can be made for nuclear power reactors before they are built, based on their detailed design. Table 7.1 shows calculations made for two PWRs proposed in the 1970s for Rhode Island that were in fact not built. The accident class ranges from 1 (no external consequences at all) through class 8 (which the system was designed to withstand) to class 9 (not designed to withstand). Notice that the largest probable exposure or risk does not necessarily go with the largest accident; the probability of it occurring may be very small. Table 7.2 shows, for these same two proposed reactors, the calculations of radioactive does commitments of people living within 50 miles of the reactor site. Deaths and genetic effects are figured according to the type of radiation release (e.g., 8000 whole body person-rem per mortality, etc).

The health consequences implied from these tables are very small, and the Reactor Safety Study, in its examples, came to the same conclusion. Figure 7.17 shows two figures from the Executive Summary. The Report put the probability of a core melt at 1/20,000 per reactor-year, and of substantial public radioactive release from it much less. The uncertainty was stated as being about a factor 10, either larger or smaller.

The Reactor Safety Study, particularly its executive summary which was an attempt to interpret the 30-cm-thick report (including its appendices) to the general public, caused great controversy. Figure 7.17 referred only to early deaths (e.g., not to latent cancers) but the summary was obscure on this and other matters. The report was welcomed by the nuclear industry and often attacked by critics of nuclear power. In general, the report has stood up well, both for its general methodology and most of its calculations in their order of magnitude; this is particularly noteworthy, considering that it was the first attempt to apply these methods in detail to nuclear power systems. More on that shortly.

The controversy that greeted WASH-1400 persuaded the Nuclear Regulatory Commission in 1977 to commission an independent group to review it. NUREG/CR-04~~4~~0, colloquially 0400 named the Lewis Report after its Group chairman, duly appeared (USNRC 1978). What happened then is instructive of how complex and intellectually honest and earnest attempts to prepare balanced assessments get frustrated by successive stages of selective filtration. The tale is worth recounting in some detail.

In the _body_ of the report, NUREG/CR-0400 says, _inter alia_

1. There were some bad statistical treatments (e.g., the "square-root bounding model").

2. The error bounds should have been considerably larger (both up and down).

3. Some serious common-mode failures may have been overlooked.

4. The short-term and long-term fatalities were somewhat muddled, or hard to distinguish.

5. WASH 1400 in some ways was _too_ pessimistic, e.g., effect of beneficial actions by people, hard to preduct or quantify.

6. The peer review was too flimsy.

7. WASH 1400 should not be used blindly, just as a source of numbers to quote, in assessing reactor safety. Different reactors are different, other uncertainties need to be evaluated, etc.

8. Nevertheless, WASH 1400 was a valuable piece of work, and advanced the methodology and laid a good foundation.

9. In a most unusual section (p. 41-43) the report deals with allegations by Mr. Dan Ford of the Union of Concerned Scientists that the workers on WASH 1400 acted dishonestly, in suppressing information. I quote the last paragraph of the Lewis Report on their page 43; it dismisses the UCS allegation thus:

> "We consider allegations of dishonesty to be deserving of the most serious and careful study; each must be backed up ~~to~~ by evidence commensurate with the seriousness of the charge. It is understandable that an incident such as this should raise doubts among the skeptical as to the overall honesty of the RSS effort. However, this allegation of dishonesty is without merit in our view. Furthermore, we do not accept the argument that this incident can be used as a 'case study,' generalizable to reveal lessons as to the intellectual integrity of the larger RSS effort."

Turning now to the summary of NUREG/CR-0400, we find most of the above sentiments, expressed as follows, in this order:

1. WASH 1400 was a conscientious and honest effort.

2. Found a number of sources of both conservatism and non-conversatism -- which are difficult to balance.

3. The dispersion of radioactive material and the biological effects models should be improved and updated before they are applied in the regulatory and licensing process.

4. Found that the methodology, which was an important advance over earlier methodologies applied to reactor risks, is sound and should be used more widely.

5. WASH 1400 is inscrutable -- difficult to follow -- executive summary is a poor description.

6. The fault tree/event tree methodology is sound, and both can and should be more widely used by NRC. The implementation in WASH 1400 was a pioneering step, but leaves much to be desired.

There was no mention of Dan Ford/UCS in the summary.

Now what did the Nuclear Regulatory Commission do, on receipt of this report? It wrote to every known recipient of WASH 1400, saying that the commission has reexamined it's (sic) views regarding the study in light of the Review Group's critique. In the NRC's words:

> "While praising the study's general methodology and recognizing its contribution to assessing the risks of nuclear power, the Review Group was critical of the Executive Summary, the procedure followed in producing the final report, and the calculations in the body of the report."

(Then followed 31 lines of "major failings," plus 16 lines of "major achievements -- despite its shortcomings").

Then the commission said it:

" ... withdraws any explicit or implicit past endorsement of the Executive Summary"

" ... agrees the peer review process was inadequate -- take whatever corrective action is necessary ..."

" ... accepts the Review Group's conclusion that absolute values should not be used uncritically ... The Commission does not regard as reliable the Reactor Safety Study's numerical estimate of the overall risk of reactor accident."

" ... commission correspondence involving WASH 1400 is being reviewed and corrective action as necessary will be taken"

" ... expects the staff to make use [of component parts of the study] as appropriate, that is where the data base is adequate ..."

" ... has provided additional detailed instructions to the NRC staff concerning continued use of risk assessment techniques ..."

What happened in the general press? The general press account was that the Lewis Report had discredited WASH 1400 and the NRC had accepted the verdict. The Union of Concerned Scientists claimed victory.

This and other interpretations inspired (Lewis 1980) to write his own assessment independent of institutional filtering; it makes excellent reading.

Does the Three-Mile-Island ("TMI-2," being the number 2 reactor at this location on the Susquehanna River near Harrisburg, Pennsylvania) accident 28 March 1979, fit this series of analyses? Yes and no. It showed that the equipment was on the whole more rugged than the median estimates put it; but the operators, company, industry and other sectors were not well enough organized to cope with such events. The media, in the name of public responsibility, enjoyed a week of unlicensed sensationalism. The Presidential Kemeny Commission Report (Kemeny 1979, 1980) makes these points clear. (See also Lewis 1980.)

What happened at TMI is easily seen from Figs. 7.3-7.6. At 4:00 a.m., the steam turbines tripped and left the reactor running, with no heat being taken out of the steam generators any more. The reactor scrammed (as the saying goes), i.e., the control rods went in (Fig. 7.7) and stopped the fission reaction. All this was normal procedure. At this point the residual heat from continuing radioactivity should have been taken out by the auxiliary cooling system, but valves in the system had been inadvertently shut off, and the indicator to this effect was hidden by a tag. The pressure rose in the primary system, and a pressure release valve in the top of the pressurizer (Fig. 7.6) opened briefly, and an indicator light showed this happening. That was normal, too. The relief valve was then programmed to close as the pressure dropped, and an indicator light came on to indicate compliance. But the light was wired to the actuating solenoid, and in fact the valve had not re-seated. Thus the steam generators boiled dry, and the emergency core cooling system (ECCS) came on. At this point, all would still have been in relatively good order, had not the operators, seeing the pressurizer apparently full of water, thinking that the reactor was also full of water, turned off the ECCS. So the core boiled dry too, and heated up (1500°C?) for about two hours. The zirconium in the zircalloy tubes and steam reacted to form hydrogen in the top of the pressure vessel (which was *never* in danger of exploding, despite vivid speculations to the contrary). The core suffered extensive damage; the overflow water poured into a nearby building and onto the containment vessel floor, carrying with it radioactive iodine (mainly as cesium iodide) and other soluble or vaporizable fission products released from the damaged core. The external radiation doses were very low, as determined for example by special monitors set up by the Department of Energy within about 9 hours.

This was a very serious accident, a dramatic lesson to electric utility companies, equipment vendors and the rest of the nuclear sector that nuclear reactors can be expensive and unforgiving; accidents to fossil-fired power plants can be fixed by walking in the next day or two; TMI will cost a billion dollars or more to fix.

This sequence of failures, though without specific "operator errors" etc. assigned, appears in the Wash-1400 event trees, and it leads there to core melt, 1/20,000 per reactor year. But the core did not melt, so we have here an intermediate "degraded core" accident, that had not been analyzed in depth before, and would have had considerably higher probability (but the old estimates on pre-TMI systems no longer apply, because the sequences that led to the accident have now been protected against).

The Kemeny Commission report dwelt relatively little on the equipment failure aspects of TMI; but it and many other past-TMI reports tended to agree on these following points: post-

- The operators had not been trained to deal with such accidents -- only with one failure at a time, so to speak, and that by rote, rather than being trained to understand the system in depth, including the possibility of multiple simultaneous faults.
- The reactor control rooms were designed by people who loved vast panels of virtually identical dials, levers, handles, etc., reminiscent of ancient times when the real operating wires and switches lay behind those panels. The concepts of modern control panels, with interactive display, computer-operated layouts with present-on-demand detail shown in color, now common on many information processing systems, catches on very slowly. Such combined display-control systems now become available, but principally for new installations. Had such a system been installed at TMI, the accident could

not have progressed past its initial stages except by gross neglect.

- As a result of the two previous items, the man-machine interface at reactor control rooms has been deplorable. (Sheridan 1980) writes well about this matter.
- The nuclear industry was disorganized and had no effective means to distribute meaningful information to itself about how the reactors were running. For example, the TMI reactors were made by Babcock and Wilcox, who also made the Davis-Besse plant in Ohio, which had a similar accident two years earlier -- pressurizer valve failed to close, and ECCS system turned off, which was corrected before damage occurred -- but the report of it was hung up in the company and NRC files until too late. Since then, the Nuclear Safety Analysis Center, supported by the electric utility industry and the Institute of Nuclear Power Operations have been set up to fill the gap, in the sense that the National Transportation Safety Board analyzes aircraft component failures and accidents, so as to permit ever-increasing reliability of service.
- The media, especially television, tended to thrill audiences for money and audience ratings with (in Kemeny's words), "in-depth treatment: you get

a full five minutes, with only two commercial interruptions." (Kemeny 1980)

- The Congress has difficulty following or responding to scientific and/or technological issues. Again in Kemeny's words, it sometimes presents its own scientific interpretation and asks the scientists/technologists about the implications to society, rather than the other way around. The Congressional Office of Technology Assessment (for example) can be of much help in this matter.
- The kind of events that led to TMI were warned about in WASH-1400, but tended to have been ignored by the NRC and others, who apparently mesmerized themselves about large loss-of-coolant accidents (LOCA) such as major pipe breaks, to the neglect of small ones. Lewis, in his Scientific American article, quotes his NUREG/CR-0400 report:

  "The achievements of WASH-1400 in identifying the relative importance of various accident classes have been inadequately reflected in NRC's policies. For example, WASH-1400 concluded that transients, small LOCA (loss-of-coolant accidents) and human errors are important contributors to overall risk, yet their study is not adequately reflected in the priorities of either the research or regulatory groups." These three items -- transients, small loss-of-coolant accidents and human errors -- were the central features of the Three Mile Island accident.

Reflect now in a different way on this disheveled state of affairs, unseemly in an activity of such size and importance. At least some of the partipants appear to be unaware of all the parts of the problem; or if aware, they chose to ignore those parts by selective inattention.

First, consider risk, which the WASH-1400 and other analyses define as _probability X consequence_, surely a logical approach, correct for minimizing total damage. But most people do not understand probability as the scientists and engineers would have them do, and this is particularly true about _a priori_ and _a posteriori_ probabilities. _A priori_, the chance of any one particular sequence of heads and tails coming up in a series of twenty coin tosses is about one in a million. But _a posteriori_, the probability of any sequence that _did_ turn up is one. People will understand that, but the translation to reactor accidents is not so straightforward; the event itself stands there before them. Furthermore, suspicions arise that if that accident happened once, perhaps it can happen again; maybe the probabilities were not as claimed; remember Davis-Besse, the precursor to TMI. People have also in mind extensive automobile recalls by the manufacturers, and rarely think of the parts that did not untimely fail.

The case has often been made that public acceptance or rejection relates not so much to the probabilistic risk, but to the size of an individual calamity, pretty much independent of the chance of it occurring. Proponents of such a view recite statistics of automobile fatalities -- 50,000 per year in the U.S., a number apparently deemed high but acceptable. Then again, it is claimed that people are much more tolerant of voluntary risk (e.g., of driving a car) than of involuntary risk (e.g., exposure to radiation from a nuclear power plant), and accident statistics for voluntary and involuntary activities support such a claim.

But there must be more to it: nuclear war would be a vast calamity, and its probability of happening seems surely larger than that of any single nuclear reactor suffering an uncontrolled accident, let alone all of them. It is a relatively involuntary risk; few would vote to try it out. Yet it was difficult to stir up public consciousness on that issue until the early 1980s.

The pro/anti nuclear argument over acceptability of nuclear power, and especially about reactor accidents has aspects that would be bizarrely amusing, were they not about such a serious topic. For example, the entire WASH-1400 Reactor Safety Analysis took as specific examples only two specific real reactors; its authors stated this clearly, and also the fact that all such specific calculations must be based on real designs, because so much depends on the exact configuration. Yet both the pro- and anti-nuclear groups chose not to mention this, the former because they wanted to use WASH-1400 to claim that nuclear power was quite generally safe, and the latter because they wanted to hold up WASH-1400's shortcomings as universally as possible.

Is nuclear power safe? Without qualifications -- "Compared to what?"—We see the question is meaningless. If by safe we mean is it safe enough for general deployment under carefully controlled and continually improved conditions, I think the answer is a yes. But this issue will be re-visited in a later section dealing with public acceptance.

7.6 NUCLEAR WASTES: MAINLY TECHNOLOGICAL ISSUES

Dealing with hazardous or obnoxious wastes has two principal aspects: (1) the base of scientific and technical knowledge, from which the technological option-space for resolution can be developed; (2) the political and institutional arrangements that almost invariably require some transfer of costs and benefits, the irresolution of which often leads to two consequences: (a) wastes tend to stay for a long time where they are first put; (b) regarding their later movement, the "Not in My Back Yard" or

"NIMBY" reaction. This applies to chemical as well as nuclear wastes. Nuclear wastes are much better organized, better collected in known places, occupy much smaller volumes, and offer much less total biologic or chemical hazard than do the chemical ones, facts that only now get much public attention.

Wastes from the civilian nuclear industry and the nuclear weapons programs fall into several categories. Low-level waste (LLW) produced in the civilian sector consists of tools, clothes, and other items that have been or are, or could reasonably be suspected to be, contaminated with small amounts of radioactive material. Three active sites existed in 1982 for its disposal in the U.S. -- Barnwell, South Carolina; Beatty, Nevada; Hanford, Washington, all operated by the Federal Government. Several other sites were closed in the mid-1970's, and Federal Law now aims at turning over responsibility for disposal of this material to the individual states, or (better still) consortia of them. The activity of this material is variable; some of the LLW may require appreciable shielding, but others will require virtually none. Its volume tends to be large, and much has been written about both the need for good initial housekeeping and techniques to reduce its volume (U.S. NRC 1981).

The uranium mill tailings were discussed briefly in Sec. 6.2, and will not be referred to again here.

Transuranic (TRU) wastes are defined as non-high-level waste containing or suspected to contain α-emitting transuranic elements and/or U-233 in excess of 10 nCi/g. This seems excessively low, being about the activity level of 0.3% uranium ore. In the virtual absence of reprocessing of commercial spent fuel, most TRU waste arises from nuclear weapons programs, with smaller additions from naval reactors and various R&D activities. Again, the volume is large per unit of activity. The Federal Government handles disposal of all TRU waste, and is expected to continue.

By far the greatest radioactive burden, although it has the smallest actual volume, is in spent fuel or the high-level waste from its reprocessing: fission products plus unextracted plutonium and other TRU wastes incorporated in them, and their still active decay products. Most attention has (properly) focused on this material and how it will be handled, as summarized in the remainder of this section.

Table 7.3, (from Lester 1982) lists the present U.S. inventory, 1980 production rates and projected inventories of these various categories in the year 2000.

The activity and corresponding hazard of spent fuel and/or high-level wastes are very large, for example about 10^{10}Ci in the fuel of a 1000 MWE reactor at the moment of shut-down after full operation. Much of this activity decays rapidly, even during the first day; what remains for a long time is of principal interest here. Figure 7.18, from Malbrain and Lester, shows the ingestion hazard of these wastes in two forms, according to two successive estimates. It has become conventional to measure this hazard in terms of the amount of water (here meter^3) required to dilute an amount of the waste (here metric tons of heavy metal, "MTHM") to internationally accepted standards for drinking water, if all the waste is dissolved in it. Various features associated with this figure will be discussed below. The inhalation hazard curve (e.g., m^3 of air at maximum permissible concentration per MTHM) declines much more slowly, because of the presence of plutonium and other α-emitting elements, which cause lung cancer at very low doses. However, every scheme seriously proposed for disposing of these wastes has them sequestered in forms and places so unlikely to lead to airborne contamination that the ingestion hazards chiefly determine both the technology and the policy.

Spent fuel and high-level wastes fall into two major and distinct categories, those produced in commercial power plant operation, and those produced in weapons programs, especially during the period before (say) the early 1970's. The commercial material now dominates and will increasingly do so; it consists almost entirely of unreprocessed spent fuel, and will be considered first. Will the spent fuel be reprocessed at all? Reprocessing costs have been estimated in 1982 to be about \$600/kg of heavy metal, which makes the venture quite uneconomic for recycling of plutonium in light water reactors. If that reprocessing cost persists, and uranium from sea-water (for example) costs less, then the economic outlook for both commercial reprocessing and breeder reactors themselves looks very uncertain, or worse, except on such a long term as not to fall in the present technological age. Furthermore, the spent fuel itself is a highly refractory and insoluble ceramic, so disposing of it without reprocessing has benefits. A large additional benefit is the ability to control the fate of plutonium much more assuredly, as discussed in section 7.9 on weapons and proliferation. Furthermore, the various TRU and low-level wastes inevitably associated with reprocessing never appear.

Against these considerable advantages are some disadvantages. A small disadvantage is that the spent fuel from 1 GWe-year of power amounts to about 9 m^3, whereas the HLW separated and solidified amounts to 2 m^3; but along with that comes 100-200 m^3 of TRU waste, albeit at much lower activity level. Now turn to the more detailed study of Fig. 7.18. The latest opinions of radioactive hazards are those given by the International Commission on Radiation Protection, the so-called ICRP-30 data. Consider those data first, in particular as applied to spent fuel. The ingestion hazard declines slowly, with a broad plateau extending to about 500 years; this 500 year bulge arises from formation of Am-241 from Pu-241, which decays with a 13.2 year half-life. The Am-241 has a half-life of 458 years, decaying to Np-237, giving the second smaller plateau that lasts to about 2 million years. This chain Pu-241 (β-decay) → Am241 (α-decay) → Np-237 (α-decay) contributes most of the long-lived hazard of the spent fuel.

Suppose now the fuel is reprocessed; by this is meant removal of 99.5% of plutonium and uranium, corresponding to some early estimates of the best strategy for Pu and U recycle; then the HLW curve of Fig. 7.18 results, and again the Am-241 and Np-237 dominate the long term, but this time only from what was formed while it was in the reactor. But there is a catch to this curve; if reprocessing is delayed for a decade (or longer), the Pu-241 has decayed to Am-241, and the reprocessed HLW curve will approach the spent fuel one. Opinion now inclines toward storing spent fuel for years, even decades, before reprocessing (if ever), so in fact, the upper ICRP-30 curve will probably apply to it.

Now compare the dotted curves of Fig. 7.18, calculated on the basis of the so-called 10CFR20 radioactive estimates, which formed the basis of hazard calculations until 1982. The change is dramatic and important. The early hazards from fission products, mainly Sr-90, Cs-137 and Ce-144 had been significantly overestimated in 10CFR20, but the effects of Am-241 and Pu-237 have been seriously underestimated.

A little-known fact is that the 10CFR20-based estimates would have led to almost all the societal hazard ever to be undergone on account of spent fuel, and especially HLW -- from its generation out to infinite time -- accumulated during ~~occurring in~~ the first hundred years, and half that integrated total would have accumulated in the first 30 years. The past debate over the need for perpetual care, etc., might have been different, if anyone had bothered to integrate the dotted curves of Fig. 7.18 over time, and reflect on the results.

To the extent that the ICRP-30 radiation hazards are spread out in time after all, Figure 7.19 shows the total integrated hazard borne by society from the time of production of the spent fuel (or HLW), out to some year of concern. However, note that of all the projected hazard of spent fuel out to 10^5 years, almost half occurs during the first thousand. The log-log curves, necessary to show the data over such wide ranges, are visually deceptive.

The two "U-ore base" curves of Fig. 7.19 correspond to considering the ingestion hazard to have declined to the same level as that posed by the amount of uranium ore required to have produced the fuel (see also Fig. 7.18). This has been argued to be a logical stopping-point of public concern, especially if the fuel or HLW have been incarcerated in deep repositories.

As stated earlier, nearly all the long-term effects arise from the transuranics remaining in the spent fuel or HLW. According to ICRP-30, the fission products pose an instantaneous hazard that lies below all the curves of Fig. 7.18, and goes virtually to zero at about 600 years. Figure 7.19 shows the integrated hazard. It is virtually all over by about 200 years. A policy implication of that fact will be taken up later.

The standard present reprocessing method is called the PUREX process, wherein the fuel pins are chopped and the ceramic fuel pellets plus all their contained fission products are dissolved in nitric acid. The uranium and plutonium are extracted by counter-flowing this nitric acid solution with an organic liquid (tributyl phosphate in kerosene) into which the U and Pu selectively dissolve (leaving a small amount of the Pu in the HNO_3 solution, leading to the 99.5% recovery mentioned earlier). The U and Pu are further separated and extracted; the nitric acid contains the fission products plus an estimated 0.5% of the original Pu and all the other transuranics. Opinions have been expressed that modern ion-exchange techniques could purify the HLW much better, so as to approximate more closely the bottom curve of Fig. 7.19. The separated Am, Np, etc. could in principle be turned into fission products by reinsertion in a reactor.

The reprocessing-disposal plan for the HLW in nitric acid solution is to evaporate it, calcine it (i.e., heat it to turn it into oxides by driving off the acid), then adding either glass-forming or ceramic-forming fillers to make either a borosilicate or phosphate glass or an inert ceramic. This waste form, cast in slugs, would receive final disposal in a repository.

All these things have been done, either on pilot-plant or full commercial scale; Fig. 7.20 shows schematically the burial of such waste forms in multiple layers of protection, including an overpack that would absorb by ion exchange any waste elements that managed to leak out by mischance (from Lkingsberg and Duguid 1982).

Many suitable disposal sites exist for either unreprocessed spent fuel or reprocessed HLW in the U.S., and opinions among technically informed persons in the U.S. and elsewhere are that all these stages, including ultimate disposal, are technologically feasible, and that even very severe restrictions on permissible release can be met. To show how severe these restrictions are contemplated to be, note Figure 7.21 (from Hinga et al. 1982) -- the item at the bottom refers to HLW repositories. The authors remark about this figure:

> "The PEA standards under consideration are minimum performance criteria and represent a maximum of 0.01 deaths per year to the U.S. population for a period of 10,000 years after disposal for each

repository. This standard, or another more or less rigid, will have to be publicly accepted before the simple question, "Is a repository safe?" can be answered. For perspective, the average medical dose, the dose to the U.S. ~~P~~p opulation that would be necessary to cause roughly the same risk as automobile and bicycle use, the risk due to accidental drowning, and an EPA estimate of the dose to an average U.S. individual from unmined uranium ore are shown.

"The figure also demonstrates a few of the complexities in assessing radiation doses. The natural background for individuals in the U.S. can vary by about a factor of three. Most of the dose is a function of altitude and local rock type. A person living in a brick house may receive about 40 m rem per year more than a person living in a wooden house. Some of the background dose comes internally from potassium-40 (which is 0.0118% of natural potassium) in body tissues. Various elements such as radium are not distributed evenly when they are absorbed into the body, resulting in very different doses to various parts of ~~the body~~.

An average dose to individuals from radon-222, a gas that dissolves in body tissues and the blood, is also shown. This radon tends to equilibrate with the radon in the atmosphere that can vary up to three orders of magnitude at a single location, and two orders of magnitude in a single day. Its concentration is dependent on daily and seasonal cycles and on the weather. Radioactive daughter products of radon-222 are not gases and, when formed, attach to particles that may in turn be respired, giving an additional dose to the lungs. With these difficulties, one can understand why figures on radiation doses are often listed as approximate."

If similar standards for long term release of hazardous material were applied to coal-burning power plants or to most large industries, they would be forced to cease operations immediately.

Regarding suitable sites, the following are the principal contenders.

(a) Extensive salt deposits

Attention until the early 1970's focused almost exclusively on deposits several hundred meters thick. They are extensive in the U.S. and underlie much of the U.S. midwest, and elsewhere (e.g., New Mexico, where a Waste-Isolation pilot Project has been underway since the late 1970's). Their advantages are: no water running through; easy to mine; geologic stability; self-sealing at the pressures and temperatures expected. Their principal disadvantages are that some sites have been drilled earlier with no records kept, and the access holes themselves could let water in, thus compromising the integrity.

(b) <u>Hard Rocks</u>

Large granite and basalt formations exist in the Washington-Oregon-Idaho regions and the Wisconsin-Michigan regions of the U.S., and granite formations exist in New England, California, and east of the Appalachian mountains. Their advantages are good stability, long experience with working in such material, and (if desired) retrievability. Disadvantages are less predictability about water intrusion from underground passages; but some of these geologic structures have drainage paths that lead beneath the sedimentary deposits at the continental edge, thus ensuring very unlikely re-emergence (Bredehoeft and Maini 1981, for example).

(c) <u>Sub-seabed</u>

Some of the oceanic tectonic plates are geologically much quieter and more predictable than the continents, which latter float on the mantle as clumps of light froth on hot soup. These plates grow from ridges in mid-ocean, move away a few cm/year, and after a hundred million years or more are subducted beneath the floating continents. Some regions are particularly quiescent, contain no valuable surface minerals, are covered with think layers of ion-exchanging sediment, so look attractive, at least in a preliminary way. One such region lies approximately half-way between Hawaii and the Kurile Islands. Figure 7.22

from Hinga et al. shows a stylized profile. Other regions of the Pacific and Atlantic Oceans are being studied.

Unlikely or non-viable prospects are:

- o In Antarctic or Greenland ice; the heat would be too much, except for old wastes, and the stability is not good.
- o Outer space (at present); the dangers of an abort or short-fall are excessive.
- o Burnout in reactors or controlled fusion blankets. The separated transuranics could be burned out (thus turning the entire waste problem into a less-than-1000-year one) but the complications of reprocessing, encapsulating concentrated TRU waste into pseudo-fuel elements etc. have been noted; and the fission product wastes would require vast neutron fluxes from additional reactors, a self-defeating scheme.

All that has been said so far applies to wastes from commercial power plants. Some of it applies also to HLW generated in the weapons program, but significant differences complicate the story. The burnup of this material is small (700 mwd/ton, rather than 33,000) in order to minimize the formation of Pu-240 by additional neutron absorption in Pu-239. Thus the fission products have much the same composition, but the higher transuranics are much scarcer, and the active materials are much more dilute at the nitric acid solution stage. These differences would introduce no particular complications to what has been said above.

The big difference arose from what the U.S. Government did in earlier years with the nitric acid solution containing the HLW. The volume of solution was large (at one time about 10^8 gallons); stainless steel would contain it satisfactorily, but at the time of decision in building the reprocessing facilities (1940's-1960's) stainless steel was in short supply and/or very expensive. Thus almost all these wastes were neutralized with NaOH and placed in mild steel tanks, in Hanford, Washington, and Savannah River, South Carolina. Unfortunately, the bulk of the dissolved salts gradually precipitate under these circumstances, so the large underground tanks (600,000 gallons, for example), with their internal reinforcing struts, are very hard to clean out. The salt cannot be re-dissolved with acid: the tanks would dissolve too. Some experiments have been tried to flush out the contents with water jets, with encouraging results, but the work was in an early stage in 1982. Many of the tanks, especially at Hanford, are in poor condition, and some have leaked; many of the Hanford tank contents have been dried to contain a salt-cake, and there they remain. If the wastes could somehow be removed by a (remote) process, they could be treated in new stainless steel containers, and handled by adaptations of the commercial techniques. But cleaning those Augean stables has been estimated to cost $20 billion.

7.7 NUCLEAR WASTES: MAINLY INSTITUTIONAL ISSUES

This partial account of how the wastes from plutonium production reactors were handled brings us close to the combination of technological and institutional complexities that brought the nuclear waste program into both public and private confusion. Legitimate questions have been raised about the adequacy of even the more reliable technological features, for example whether the glassified waste forms will dissolve in a relatively short time (a few centuries) under some conditions of elevated temperature and inadvertent water intrusion (Bates, Jardine and Steindler 1982, for example). But all those problems seem to be under control (as one of the attached problems shows).

It became clear in the 1960's to many persons inside the nuclear program that the waste problem was being handled by the AEC in a manner that would lead to trouble; so it turned out. The problem was not being properly explained to the public, the Congress, or to other groups. Those outside the program had insufficient knowledge, and those inside were adjured by considerable pressure from AEC headquarters to keep as low a profile as possible, on pain of suffering organizational displeasure. This was particularly true of the weapons wastes problems which appeared in the 1960's. One got the impression that the policy was to keep the lid on the topic until those in charge had completed their terms of office. Regarding the commercial high-level wastes, the Oak Ridge National Laboratory was given specific technical tasks with respect to storage in thick salt beds, particularly with respect to a site near Lyons, Kansas, originally selected mainly because it was abandoned and almost free for the asking. Originally it was to be only a test site with no intention to store radioactive material permanently. But bit by bit, as the policy shifted to using it for permanent disposal, ORNL was made aware that its role was purely technical, and all other issues would be handled elsewhere. Furthermore, the task was to be done within a rigidly prescribed total budget -- about $25 million. These foolish arrangements led to selective inattention, for example inattention to the fact that the American Salt Company was solution-mining the same salt bed less than two miles away; or to the fact that the State of Kansas was getting virtually no benefit from the proposed arrangements. Senator Dole of Kansas complained in the Congress in 1971 about the same time that attention turned elsewhere.

An early public assessment of the technical options (but with little mention of the AEC's reluctance to ventilate the problem) was made (by Kubo and Rose, 1973) and after that a vast flood of material appeared. The large increase in funds allotted to the waste disposal program since the early 1970's led to less than proportionate progress. Inspection of the many analyses, most of them forgotten by the 1980's, suggests that many persons and organizations in the trade were primarily more concerned with looking good than doing good. This attitude appears throughout the bureaucracy, where the challenge seemed to be to find an ecological niche or study space in which to fit one more report, or a cross-cutting review of other studies, or whatever. This kind of option space, like the Hilbert space of the mathematicians, has infinite size and dimensions; as more studies get done, more room exists for combinations of them.

The case of the small nuclear fuel reprocessing plant at West Valley, New York (30 miles south of the City of Buffalo), illustrates many of the technological and institutional complexities that developed. An account is given (by Lester and Rose, 1977). The plant was opened in 1966 by Nuclear Fuel Services Inc. (NFS) and closed in 1972, purportedly for modification, but never reopened, leaving as a principal legacy 600,000 gallons of neutralized high-level waste solution in a mild steel tank, precipitated in the bottom -- a tale of the Savannah River weapons plant over again, in miniature. The circumstances of why the plant was built that way as late as 1966 provide opportunities to blame the various participants: the NFS itself; the Getty Oil Company which owns a controlling interest in NFS; W. R. Grace and Company, which started the venture; New York State, which encouraged it; the U.S. Federal Government, which through the (then) AEC provided technical information on operating license and fuel reprocessing contracts without which the venture would have been economically unviable. Such criticism would be uncharitable, but seldom entirely groundless. No out-and-out villains appear, and most participants acted at the time as seemed best under the circumstances; but the time perspectives and assessments were inadequate. For example, the promised AEC reprocessing contract was insufficiently generous to permit installing large stainless steel tanks, so the long-term sludge problem became selectively ignored.

Regarding this waste in the tank, several technical options might be explored: flushing out the wastes (but if only part could be removed, the benefit might not be worth the effort); or drying the wastes <u>in situ</u>; or some combination. Also, who would pay? The NRC planned (in 1977) to do rule-making about the plant in 1980, when NFS was to turn the whole site over to New York State. By waiting that long, the NRC and others would (and did) lose several years. Also the NRC (and others) selectively ignored the main issue, which was getting <u>some</u> kind of public consensus on what to do. The route they were following would lead to court challenger stretching out forever, the problem still unsolved, but (important to the establishment) no one to blame. West Valley, because of the nature of its wastes, posed problems more like those of dealing with the old seapons wastes rather than with any future commercial wastes; nevertheless it required a unique approach and unique NRC rules. But a unique rule is an edict, just as a unique uniform is a costume. The only sensible way to solve the problem would be for the NRC, DOE, the Congress, the State of New York, Nuclear Fuel Services, and the major public interest groups to try to find some mutual trust, then proceed cautiously ~~jointly~~ with experimental studies to find out what the problem really looked like, what could be done, and what seemed in the best interests of all.

A key to progress was for the Congress to require the Executive Branch (the then Energy Research and Development Administration) and the NRC to proceed with exploring the feasibility of various options, with the matter of who was to pay deferred until later; in any event, the Federal Government was likely to be substantially liable, because much of the West Valley HLW arose from spent fuel from the Hanford Washington N-reactor, a weapons-material-producer. So the Lester-Rose proposal developed in detail, at the invitation of the U.S. Congress House Subcommittee on the Environment Energy and Resources in 1977. Every centrally concerned group privately agreed with its recommendations, but every group ignored it, I believe for these reasons:

- The Congress, because it would have to initiate action, and start firmly down a path it had never trod -- to mandate a solution to the nuclear waste problem, a path finally trod in 1982.
- ERDA, because they had no legal responsibility to initiate action, and would only invite trouble if they started, and draw more attention to weapons

wastes lurking in Savannah River and Hanford.

- o The NRC, which had rules and timetables.
- o The State of New York, who could be expected to contribute if they volunteered to take the initiative.
- o Nuclear Fuel Services, who would agree to anything ordered and paid for by the Government, but found maximum security in not attracting attention.
- o The intervenors, who found no simple issues to focus on.

Let us now return to the main issues. Despite recognition of the many difficulties, the nuclear waste management problem continued without satisfactory resolution until 1982. At that time, 8000 metric tons of spent fuel from commercial reactors were stored in spent fuel pools on site, and some reactors would be required to shut down by 1986 if no away-from reactor ("AFR") storage could be arranged. Even with a prompt start on developing test and demonstration HLW ultimate disposal sites, most of the 72,000 tons of spent fuel expected to exist by the year 2000 would be in temporary storage. A key to progress was the assessment performed by the Congressional Office of Technology Assessment (OTA) which, at the Congress express invitation, broke with its non-advocacy tradition and offered a program for Congressional action. Up to 1982, the Congress had never required in law the Executive Branch to develop nuclear waste repositories on any specific timetable; but by doing so, the Congress could cut the knot of prior vacillation, and help to restore public confidence. The OTA saw no insurmountable technical obstacles, and proposed a program with three key elements (OTA 1982):

A. Commitment in law by the Congress to these goals:

(1) Develop several sites on a firm schedule

(2) Contract with electric utilities to accept commercial waste at a respoitory (or repositories) on a conservative date when a repository would be available

(3) To aid the interim storage efforts by utilities, with dry storage demonstrations and provision of some Federal storage capacity

B. Creation of institutional mechanisms to achieve the goals:

(1) Congressional approval of a binding management action program to guarantee meeting the goals

(2) Assured funding via a mandatory user fee, paid by the utilities

(3) Assurance of adequate and stable managerial resources by creation of an independent, single-purpose waste management agency

C. Credible measures to address concerns by states and other groups:

(1) Explicit plans and assured funds for involvement

of lay and technical publics

(2) Development of a regulatory process that allows for the one-of-a-kind nature of the problem

(3) Provision for dealing with state and local concerns such as a formal role in siting decisions and impact studies.

The activities B2 and B3 on funding and creation of a waste management authority have some similarity to proposals for a single-purpose semi-public agency first put forward in logical detail (by Willrich and Lester 1977).

This assessment and other stimuli persuaded the U.S. Congress to pass the Nuclear Waste Policy Act of 1982 (December), requiring the U.S. Government to develop two nuclear waste repositories suitable for either spent fuel or HLW, to start regular operation in the late 1990's. Each final site was to be chosen from among three prospective ones, in order to ensure that the first impressions would not necessarily become last impressions. Thus, one hopes to be emerging from a dilemma succinctly described by Lester (1982): (a) from the point of view of some persons, the acceptability of nuclear power itself awaits the development of a solution to the waste problem; (b) from the point of view of others, how to proceed with spent fuel and HLW awaits a fundamental decision about the future of nuclear power. Something must give; the solution must be found mainly in the in the public sector, because the time perspectives are totally beyond those of the private sector.

All this discussion has focused mainly on U.S. problems and opportunities. Some of it applies straightforwardly to other countries but some does not. The United Kingdom and France reprocess spent fuel for other countries, which want the plutonium back, and a consensus grows that the originating country must be prepared to accept the (solidified) HLW also, a point made as early as 1973 (by Rose and Tenaglia 1973) in connection with a study of the responsibility and longevity of nation-states with respect to attending to long-term problems. But some countries cannot find suitable national sites, for example, Japan. Subseabed disposal looks still uncertain, but very possibly much more attractive than was thought a few years ago. For emplacement in suitable sites (described briefly earlier in this section), the percolation or diffusion of material to the surface (of the seabed) is predicted to be negligibly small. In situ tests with benign tracers must be performed to confirm such estimates, but the state of the art is much better than is generally recognized. For example, it is possible to bore a hole in the ocean floor 4000 meters down, then later return and re-enter the same hole. Thus wastes could even be stored and retrieved (though at considerable expense).

Surely the topic is a sensitive one, especially in the

Pacific Ocean, where the history of nuclear tests has left bitter memories (but about what happened to islands and shallow lagoons, a very different matter from what is being considered here). The debate will also be colored by the history of less careful dumping of low-level wastes in both the Atlantic and Pacific Oceans. For better or worse, international protocols presently discourage ocean disposal of such eastes, no matter how carefully and securely ~~em-ployed~~ emplaced, that excite overt feelings of apprehension and guilt reminiscent of Macbeth's lamentations.* The ocean is, surprisingly enough, populated with selectively radioactive species of animals already, for example, deep-pelagic penaeid shrimp, whose hepatopancreas receives 100 rem/yr by concentrating naturally-occurring Po-210 (Cherry and Heyraud 1981). Such information can be used either to advocate ocean disposal -- the activity is present anyway, or to decry it -- don't make things any worse.

Optimal strategies for disposing of nuclear wastes depend on what we guess future societies will be like. The following passage from Kubo and Rose in 1973 outlined the principal dilemma in these words:

> Suppose we know that our social structure will persist unperturbed and that we will remain fully responsible up to a time T many years in the future; then society will collapse completely and we will

revert to savages. Suppose also that we feel as responsible toward the savages as toward ourselves, and that no reasonable technological option is too expensive for us to afford. (In this hypothetical example, we exclude disposal in space and some other option-terminating strategems.) Under those circumstances we might choose, until nearly time T, to store irreducible nuclear wastes in surface mausolea built to withstand natural disasters, and to watch them assiduously -- each radioactive waste container on its own plinth in a gallery, so to speak. We gain the advantage of preserving technological options, in case anything unforeseen goes awry. But shortly before time T we would transfer those wastes to some subterranean place, chosen, if possible, so that the geologic strata themselves were no special attraction, and there seal them forever as best we could.

The two strategems entail very different features and trade-offs -- the first retains options and provides more safety against both error and disasters, but at a cost of full societal responsibility; the second guards against an irresponsible society at the cost of increased environmental risk. One stresses complete retrievability, the other stresses irretrievability. Deciding which to choose was not a technological matter for that imagined society; it depended on two uncertain things: (1) present assessment of future societal stability, and (ii) depth of responsibility toward future people. Our own choices depend on these two humanistic issues, just as in the caricature above.

Of course technology enters more than that. What mausoleum, and what subterranean disposal? Can the radioactive inventory be reduced or separated into more easily handled materials? Do safe, inaccessible places exist? These questions and more influence the major decisions, and all require study.

The problem is still with us, but recent assessments about nuclear and chemical wastes and possible disposal schemes comes to our aid.

First, the management responsibility should fall on national governments, because (a) the time perspectives of the private sector (and hence the economic incentives) do not match those of the nuclear or chemical wastes, even if the time is as short as a century; (b) international organizations tend to be more fragile, and if an international consortium collapses, the responsibility necessarily falls back on the nations where the physical facilities actually lie. This was also discussed by Rose and Tenaglia. The idea of national control does not preclude the usefulness of private or semi-public participants operating on behalf of the public sector; nor does it preclude useful international arrangements.

Second, the nuclear and toxic chemical wastes should be assessed and handled by the same government agency. Many of the time perspectives turn out to be similar. The present imbalance between large effort on nuclear wastes and relatively much less effort (on a unit hazard basis) on chemical toxic wastes would then tend to be rectified. This is not to say that chemical and nuclear wastes would be disposed of in the same way.

Third, because of the vastly large apparent hazard of chemical wastes, it makes little sense to reprocess spent fuel on a hazard justification, unless the chemical ones are handled, processed and sequestered much less cavalierly than at present. However, if the nuclear wastes are to be reprocessed for other reasons, the ICRP-30 hazard estimates suggest that the idea should be exhumed of removing all the transuranics (not just uranium and plutonium) and disposing of them as pseudo-fuel in reactors. In that case the nuclear waste problem becomes trivial: a few hundred years of relatively modest hazard, for which engineered surface facilities would be adequate.

Only the development of scientifically reliable and publicly believed data will permit resolution of all these matters, whether on land or beneath the sea, and the sooner the better. The commercial wastes increase, the weapons wastes await regardless of what happens to civilian nuclear power, and a decade has been at least partly wasted.

7.8 COSTS OF NUCLEAR POWER

Most of the cost of nuclear power arises from the cost of the plant itself. This is not the case for coal-fired plants (except where coal is particularly cheap), and <u>a fortiori</u> not the case for oil. To see that this is so, consider Table 7.4, which lists approximate fuel costs and energy utilization in electric power plants. The difference between fuels is so large as to override modest inaccuracies of cost.

With this in mind, turn now to the plant capital cost. The first large U.S. commercial nuclear plants were built at \$135-150/kWe, but generally at a loss to the manufacturer who offered complete ("turn key") packages, and under-estimated the final cost. 1982 estimates for future delivery were more than an order of magnitude higher. kWe

Several things happened to increase the cost, the first of which was the manufacturers' realization that the cost should have been higher in the first place. The second was changing regulations for construction, mainly required by increased safety standards, that virtually doubled the amount of steel and concrete per kilowatt capacity in the plants between the mid 1960's and the mid 1970's. Third, the time between commitment to build and initial commercial operation increased drastically from about 6 years at the beginning to about 12 years at present; that stretch-out, coupled with the rapid increase in interest rates, increased the cost still further. (Eden et al. 1981) quote U.S. government cost estimates rising from $140/kWe for 1967 start and 1972 completion, to $715/kWe for 1976-86 start-completion, all in current dollars corresponding to the start of construction. kWe / kWe

These costs are now yet higher. Figure 7.23 from Ebasco Services Inc. (Olds 1981) shows their 1980 estimmates of costs (in 1980 dollars) for power plants coming into commercial operation in 1992. Note the moderate difference in direct construction and engineering costs ($646, $692 and $979 for the three cases shown), and the large difference in allowance for funds during construction ("AFUDC"). This latter term replaces what was called interest during construction, recognizes that the funds are obtained and spent at various times during the activity, and that the finance charges do not correspond to interest on the total cost for some fixed period. The escalation during construction was judged to be 8%/yr, and AFUDC was based on money being available at 9.5%/yr. Those numbers fluctuate with time. Olds

Estimates of future cost vary with local conditions and with who makes the estimates. (Corey 1981) gives a detailed account of costs at the Commonwealth Edison Company in Chicago, both for past performance and future expectations, and the following data come from his report. Table 7.5 shows data for the period 1977-1980, allowing \$0.002/kWhe for eventual nuclear fuel disposal costs. The kWhe factor of about 2 advantage for nuclear power in 1980 reflects in part the historically lower cost of nuclear plants, compared with expected future costs.

Turning now to estimated future costs, Table 7.6 shows Corey's estimates for costs in 1980 for 1991 operation, for fixed cost of money during the period, as described in note b of the table. The "zero escalation" refers to the imaginary cost of building the plant instantaneously in 1980, and includes no interest or escalation. Thus compare \$1149 or \$785 in Table 7.6 with the base costs \$979 and \$692 in Figure 7.23; differences of 10-15%, like this, are common, and represent different locations, plant specifications, labor costs, etc. The Commonwealth Edison cost of \$2035 or \$1695 could be compared with Ebasco's \$2557 and \$1645 in Fig. 7.23.

Table 7.7 shows the estimated total busbar costs for the reactors described in Table 7.6. For the nuclear plants, the carrying charges dominate, but for the coal plants, carrying charges constitute about half the total, figured on the first ten years of operation, and much less over the full service life. Here, coal cost was stated as \$1.35 per million BTU for high sulfur coal, \$1.50 per million ~~BTU~~ Btu for low sulfur coal (from Montana), and all costs increased at 6, 7-1/2 or 10%/year.

In every case, nuclear power turns out to be cheaper; but as Corey points out, the difference is not so great as to swamp all other considerations, such as maintaining some diversity of options for the Company (e.g., in case of interruption of coal supply, or unexpected service difficulties with nuclear plants). Transportation constitutes about 70% of the delivered cost of coal in Chicago, according to Corey; thus changes in location or in technology of coal transport (e.g., via coal slurry pipelines) could tip the economic balance the other way. Nevertheless, the approximate 15% cost advantage of nuclear power is typical for the U.S.

These costs of nuclear power are high; but coal and especially oil are higher. In other countries without copious coal, such as France, Japan, Korea and Taiwan, the disparity is even greater. Why is it then that in the U.S. no nuclear plants have been ordered between 1978 and 1984 (when this is written), but many have been canceled, and the prospect of any nuclear plant orders before (say) 1990 is dim? More than that, why is it that some nuclear plants came on line in the 1980-82 period at a cost of about $1000/kWe, comparable to modern coal-fired units with effluent controls, yet others cost $3000/kWe, still uncompleted?

The nuclear steam supply system of an electrical generating plant usually costs not more than about 20% of the total. Its existence also increases the cost of the balance of the plant: emergency water and power, protection against damaging the nuclear system in case of a steam turbine breakup, more security facilities, etc. However, the furnace, steam pipes, effluent controls and coal-handling equipment of a coal-fired plant are also expensive. From such cost comparisons, one might expect complete nuclear plants to cost about 10-20% more than their coal-fired equivalents.

Nevertheless, much larger differences in nuclear costs exist, and much of the answer lies with the quality of electric utility and architect-engineer management. Nuclear power plants require a higher degree of technical and managerial skill in their construction and operation than do coal-fired (or oil- or gas-fired) plants. Some electric utility companies are well-prepared for the task; the Commonwealth Edison Company, whose cost data were given in the tables, is one of them, and several others could be cited. For them, nuclear power plants have been built approximately on budget, on time. Many other electric power companies were relatively unprepared for the task, and found themselves in a morass of technical, regulatory and environmental difficulties peculiar to nuclear power. These complications and delays led not only into increased cost of the nuclear part, but tended to throw the entire construction program into disarray. Thus the nuclear part levered the entire cost far beyond what would have been dictated by engineering considerations alone.

Aggravating these difficulties was the drop in growth rate of electricity demand in the U.S., from about 7%/year throughout seven decades before 1970, to about 2%/year by 1980, and even a slight shrinkage in 1982 (possibly arising from the economic recession). Thus the electric sector became substantially overbuilt in many parts of the country, and many nuclear plants ordered enthusiastically in the early 1970's because of rising oil and coal prices were postponed, or their completion was slowed. The additional burden of high interest rates in the late 1970's and early 1980's made some partly-built nuclear plants an intolerable economic burden to electric utility companies; payback lay so far in the future that it was more attractive to cancel than to proceed. Indeed, some banks made cancellation of partly completed plants by utilities a condition on continued financing.

All this suggests that if the cost of money remains well below its 1980-82 peak, if electric power demand increases at even 2%/year, the public climate is not adverse, and the various utility, government and other professional groups resolve some residual problems, nuclear power plants will be ordered from about 1990 onward, as the present excess generating capacity dwindles away. I believe that the probability of these things happening is moderately good. Not so clear is whether the technological and engineering lead will still reside in the U.S., or will have shifted to Japan and/or Europe.

7.9 NUCLEAR POWER AND NUCLEAR WEAPONS PROLIFERATION

Preventing widespread nuclear war brings us only to the threshold of a more just, participatory and sustainable society, hence should be important to all people. The connections between civilian nuclear power on the one hand, and nuclear weapons and international stability on the other are complex; this section summarizes some of the main issues.

Some have claimed that the connection between nuclear power and nuclear weapons is absolute, intimate and essential*; if that were true, we could solve the nuclear war problem by banning all nuclear power. Unfortunately, things are not so simple; the connection is more tenuous and subtle.

First, here is a brief historical overview, especially about U.S. actions. In 1945-56, the U.S. had a virtual monopoly on nuclear technology, and offered via the so-called Baruch Plan to surrender this monopoly to the fledgling United Nations in exchange for effective global control. The USSR cast its First Security Council veto against it, so the U.S. until 1954 kept its nuclear power research and development largely to itself. In the meantime, the USSR and the UK produced nuclear weapons, and later civilian nuclear power reactors.

In 1953-54, seeing no way to keep nuclear power out of general world trade, or to stop weapon proliferation by a process of secrecy and denial, President Eisenhower initiated the Atoms for Peace program, as one of peaceful collaboration. So through the 1960's there was global interest to develop the benefits of nuclear power, but not the disbenefits of the bomb. Meanwhile, France and China had exploded nuclear weapons, and the USSR and the U.S. continued their vertical proliferation.

The Nuclear Non-proliferation Treaty (NPT) drafted in its final form in 1969 has been the most serious attempt to date to reduce the weapon hazards, and foster peaceful collaboration. Its main provisions are these:

- The (then) nuclear weapons states that are signatories agree not to transfer technology or materials applicable to making nuclear weapons to any non-weapons state.
- The non-weapons signatories agree not to develop nuclear weapons, and to open their civilian nuclear programs to international (International Atomic Energy Agency, IAEA) inspection.

- o Countries having substantial nuclear expertise agree to assist other countries in developing nuclear power for peaceful purposes.
- o The nuclear weapons states take positive steps toward stopping their nuclear weapons roles and to reduce their nuclear weapons stockpiles.

In 1982, about 116 countries had signed the NPT, including the U.S. and the USSR; but some important ones had not: Brasil, France, India, Israel, South Africa, for instance. The inequalities in the NPT between nuclear-weapons states and non-nuclear-weapons states, and the ambiguity of where the dividing line between "sensitive" and "non-sensitive" technology should be drawn, were obvious from the start, but it was the best that could be done at the time.

Several circumstances in the mid-1970's caused the U.S. to re-think its position. The IAEA inspection capability was and continues to be inadequate, because of low budget and the need for advance notice of inspection in many cases. India had exploded a nuclear device in 1974; Israel and South Africa were suspected of producing nuclear weapons secretly, and others seemed likely to be interested in acquiring them (e.g., Pakistan and Libya).

In 1976 the U.S. started on a different policy, which became fully developed by the Carter Administration in 1977, which changed the U.S. image at home and abroad, and continued its effect into the 1980's. Citing the problems just mentioned, the U.S. would take steps to restrict export of material and technology related to the nuclear fuel cycle and to restrict the re-transfer of exported U.S. nuclear technology to third parties. The U.S. would defer indefinitely the reprocessing of spent nuclear fuel from domestic nuclear power plants, and would try to persuade other nations to follow this good example. The U.S. would increase its capacity to provide enriched uranium for LWRs overseas, to be used according to strict U.S. material accounting rules. The U.S. would also de-emphasize development of breeder reactors, in particular the Clinch River Breeder Reactor (CRBR). (Rose and Lester 1978) gave an early-1978 policy analysis of all this, and what follows incorporates some parts of it, in summary.

The need to re-focus global attention on the horizontal proliferation, as it is called, was clear enough, with many countries making plans for large (and often unrealistic) nuclear futures. The new U.S. policy stimulated many critical comments, among which were:

- stopping the CRBR (a possibly meritorious action but one requiring its own justification) and stopping weapons proliferation had little apparent connection, and the latter action was seen in some quarters as an excuse for the former.

- The U.S. "no-reprocessing" example was incomplete; production of plutonium for nuclear weapons continued as before.
- According to some persons, the new policy would present the U.S. as an unreliable partner, which would damage U.S. nuclear trade relations, as foreign buyers turned elsewhere for materials and services. Uranium that had passed through U.S. hands would acquire a pejorative label.
- The U.S. Administration, far from being naive in all this, wanted the U.S. nuclear sector to collapse, and this policy change was part of the program.
- Contrary to both the two points just above, the U.S. move to support LWRs and their fuel cycles abroad via U.S.-controlled things was seen by others as an aid (albeit clumsy) to the overbuilt and ailing U.S. civilian nuclear industry.
- Implied in the new policy was a redrawing of the line separating peaceful uses of nuclear energy from violent ones, and therefore a redefinition of proliferation. Traditionally the latter had been defined as the acquisition of nuclear weapons. Now, however, the new U.S. position was being interpreted as an attempt to redefine

proliferation as the capability of acquiring nuclear weapons. Had this always been the case, it could be argued, negotiating the Nonproliferation Treaty would have been impossible in the first place.

To this the U.S. Administration replied that the sections in the NPT on peaceful collaboration must be interpreted in the light of the sections that prohibit nuclear weapons materials and technology, and clearly spent nuclear fuel and many other nuclear things could be applied to producing weapons.

- o Neither the U.S. or the USSR had appeared to pay any attention to the NPT requirement to ameliorate their nuclear arms race; 10,000 megatons was much more important than a few kilotrons (though all are to be deplored) and the U.S. should re-examine its priorities.
- o The U.S. attitude was insensitive to the needs of many other countries that, unlike the U.S., had no large indigenous supplies of fossil fuels; for them, vulnerable as they were to international oil prices and without the U.S. options available to them, decreasing ~~increasing~~ international trade in civilian nuclear systems seemed unreasonable.

o The new U.S. restrictions would not work anyway, and might in fact have the opposite effect.

The perception of the U.S. Administration then, and of other groups then and now can be analyzed with the aid of a sequential logic diagram, Figure 7.24, which is useful in clarifying some of the main proliferation-related trains of thought and their impact on international security. Several paths appear in the diagram. Concentrate first upon the solid lines, and the boxes that they connect. Two main sets of solid lines appear there. First, there is the horizontal decision path that could be followed by a nation (let us call it Y) that does not now possess the nuclear technologies in question. The central questions affecting international stability are whether or not nation Y decides to develop a general capability with respect to nuclear weapons and once it has decided to do so, how long it would take to acquire that capability.

The second set of solid lines at the left of the figure connects several vertically arranged inputs to Y's dicisions. The U.S. saw the capability to reprocess nuclear fuel as a stimulant to weapons proliferation because Y would then have a source of seapons-grade fissionable material: such accessibility might be instrumental in a decision by Y to acquire nuclear weapons, and in any case once the decision had been made the reprocessing capability would help Y to move toward the right in the diagram: toward the weapons themselves.

The sequential arrangement of events so far depicted is too simple. A decision to acquire nuclear weapons might be a prolonged process, and it could be made in parallel with (or could even follow) the acquisition of some of the technological components of a civilian nuclear-power program, which would also be useful for the development of a weapons system. For example, that would be the case with a commercial reprocessing plant, assuming that in its normal operating procedure it produces plutonium separated partially or completely from the other constituents of irradiated fuel. Such a reprocessing plant would therefore be ambiguously perceived by observers even if that were not the intention of a peaceful nation Y. The Administration saw that by substantially restricting its nuclear exports (the black bar at the upper left of the figure) a substantial barrier would be erected against Y's either sliding consciously or sliding unconsciously into a technological competence applicable to the manufacture of weapons.

Of course the Administration realized that other routes exist whereby Y could obtain fissionable material suitable for weapons. First, it might import the necessary technology from elsewhere, but for some time the U.S. had been actively attempting to close those routes by seeking to persuade the other major suppliers of nuclear materials and equipment to exercise restraint in the transfer of "sensitive" items that might offer increased access to weapons-grade material.

All the other routes involve a conscious decision by nation Y and a substantial effort on its part. It could develop its own civilian fuel-reprocessing technology, fully intending peaceful uses only, then have it subverted later after a change of attitude on the part of its government. Alternatively, it would attempt the production of weapons-grade plutonium in research reactors (as India did for its 1974 nuclear explosion) or in a small clandestine reactor, in either case recovering the plutonium from the irradiated fuel in a small reprocessing plant built expressly for the purpose, a task much easier (and cheaper) than the development of the technology and the construction of the plants for commercial reprocessing. Still another alternative could involve diverting irradiated commercial fuel to a clandestine reprocessing plant from a temporary storage facility, where it might have been awaiting either commercial reprocessing or, in the case of a once-through fuel cycle, ultimate disposal.

Rather than work with plutonium from spent fuel Y might attempt to extract U-235 either from natural uranium or from LWR fuel. Several candidate processes appear in the figure.

Turning to seemingly more bizarre activities, country Y might employ agents to steal material from abroad or buy it in a black market, an open market or an intermediate "gray" market. It could receive such material as a gift or a loan from another government. It might steal an assembled weapon or even be given one. None of these activities can be excluded, and some may be more likely to occur than those described above.

A really effective barrier to weapons proliferation would involve blocking all the lines marked with a black bar in the diagram. That is impossible, but the U.S. was only trying to make weapons proliferation substantially more difficult. Combining technological denial with an assortment of incentives related to the supply of enrichment services for light-water-reactor fuel (to be used by Y under tightly specified conditions) would, the Administration thought, significantly increase international stability.

Several other decision paths of a different nature exist, on which the U.S. Government has only an indirect influence: the principal ones are marked with light-colored bars. Why does Y decide to acquire a weapons capability in the first place? Why does it actually build nuclear bombs? Why might it use them? The answers to such questions depend on many things, and a long-term policy not to proceed at any one of these decision points makes all the technological elaborations irrelevant. The converse, however, is not necessarily true. A decision to proceed might be heavily influenced by the technological capability in place at that time.

Up to this point, the U.S. actions appear either beneficial or at worst ineffectual. That was the U.S. Administration's logic at the time.

Now examine the dashed lines and the additional boxes that they connect. All these paths are more or less destabilizing. First, more pressure arises on other fuel resources both in the U.S. and abroad, which would be aggravated by continued high U.S. oil imports (fortunately the U.S. imports did decline, but the global relief may not be long-lasting); the U.S. nuclear sector was in danger of collapse, and these further restrictions could push it further in that direction. Japan and most of the advanced industrial nations of Europe have meager fossil fuel supplies themselves. All of them see an increased incentive to push ahead with their own nuclear programs, including reprocessing and breeder reactors, and look for suppliers with long-term stable policies, not mercurial ones.

What did leaders of developing countries see? They saw a rich U.S. liable to forego nuclear power, and continued pressure on the world's supply of oil. They saw, among other things, an offer of nuclear-fuel supplies that would bind them to the goodwill of the U.S. and other developed countries for even limited nuclear assistance. They saw the growing appearance of a world divided into an oligopoly of developed states that turns into an oligarchy as nuclear power becomes more important throughout the world, and a coterie of less developed nations that must fall farther and farther behind. The inevitable result was an increasing distrust of the U.S. as a reliable partner, the consequences of which will be felt through the 1980's.

As remarked before, all these additional considerations shown by the dotted lines in the figure are destabilizing.

Not only does country Y find logical incentives to install domestic nuclear-fuel facilities, but also it perceives a world more fragmented and less secure. Feeling less secure itself, it naturally imagines others feeling the same way and hence it must increase its own security unilaterally. Escalation of uncertainty leads to escalation of international instability; a program originally intended by the U.S. to decrease the dangers of nuclear proliferation inadvertently has the opposite effect. Meanwhile the U.S. isolated itself from the mainstream of world nuclear policy, and its ability to favorably affect that policy diminished.

Every five years, an NPT review conference convenes (1975, 1980, (1985?)) to assess the state of affairs. At the 1980 conference in Geneva, Committee I execrated all three NPT weapons states (Great Britain, U.S., U.S.S.R.) for negative progress toward nuclear arms reduction; in Committee II, the U.S., Canada and Australia came under severe attack, especially by the "Group of 77" non-aligned nations for unilateral imposition of export restrictions, generally along the line just described. Some declared that the NPT was dead, but that was hyperbolic. No non-weapons states that were parties to the NPT had violated it; despite its shortcomings, it remains important to world security, in need of support and strengthening rather than rejection.

Along with the attitudes criticized so far, the U.S. did some good things. By calling for and supporting the International Fuel Cycle Evaluation (INFCE) and domestically its Nonproliferation Alternative Systems Assessment Program (NASAP), it re-focused attention on the entire question of fuel cycles, reactor types, and safeguards. The reports of those studies in 1979/80 concluded that there was no technical fix to prevent weapons proliferation. Technology would help, but the main thrust had to be political and social. It was much easier to build a small dedicated plutonium-producing reactor and reprocessing laboratory in secret for $50-100 million than to try to subvert a large visible public facility.

Nevertheless, that last argument and others of the same sort, often made in order to claim that restrictions are useless, is partly flawed. The secret reactor (or centrifuge, etc.) will need some trained engineers to build and run it and use its products; their existence will not escape the notice of attentive governments abroad, and the price of camouflage may be a civilian nuclear program.

Next, consider international safeguards themselves, of the sort that are of interest to the IAEA. (Kratzer 1980) presents a very readable summary. As he says, the problem is more akin to measuring bean-stalks than to counting the beans. Regarding the technology of it, the consensus has developed that the aim is to be able to detect with a high degree of assurance, the diversion of a quantity of potential explosive material corresponding to an explosive device, before that device could be constructed from the diverted material. Increased deployment of nuclear systems, and especially of fuel reprocessing plants, makes the problem increasingly difficult as time passes.

Two approaches complement each other: materials accountability on the one hand, and containment and surveillance on the other. Some advantages and disadvantages are shown in Table 7.8, but the qualities are more relative than absolute. In any event, detailed access is needed to the plant: to ensure that the data are true, and not fabricated; to ensure that samples of solutions are not bogus; to check for dummy fuel elements in the reactor by checking its performance; to check for dummy spent fuel by checking Carenkov radiation in the spent fuel pool; and many other tests. The inspectors must be as familiar with the plant as the technicians and engineers assigned to operate it, which requires a degree of international access and forebearance hitherto rarely seen.

These difficulties associated with independent verification, especially of flows of chemicals, and support, ~~and~~ underscore the U.S. (and other countries') search for fuel cycles in which simple counting of items suffices for the whole cycle -- for example, counting fuel rods and bundles, which can be done with good probability of success. That reason, among others, makes the idea of optimized non-reprocessing fuel cycles attractive. Getting uranium from sea water at a price lower than reprocessing would yield both political and economic benefits.

To conclude this section, we return again to the question of why nations want to build nuclear bombs in the first place. Consider countries that could have made them but chose not to: Australia, Belgium, Canada, Italy, Japan, Netherlands, Sweden, Switzerland, West Germany, for example. They are all relatively secure, do not feel oppressed, have strong democratic institutions and mechanisms for public debate of important policy questions, and find their security in international cooperation, a security that would dimish rather than increase if they made nuclear weapons. Lists of prospective proliferators -- Argentina, Israel, Iraq, Libya, Pakistan, South Korea, for instance -- show a partly or completely opposite set of circumstances. Policies based primarily on denial might appear to work in the short term, but are liable to hinder the formation of a more constructively cooperative world in the long term.

The whole matter is quite different from, say, that of national gun control, which has sometimes been used analogically in arguments supporting national or international prohibition of nuclear power. Nearly all countries impose strict limitations on the rights of their citizens to possess guns. Were there an effective and accepted world government, such a prohibition on nuclear arms as a matter of (global) law would be both logical and practical. In the absence of such an organization, or at least in the absence of a much more widespread affection of its citizens and individual governments for one another, some countries will imagine themselves to be more secure by arming themselves in a lawless world, just as some citizens went about armed in the lawless western U.S. a century ago.

All this reinforces the urgency of struggling toward a more just, participatory and sustainable world society, a theme underlying many topics in this book.

7.10 NUCLEAR POWER FOR LESS-INDUSTRIALIZED COUNTRIES

The high cost of oil, prospective availability of smaller reactors (see Sec. 7.4), uncertainty about availability of alternative energy supplies, and national ambitions, all in varying proportions excite interest for nuclear power in less-industrialized countries, especially in ones now industrializing rapidly. Against this are, inter alia, high capital costs, problems that always accompany imported technology, lack of trained manpower, often small and unreliable indigenous electric grid systems, reliability of suppliers, and complicated issues of nuclear weapons proliferation. Technology Review offers two partly opposing views (Miller 1979, Egan and Arungu-Olende 1980), the first dealing more with problems of international security and proliferation, the second more with costs, ~~[illegible]~~ appropriateness, and so forth.

Nuclear power for an industrializing country is different from, say, having a national airline that competes for world trade with wide-body jets. All the Boeing 747's and Douglas DC-10's are made to the same standards in factories. Safety standards and retrofits are generally agreed upon universally, and enforcement is effective and automatic: if one country will not make its airplanes safe, other countries won't let them fly there. Much, even most, of the major maintenance and repair can be contracted to organizations in other countries if necessary, and whole modules -- engines, wheels, etc., can be flown in and replaced easily. Thus a highly competent flying, scheduling, business and routine service staff can run such an airline successfully. Contrarily, a nuclear reactor is (up to now) largely custom-built, immovable, must be serviced on site, is far less controlled by international safety standards, and requires extensive indigenous skills to maintain.

Until the early 1970's, interest in this matter was small: oil was cheap, reactors were large and growing larger with no good small ones being offered, and so forth. The year 1973 started to change those perceptions, and the then-U.S. Atomic Energy Commission contracted for a study to be made. The resulting report (Barber Associates 1975) pessimized the prospects, partly by (a) assuming that only 1000 MWe reactors would be available; (b) assuming that 20,000 MWe grids would be required to incorporate them successfully; (c) taking insufficient account of the expected rate of growth of energy, and especially of electric power; (d) not foreseeing yet higher oil prices in 1979-1980.

The period following 1975 introduced new circumstances. Restrictions by the nuclear supplier nations infuriated rather than pacified some industrializing countries. Preliminary and final results of the INFCE study tended to show that processes of technical control or denial were liable to be ineffective in the long run; the later oil price rises cut out energy options; nuclear suppliers, especially outside the U.S., cast about for new markets. Egan gives an account of all this, including analyses of prospective suppliers and (especially) of what the prospective market might be (Egan 1981); some of what follows comes from that.

Consider the present nuclear power deployment in South and East Asia. Japan is highly industrialized, but in the early 1950s ~~1905's~~ its industry was just starting to rebuild, a fact noted by governments of less-industrialized countries in the region and elsewhere. Table 7.9 lists all reactors operating or under active construction as of late 1981. Notice the trend: buy one, then on the next do part of the work jointly under license, and part domestically; then do it all domestically. 4150 MWe of nuclear-electric power systems, all domestically built, started up in the period 1976-78, and 9700 MWe are similarly underway for 1982-86 startup.

Next consider Korea and Taiwan, Table 7.10. The table shows large U.S. involvement, but a shift in Korea to non-U.S. sources. These two countries devote a higher fraction of their Gross National Product to nuclear power development than any others in the world. Other countries in the region see these examples and seriously consider following suit, a decade or two later in time.

India has developed a complete indigenous nuclear industry, based on the CANDU heavy water reactor, and could in future years export these reactors to other countries at a cost that India claimed to be below \$1000/kWe (1978) for the complete plant. ~~The Philippine reactor~~ was, ~~in the~~ opinion of ~~many,~~ prematurely decided ~~upon.~~

Modern load-shedding controllers for electric power systems coupled with low-capital-cost emergency generators for critical places permit generators to be installed that are 10-15% of the system size. Therefore study now Table 7.11, taken from Egan's work, that lists projected total system capacities for 78 countries. The projections are based on 1976 data (some updated to 1979) and growth rates from E. A. Moore, Electricity Supply and Demand Forecast for the Developing Countries, World Bank Energy, Water and Telecommunications Department, January 1979.

If:

- o the growth rates are as high as projected,
- o the country grids were connected and not (often) fragmented,
- o nuclear power was the best option, usually among several available,

then a large market would appear for small nuclear reactors. On the other hand:

- o even if the projected growth rates are 50% too high, the 1990 projected capacities appear in 1995, still not far in the future.
- o The 10% maximum size criterion is, if anything, conservative, if the system is designed to come with it.
- o Adjoining countries could collaborate on joint projects.

It would be a mistake to imagine that small reactors are any panacaea; other options will often be much better, for example indigenous natural gas for Bangladesh and hydropower from the Itaipu project on the Parana River for Paraguay; but even so, a significant selective market appears to exist, which explains the renewed interest in the early 1980's.

Small factory-built units, delivered on barges, with non-reprocessing fuel cycles will appear more attractive than other kinds, if the purchasing country views the supplier to be reliable in the long term; coupled with effective and accepted international safeguards, such reactors need not be viewed as dangerous seeds of weapons proliferation.

Rapid urganization is a problem in many less- urban
industrialized and presently industrializing countries: 30 million people in Mexico City, and 20 million in each of Sao Paulo and Calcutta, by the year 2000, according to some estimates. Energy for these large urgan complexes will be hard to supply in a non-polluting way except by electricity, and nuclear power seems to be one of the better options in that case. In those three countries (Mexico, Brazil, India), high capital cost and lack of sufficient trained personnel are not so limiting as in most of the other presently-industrializing or less industrialized countries.

The case of oil-exporting countries that have large investment surpluses is particularly interesting; (Stauffer 1981) suggests that nuclear power may be particularly attractive to them, making the points that:

- o to them, the opportunity cost of capital is small.
- o Most of them are attempting to industrialize rapidly.

- o Considering that the oil could be sold at $28-30 per barrel (1982 prices), electric power by oil-burning is expensive for these oil exporters, too.
- o most natural gas, presently cheap and surplus in the middle east, is liable to be committed by 199[illegible], thereby removing it as a cheap fuel for electric power generation.

Iran in the mid-1970's began such a program for those very reasons, stopped it in the late 1970's, and started to exhume it in the early 1980's. Other likely candidates are Kuwait, Saudi Arabia, the United Arab Emirates, Iraq, and Algeria, perhaps in about that order. Iraq

7.11 THE PUBLIC ACCEPTANCE OF NUCLEAR POWER: PROLIFERATION OF UNCERTAINTY

The previous sections recount many of the causes that affected public acceptability and the fortunes of the nuclear power industry, especially in the United States, but also elsewhere. Cost, safety, long-run hazards, connections with nuclear weapons, etc., all played their role, but there was more to the story of how the nuclear power debate came in the mid-1970's to be conducted with all the grace and dignity of a duel in the dark with chain saws.

Some history helps here. After WWII, a heated debate arose whether nuclear research, weapons and (prospectively) nuclear power would continue to be controlled by the military sector or the civilian one. The latter view prevailed, at least in law, so the United States Atomic Energy Commission (AEC) was formed in 1946 under civilian control. Five AEC commissioners appointed by the President were to act as a full-time Board of Directors, with the General Manager beneath them being the principal executive officer. Recognizing the peculiar circumstances then surrounding nuclear work, the U.S. Congress established a Joint Committee on Atomic Energy (JCAE) with members from both the Senate and House of Representatives. All matters pertaining to nuclear energy, civilian or military, fell under its exclusive jurisdiction. In principle, the JCAE was subservient to both House and Senate, but most members of those bodies, being minimally informed and in no position to provide detailed oversight, were content to approve JCAE proposals, provided the latter did not intrude appreciably in other Congressional affairs.

Therefore if nuclear power issues could be kept substantially disengaged from others that would legitimately involve other Congressional sectors, the JCAE-AEC together could and did maintain a control unique in modern U.S. Federal experience -- via classification of materials, and of budgets and programs. Outside the system few critics existed, who in any event had poor access, even to unclassified information; workers inside tended to associate with AEC goals, not by diabolic intent, but mainly by simple commonality of interest.

Throughout the 1960's and until the early 1970's, the Congressional JCAE expanded its original legislative and oversight roles, and came more to resemble a managing board of directors. AEC Commissioners each took lead responsibility for particular sectors of the AEC's work -- research, reactor development, weapons, etc. To accomplish its technical tasks, the AEC established -- partly de novo and partly by conversion of its WWII nuclear weapons research and development laboratories at Oak Ridge, Los Alamos and elsewhere -- a series of large national laboratories that became patterns for research establishments elsewhere. Excellent in their specialties, their charter was nevertheless circumscribed; rather than working on large national problems in the holistic sense becoming understood in the 1970's and 1980's, their tasks were mainly confined to basic and applied sciences and engineering applicable to or connected with nuclear phenomena.

These patron-client relationships worked well throughout the 1950's and 1960's, according to the spirit of the times. The future of nuclear power looked good; the Sierra Club declared itself in favor of nuclear power, as a salvation from the miseries associated with coal.

But even then, some wrote that the arrangements would lead to grief, via elitism, over-confidence, lack of sufficient public participation, goals too narrowly visualized or structured, and so forth. One of these was David B. Lilienthal, retired first chairman of the AEC, who formerly as chairman of the Tennessee Valley Authority had transformed it from ideas to reality.

The period 1968-1972 saw events that would change all this, including public attitudes to nuclear power, even though some of the results would not become obvious until later. Four principal ones come to mind: (1) effectiveness of emergency core cooling systems; (2) AEC refusal to expand or convert its role (or that of its laboratories) to include growing broad environmental concerns (or to consider the question "nuclear power -- compared to what?"); (3) several institutional changes, of which the most publicized was a U.S. court decision ("Calvert Cliffs") that nuclear power plants could not be built without full environmental impact statements being prepared; (4) public concern over nuclear waste. A few words are in order about each.

In the late 1960's, inquiries were made by competent concerned scientists that the emergency core cooling system might not function as expected, in case of a large pipe rupture in an LWR; for example, the pressure of steam generated by water on hot fuel rods might prevent water from reaching other rods, which might melt. Somewhat earlier,the AEC had ordered the Brookhaven National Laboratory to prepare a report describing the maximum public damage that might occur after a severe nuclear accident, virtually without regard to probability or improbability. That report (WASH-760), plus the AEC's failure to respond adequately to the emergency core cooling inquiries, and other unresponsiveness led to the formation of the Union of Concerned Scientists, which brought suit against the AEC, and generally organized opposition to nuclear power, sometimes on substantial grounds and sometimes on frivolous ones (for example, holding up operation of the Boston Edison Co. Pilgrim nuclear power plant for four months in 1974 on a pure technicality over the use of 7 x 7 fuel rod bundles vs. 8 x 8 bundles, causing an increased expense for purchased power of $27 million). Later, many other groups joined the attack, which continues although somewhat abated, at present.

The second reason -- AEC intransigence against changing or expanding its role to respond to new concerns -- showed up in its adamant refusal in 1970-71 to permit its national laboratories to take on significantly larger environmental roles, despite prior intimations to the contrary (Rose 1974). The AEC and JCAE reluctance was natural, given their charter, which would be weakened if not destroyed if they had to share power with other Congressional Committees and Executive Departments of the Administration. The same reaction attended proposals in 1970-71 that the AEC expand its role to include coal research, energy conservation, and so forth, which again would have meant sharing power, therefore the partial or total eclipse of the JCAE.

The third set of causes, typified by the decision by a U.S. circuit court that the Calvert Cliffs nuclear plant could not be built without a full environmental impact statement (EIS) being prepared, ran against the then-AEC view that only nuclear-related matters need be considered, which would have maintained the nuclear sector almost wholly within the purview of the AEC.

Such decisions were heralded at the time as a victory for the environmentalists, but they were more: from then on, the AEC had to deal more closely with the Environmental Protection Agency and other Federal departments, and the JCAE's days of exclusivity and even existence began to be numbered. Within two years, the AEC was preparing EIS's for many energy-related installations, and had prepared for Executive Branch consideration a $10 billion shopping list of broad energy R&D topics (mostly for supply, but some for end use); this latter, along with similar ones prepared for the President's Office of Science and Technology, during 1972-73, and a general mood that something new was needed, led to the dissolution of the AEC and the JCAE, and the formation in 1974 of the Energy Research and Development Administration and of the Nuclear Regulatory Commission.

The fourth topic mentioned above, nuclear wastes, has already been covered in earlier sections. Although the dangers and the difficulties have been overblown by the critics, the AEC's inept handling of the problem and its misunderstanding of the degree of public concern aggravated the debate, and helped to build a broad constituency against nuclear power, and against other technological enterprises.

These and other events, accompanied by the AEC's and the nuclear industry's continued projection of a large and early nuclear-electric future and their failure to understand growing public unease, persuaded more public interest groups that something was seriously amiss, even if it was not possible to see all the difficulties from outside the system. Thus opposition to nuclear power gradually escalated from specific objections about specific matters (e.g., emergency core cooling, or adequacy of nuclear waste technology), to a much larger outcry against nuclear power <u>per se</u>, and along with it many other manifestations of high technology. Attention of many groups switched to developing strategies of how to destroy the nuclear power sector, rather than how to repair it. All this time, the nuclear sector itself kept developing its products, and declaring how safe and beneficial nuclear power would be; the oil price rises of the early 1970's led to large orders for nuclear plants by electric utility companies; but the fatal bullets were on their way, long before the TMI-accident in 1979, that cast further doubt on nuclear safety (as discussed in section 7.5).

A principal route of attack against nuclear power lay through the electric utilities themselves. Traditionally concerned with providing electric power at lowest cost, relatively unencumbered before the 1960's with many air and water quality standards, and existing in a social context of electric power demand growing at 7%/year and falling fuel prices, the electric sector had given insufficient thought to future complications. Furthermore, the electric utility sector, being fragmented in the U.S. and privately owned, had become considerably separated from the new option developers -- in this case the AEC and the major industrial suppliers. The utilities were unprepared to handle a vast panoply of issues, such as new restrictions on power plant siting, dealing with court challenges over adequacy of environmental impact statements, and disposal of apparently undisposable wastes. Throughout the 1970's, they saw themselves more and more as the recipients of problems over which they had no choice, and which were not within their power to solve.

Thus arose an indirect attack on nuclear power via the electric utilities themselves. It was they, after all, who would or would not order nuclear power plants. Some of the actions against electric power utilities were overdue anyway, and their recent resulting interest in end use and conservation are beneficial outcomes. The anti-nuclear legal actions, demonstrations and public interest statements generally aimed at the need for less electricity (therefore no nuclear power) but rarely dealt with the difficulties with coal, despite the plethora of professional and publicly-available information about it. Solar power could soon be available, many persons declared.

The electric utilities and the electric sector in general made ideal targets for the critics:

1. Contrary to automobile transport, food stores, etc. they were relatively remote from daily public concern, hence had no strong public constituency. To caricature a cynical public attitude, the electric utility companies might pretend that electricity came from power plants, but everyone knew that it came from wall plugs.
2. Decisions against new construction would hurt the industry severely and promptly, but the impact on electric power availability wo d not appear for a decade or so. Public memory of causes and actors would fade by then, if things turned out badly.
3. The electric utility sector, having to build for 30 or 40 years service life, was highly vulnerable to long-term uncertainty.
4. The electric sector was entirely unprepared for social arguments on "hard" versus "soft" technology, and the complexities of ethical and moral debate. All these challenges, delays and public outcries

turned the electric utilities away from nuclear power. Planning, construction times and costs escalated, as described earlier. The electric utilities had to plan for equipment with 30 or 40 year life. They were used to changing fuel costs, but not to the possibility that they might be financially committed to plants that would never be allowed to run, or might be put in service so far in the future that other options were more attractive. Saying no to a nuclear power plant became easier than saying yes; the electric power costs would be paid by the users, and if their regulatory and legislative representatives encouraged non-nuclear systems, so be it.

Thus the nuclear sector came to grief in the late 1970's not so much by threats of proliferation of nuclear weapons or even of specific accidents, but by a proliferation of uncertainty. Faced with vast problems if they built unusable facilities, the electric utilities in the U.S. ordered no new nuclear plants since 1978, and cancellations exceeded new orders every year since 1975.

In all this, the Federal Government throughout the years 1977-1980 often acted as if it wanted the nuclear sector to collapse, but did not want to appear responsible. Phrases like "nuclear power as a last resort," even though later modified to admit it as a rational possibility, sent messages to electric utilities and nuclear critics alike. The Executive Branch policy announced in April 1977 that foreign orders for nuclear fuel services should be re-negotiated, and the Nuclear Non-Proliferation Act of 1978 were both intended to deal with the serious and hitherto inadequately attended issue of civilian-military connections outside the U.S., but additionally discouraged many foreign governments from cooperating with the U.S. in nuclear matters more than was minimally necessary.

All this time, the U.S. nuclear suppliers and other nuclear advocates generally took the view that nuclear power was well and reasonably safely developed, that the critics were wrong or irrelevant, that logic pointed to a largely nuclear future, and paid little attention to the real nature of events around them, now consisting of both logical and illogical winds, public propaganda against technology in general, high technology in particular, and nuclear power as the paradigm of it.

Thus, the commercial nuclear-electric sector in the U.S., either failing to understand the nature of the attack against it or unable to respond coherently, virtually self-destructed by 1982, except for completion of plants ordered years earlier, and maintenance of those in service.

The nuclear sector, as it seeks to re-establish public acceptance, should reflect on how the public perceives and receives science and technology. The scientist or engineer is, at least in principle, able to share in the full understanding of the particular enterprise -- to repeat the calculations for himself, so to speak, and to confront his or her colleagues on equal terms, in approbation or disagreement. Not so the public at large, which must accept the authority of science and technology in trust. If the trust evaporates, so does the authority, and mere claims to merit trust accomplish nothing. The nuclear sector, always an inviting target, had by its earlier hyperbole and its later shortcomings undermined that trust in itself, broadened the base of criticism against it, and found that it could not recover by technological protestation.

(Polanyi 1967) writes about this social contract by which science is publicly accepted; his words apply *a fortiori* to technology, which has much more social purpose and content:

> Laymen normally accept the teachings of science not because they share its conception of reality, but because they submit to the authority of science. Hence, if they ever venture seriously to dissent from scientific opinion, a regular argument may not prove feasible. It will almost

certainly prove impracticable when the question at issue is whether a certain set of evidence is to be taken seriously or not. There may be nothing strange to the layman in the suggestion that the average periods of pregnancy of various animals are integer multiples of the number π, but he will only drive the scientist to despair if he challenges him to show why this is absurd. So he will be confronted with the scientist's blunt, unreasoning judgment, which rejects at a glance a set of data that seem convincing to the layman. He will demand in vain that the evidence should at least be properly examined and will not understand why the scientist, who prides himself on welcoming any novel idea with an open mind and on holding his own scientific theories only tentatively, sharply refuses his request.

Such conflicts between science and the general public may imperil science. It is generally supposed that science will always be protected from destructive lay interference on account of its economic benefits; but this is not so. The Soviet Government adopted the theories of Lysenko and gravely hampered all branches of biological research for thirty years, overlooking altogether the damage to its agriculture. The ruling party believed in fact that it was improving the cultivation of grain through Lysenko's use of the hereditary transmission of acquired characters, an operation which scientific genetics declared impossible. Far from preventing the attack on science, the economic motive reinforced it -- and this may frequently be the case. The great fallacies that have misled mankind for centuries were mostly practical.

7.12 ETHICAL ISSUES

Acceptability of nuclear power has become a social and ethical debate, much of it of poor quality, so polarized by contending camps that the ground between becomes the most dangerous of all. The material in the public press and journals is apparent to every reader, with questions and prepared answers distributed on each side, and statements of seemingly great nuclear, resource and economic wisdom coming from most unlikely sources.

This wretched state of affairs need not be, and is not a necessary condition of applied ethics, as (Carney 1980) points out in an article on the topic. In 1965, ethical immaturity and irresponsible literature often dominated the public discussion of highly complex moral problems in medicine, but since then the field of bioethics has developed to the stage of aiding substantially in the resolution of perplexing problems in the medical/biological field.

Continuing for a moment with Carney's analysis, one can recognize three basic elements of ethical analysis: values, obligations, and moral character or virtues. Consider the first of these -- values -- and as a specific example, safety. Is it an intrinsic good, like happiness, or a relative thing, to be judged in the light of many considerations? People pay very differently for it. The cheapest value put on human life by U.S. society in recent times was the disinclination to purchase optional seat belts for automobiles -- let alone use them -- in the 1960's, for $10/car. Ten million new cars per year, and a predicted saving of 10,000 lives per year by using seat belts, comes to $10,000/ life, a number to be reduced by the social cost of nonfatal injuries avoided if seat belts had been used. The highest value that comes to mind is the fact that the National Aeronautics and Space Administration spent $20 billion dollars to ensure a safe moon-trip for 20 astronauts, when $10 billion would have provided a marginally successful system; but society would not have tolerated that, an attitude when I endorse. The two values differ by a factor of 50,000, and plenty of intermediate cases could be cited.

Safety is a valuable but relative good. Erich Fromm, social philosopher and pyschologist, writing in a more global context against the passion for absolute safety, puts it very well:

> If someone will not touch a doorknob because he might catch a dangerous bacillus, we call this person neurotic or his behavior irrational. But we cannot tell him that what he fears is not possible. Even full-fledged paranoia demonstrates that one can be insane and yet one's capacity for purely logical thinking is not impaired.
>
> Normal thinking is based on the belief in a greater or lesser degree of probability. Paranoid-like thinking is based on the assumption of a logical possibility and wants to have absolute certainty that something could not happen even in the most remote circumstances.
>
> The healthy person makes his decisions on the basis that something is probable or improbable, and this judgment is made after thorough examination of all obtainable and relevant data; for paranoid-like thinking mere possibility is sufficient, and close empirical examination unnecessary.
>
> If we based our behavior on shear possibility, and not on realistic probability, our lives would

> be more crippled, or even endangered, by defending ourselves against the "possible" than it might be by the events that could happen if we have thought only in terms of probabilities.
>
> In individual life we know the irrationality of people who strive for absolute security -- this craving is irrational (1) because there is no absolute security in life, (2) because once it is established as the dominant goal there is no limit to the means sought for to reach this goal, (3) because in the search for this goal the person cripples himself and loses all pleasure in living.
>
> In fact, the chase after absolute security is a boomerang: it creates more insecurity than it avoids ... (Fromm 1975)

To insist on nuclear power being "absolutely safe," to decline to address the question "Nuclear Power -- Compared to What?" is to absolutize what is relative (in Carney's words) and is a serious moral mistake. From a religious point of view, it is idolatry.

Regarding obligations, society has no more obligation to develop nuclear power than to do any other prospectively beneficial thing, except as the obligation of thoughtful analysis of it vis-a-vis its alternatives

-- including the opportunity of using energy more rationally -- imposes upon us the obligation of making responsible choices for short and long terms, a topic taken up in Chapter 2 already.

Consider now virtue, and the question of inherent good and evil. Major and minor church bodies, drawn into the debate either on their own volition or used by others, have taken positions. Starting in 1975, successive study groups of the National Council of Churches of Christ (NCCC) of the USA proposed a series of assessments of "The Plutonium Economy: A Statement of Concern," the first of which, after a long indictment of all aspects of nuclear power, ended with a call for an assessment with these words:

> The unprecedented hazards of the plutonium economy demand an unprecedented political response. These are hazards so grave that every citizen should have a voice in deciding whether this is the road to energy independence we -- or anyone -- should take. All who believe that technology should serve human values should join in opposing the plutonium economy and in seeking to divert into safer and more constructive channels the vast resources being devoted to nuclear power. The responsibility for these decisions

cannot be delegated to nuclear experts, for the key issues are not technical or economic but social and ethical, and in a democracy such issues should be resolved only through the political process.

That version was rejected by the Governing Board of the NCCC, but was widely quoted as and believed to be "the church's position." The NCCC went through a succession of trial documents and finally in 1979 adopted a much broader policy statement "The Ethical Implications of Energy Production and Use." While still very critical of nuclear power, it dealt with many forms of energy, stressed justice, participation and sustainability, and recognized the difficulties and ambiguities inherent in real societal decisions.

Meanwhile, the World Council of Churches (WCC), with headquarters in Geneva, had taken a different approach, and convened a series of hearings throughout the 1970's, inviting experts representing many views to participate (Francis and Abrecht 1975, WCC's Anticipation 1976, 1977, 1979). A summary of the statement finally accepted by the WCC Central Committee in 1979 expresses my views fairly well. Slightly abbreviated it is:

(a) The nuclear debate cannot be addressed in an

Absolutist sense, without consideration of other energy options, including especially energy conservation and the possibility of technologically less complicated societies. In this respect, for many governments and peoples the issue is not as clear-cut ethically, as is for example that of racism. Failure to recognize this complexity has contributed significantly to the present dishevelled state of the debate.

(b) More specifically, energy consumption and more rational use of energy deserve much more attention than they generally receive, especially in the industrialized countries. This matter is germane to the nuclear debate because reduced (or less rapidly growing) energy demands change both the desirability and the availability of various energy supply options, including nuclear power, its chief present alternative (coal), and its chief future alternative (solar).

(c) Most of the nuclear debate is but symptomatic of a much deeper societal debate about more technology or less, about centralized versus decentralized, appropriate versus inappropriate (?), with many groups defining these terms to suit their own social or political aims.

(d) No grounds exist for *rejecting* nuclear power categorically. On the other hand, it cannot be *accepted* categorically, either; it is a conditional good, subject to reasoned acceptance under some circumstances and subject to reasoned rejection in others. The particular circumstances relate to need for energy, availability of alternative sources, the likelihood of increasing or decreasing the danger of nuclear weapon proliferation and whether nuclear power in any particular case contributes to a more just, participatory and sustainable society, or to the opposite. Certainly the scale of possible dangers and benefits exceeds that which society is accustomed to consider, and choices to proceed with or renounce civilian nuclear power should be made in each case only after profound deliberation.

These opinions, especially the fourth, raise, among others, the question of nuclear power as a categorical evil, which gives the opportunity to introduce some additional views.

The memory of Hiroshima and Nagasaki remains, and the shadow of ten thousand megatons darkens our prospect. But the evil lies not inherently in the phenomenon of nuclear fission or of any of the chemical elements, all of them parts of Creation, but in the nature of man himself, who being given free will can choose to build toward heaven or toward hell.

This involves high theology as well as high technology, and the issues need setting out. On the one hand, we have those who will claim that since the original Fall, evil entered what had before been a perfect world, and that it has been different ever since: trees are imperfect, man is sinful, and so are his works. This view has received much attention both in parts of the Christian Church and elsewhere. Since earliest times people have debated the question of whether it was proper to mine the earth, similar to today's questions about technology in general and nuclear power in particular. (Agricola 1556) in his great treatise *De Re Metallica*,* summarizes the arguments up to A.D. 1550, taking up these matters of social and moral purpose as the first priority. Regarding the opinions of those opposed to mining, he writes in part:

First, they make use of this argument: "The earth does not conceal and remove from our eyes those things which are useful and necessary to mankind ... The minerals, on the other hand, she buries far beneath in the depth of the ground; therefore, they should not be sought. But they are dug out by wicked men who, as the poets say, are the products of the Iron Age." Ovid censures their audacity in the following lines:

> And not only was the rich soil required to furnish corn and due sustenance, but men even descended into the entrails of the earth, and they dug up riches, those incentives to vice, which the earth had hidden and had removed to the Stygian shades. Then destructive iron came forth; then gold, more destructive than iron; then war came forth.

Another of their arguments is this: Metals offer to men no advantages, therefore, we ought not to search them out. For whereas man is composed of soul and body, neither is in want of minerals.

Then a little later, again regarding iron:

And next they raise a great outcry against other metals, as iron, than which, they say, nothing more pernicious could have been brought into the life of man. For it is employed in making swords, javelins, spears, pikes, arrows -- weapons by which men are wounded and which cause slaughter, robbery and wars. These things so moved the wrath of Pliny that he wrote:

> Iron is used not only in hand-to-hand fighting, but also to form the winged missiles of war: sometimes for hurling-engines, sometimes for lances, sometimes even for arrows. I look upon it as the most deadly fruit of human ingenuity. For to bring Death to men more quickly we had given wings to iron and taught it to fly.

Further, he quotes the Greek writer Philemon:

> O unseeing Plutus, would that thou hadst never appeared in the earth or in the sea or on the land, but that thou didst have thy habitation in Tartarus and Acheron, for out of thee arise all evil things which overtake mankind.*

Agricola counters these views by reminding the reader of the benefits accrued by the use of metals: ploughs, useful tools, of all sorts. He begins a philosophical passage with this:

> In the first place, then, those who speak ill of the metals and refuse to make use of them, do not see that they accuse and condemn as wicked the

Creator himself, when they assert that he fashioned some things vainly and without good cause, and thus regard Him as the Author of evils: which opinion is certainly not worthy of pious and sensible men.

In another eloquent and relevant passage of that time, (Rideman 1545) comments on greed and private exploitation, and how man can ruin all he can touch:

> Now, however, as hath been said, created things which are too high for man to draw within his grasp and collect, such as the sun with the whole course of the heavens, day, air and such like, show that not they alone, but all other created things are likewise made common to man. That they have thus remained and are not possessed by man is due to their being too high for him to bring under his power; otherwise, so evil had he become through wrong taking, he would have drawn them to himself as well as the rest and made them his property.

My purpose in recounting all this is not to pretend that uranium and plutonium are iron, but rather to reveal how similar debates have occupied the attention of people for millenia. The U.S.-sponsored newspaper *Development Forum*, just before the May 1977

U.N. Conference on Nuclear Power, attacked nuclear power; on its front page appeared an article by the Swiss philosopher and theologian (de Rougement 1977), who wrote in part:

> It is clear as daylight that the choice of nuclear power stations and retreatment plants for the infernal metal from which bombs are fashioned is daily increasing the risk of atomic war, or in other words the end of the human race ... (Nuclear power is) bound up with the use of the well named plutonium, that product of the underworld ... Pluto is lord of the shadows, he is as blind as a bat. But sunlight comes to us from heavens, from Zeus, "the far-seeing."

Compare this bizarre yet influential writing with that of Ovid and Philemon 2000 to 2500 years earlier.

We can see our present problems better after practicing on the perspectives available from history. Applied to the present nuclear debate, I see both promise and peril, and the dangerous imperfection of man, susceptible to the sins of avarice, over-ambition and hubris. Despite these weaknesses, or perhaps because of them, I believe that resolution lies in seeking states of increasing grace and *caritas*, and accepting what is in Creation with an attitude of thanksgiving, dedicating the use of these things to the good of all and not for selfish gain, which is just what Peter Rideman was writing about. In a sense, we are junior partners in Creation, and should be careful stewards over that part of it entrusted to us.

FOOTNOTES

7.20 *Leading to sudden power generation and a steam explosion. Three operators of a small primitive U.S. Army reactor were killed when (apparently) they pulled the control rods out by hand from the top of the reactor, and the top blew off from the sudden steam generation inside.

7.30 *In the late 1960's, near Detroit, the ill-fated Enrico Fermi reactor, a sodium-cooled reactor designed to be a near-breeder, had such a core-catcher made of welded plates at the bottom installed as a late modification. One of these plates came loose, blocked one of the cooling ports, and caused the core to overheat, with some damage, at almost the start of its operating life. These core-catcher plates were not shown on some of the design drawings, so the cause of the accident was at first a mystery. Even engineered safety features can introduce peculiar additional hazards.

7.35 *In November-December 1980 I tried to initiate such a debate, and contacted about 25 colleagues in senior government, industry and academic positions. All favored it except two, one of whom, later to take and accept a sub-cabinet post in the new administration, stated that there was neither time nor reason

FOOTNOTES

7.35 (cont'd) for any more discussion; the decisions had been made, and it was only a matter of assisting in the work or keeping out of the way.

7.84 *"Will all Great Neptune's ocean wash this blood clean from my hand? No, this my hand will rather the multitudinous seas incarnidine, making the green one red." Macbeth Act II, scene ii.

7.94 *The Swedish physicist and Nobel Prize winner Hannes Alfvén has said, "Atoms for peace and atoms for war are Siamese twins." So it turned out for chemical explosives, for example dynamite, whose Swedish inventor, Alfred Nobel, believed that the warful threat was so terrible that the world would eschew war forever. But who remembers him as the inventor of dynamite?

7.138 *Georgius Agricola *De Re Metallica* (1556); translated by Herbert and Lou Hoover (Dover Publ. Co. New York, republished 1950), pp. 1-24 particularly. One of the most eloquent treatises and translations of all time.

7.140 *Diogenes Laertius, II, 5

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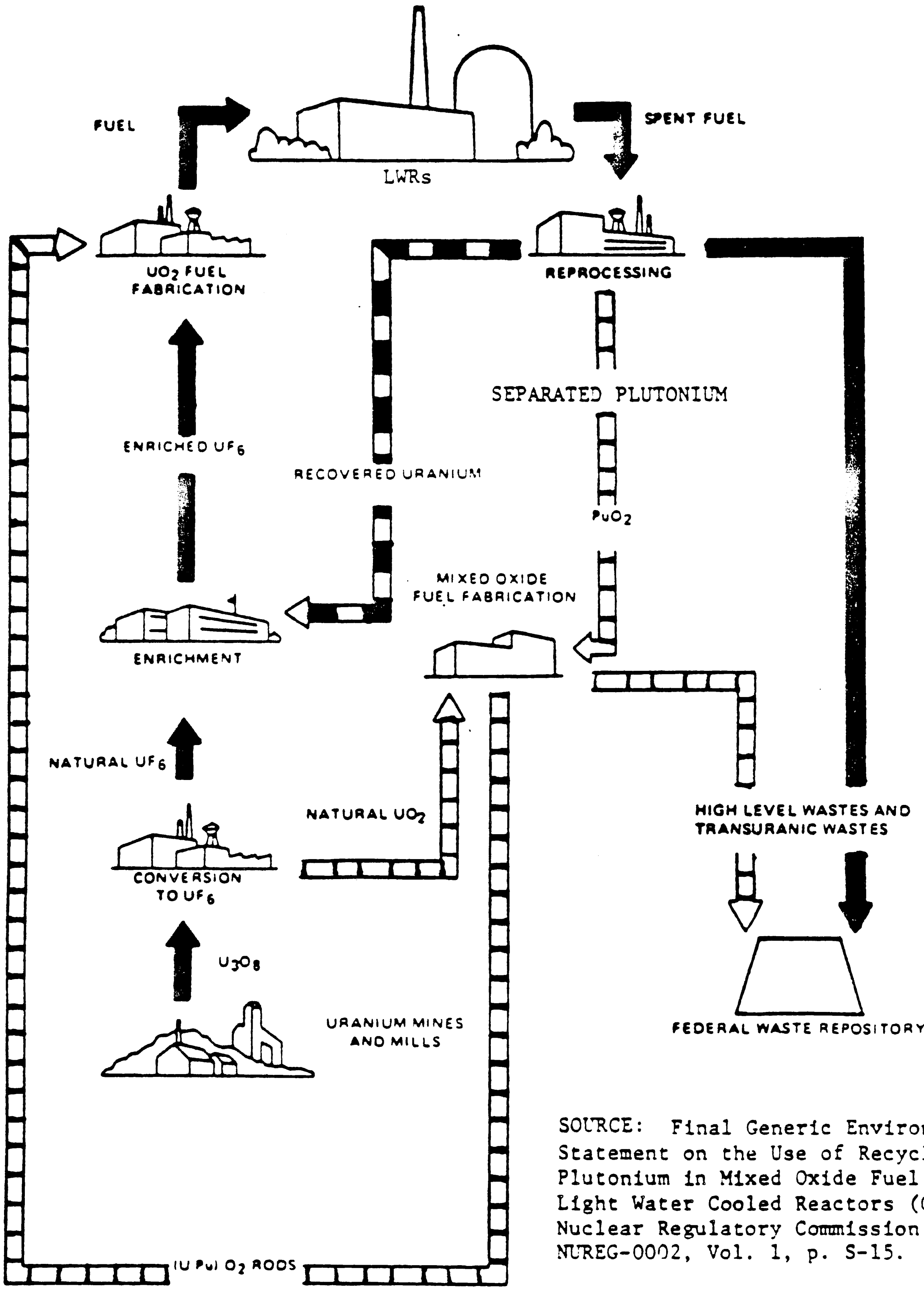


SOURCE: Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors (GESMO), Nuclear Regulatory Commission, NUREG-0002, Vol. 1, p. S-15.

Figure 7.1 PROPOSED NUCLEAR FUEL CYCLE (WITH URANIUM AND PLUTONIUM RECYCLE)

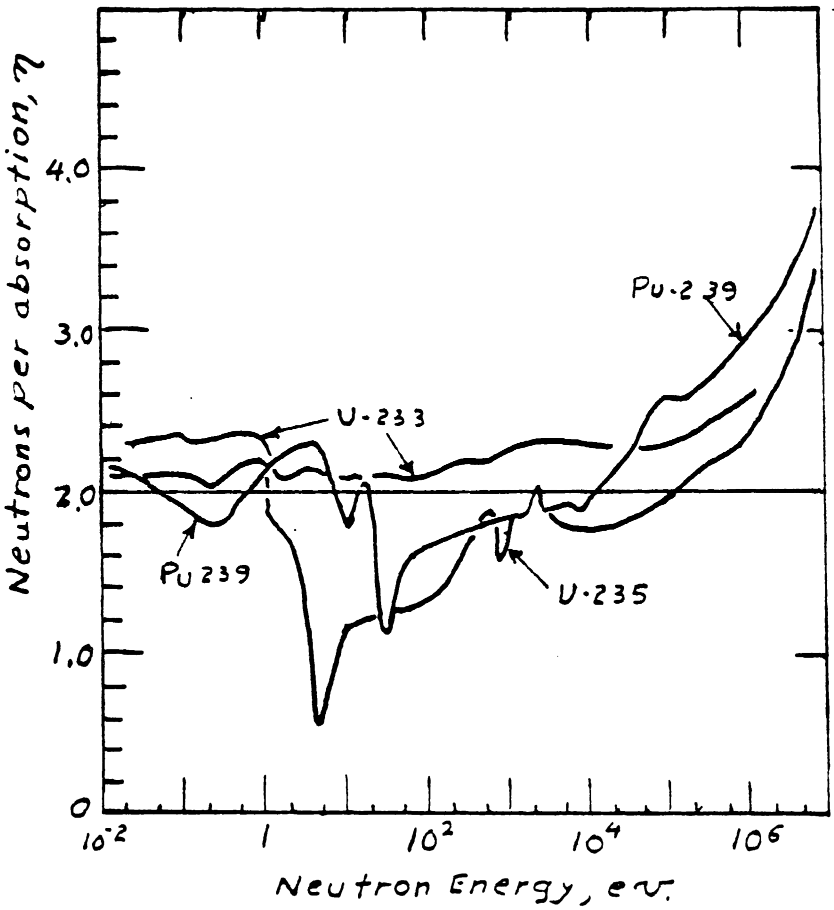


Figure 7.2 Fission yield of neutrons per neutron absorbed in U-235, U-233 and Pu-239.

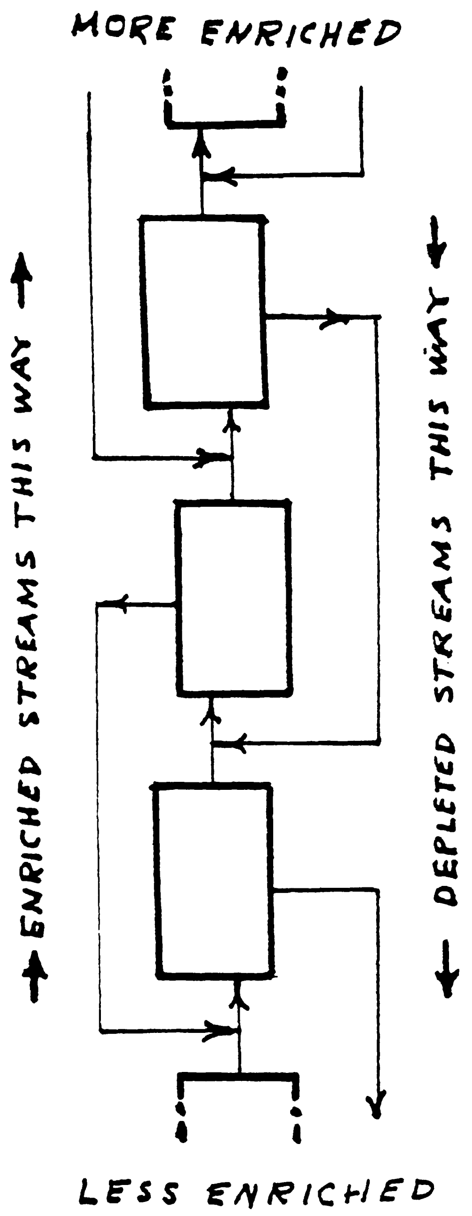


Figure 7.3 Enrichment Cascade.

Material consisting of U-235F_6 and U-238F_6 enters the bottom of one stage. The mixture, slightly enriched in the U-235 component by the process inside the stage, follows the upward path, and the depleted component follows the downward path.

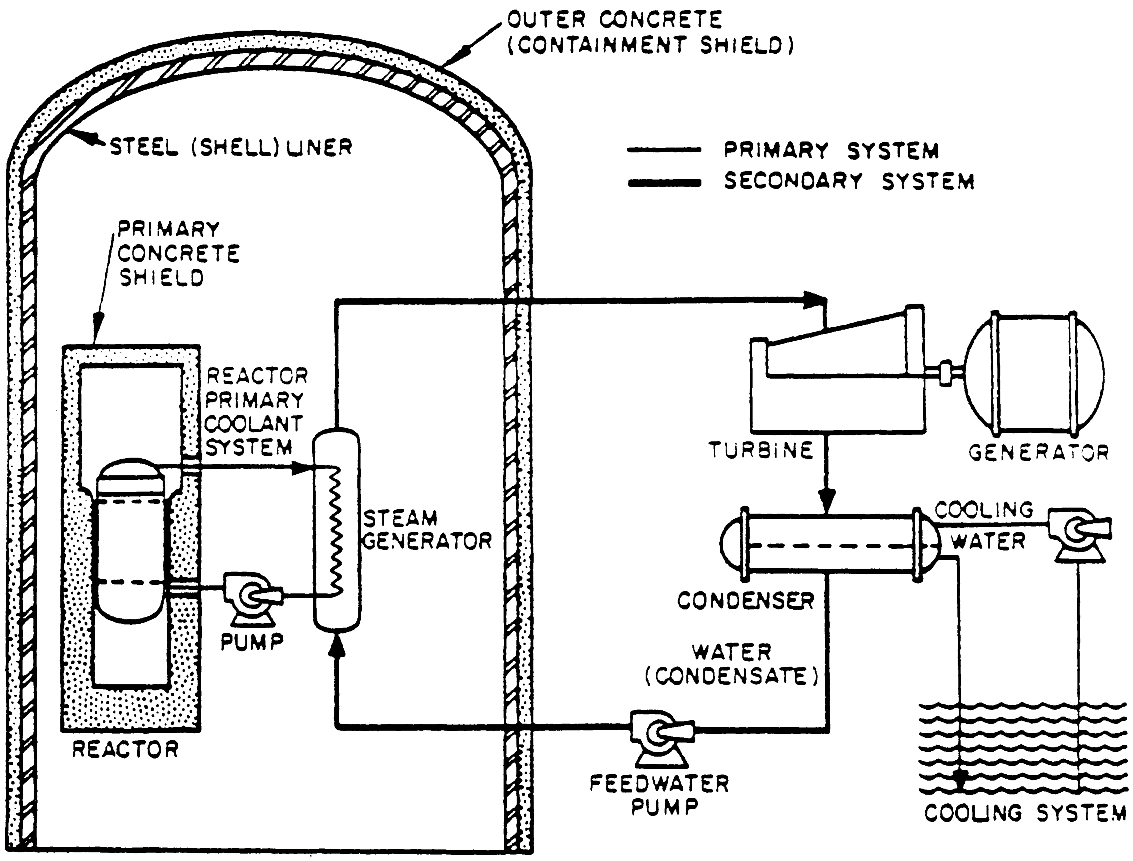


Figure 7.4 SCHEMATIC PRESSURIZED-WATER REACTOR POWER PLANT.
The primary reactor system is enclosed in a steel-lined concrete containment building. Steam generated within the building flows to the turbine-generator system (outside the building), after which it is condensed and returned to the steam generators. (Figure reproduced from ERDA-1541.)

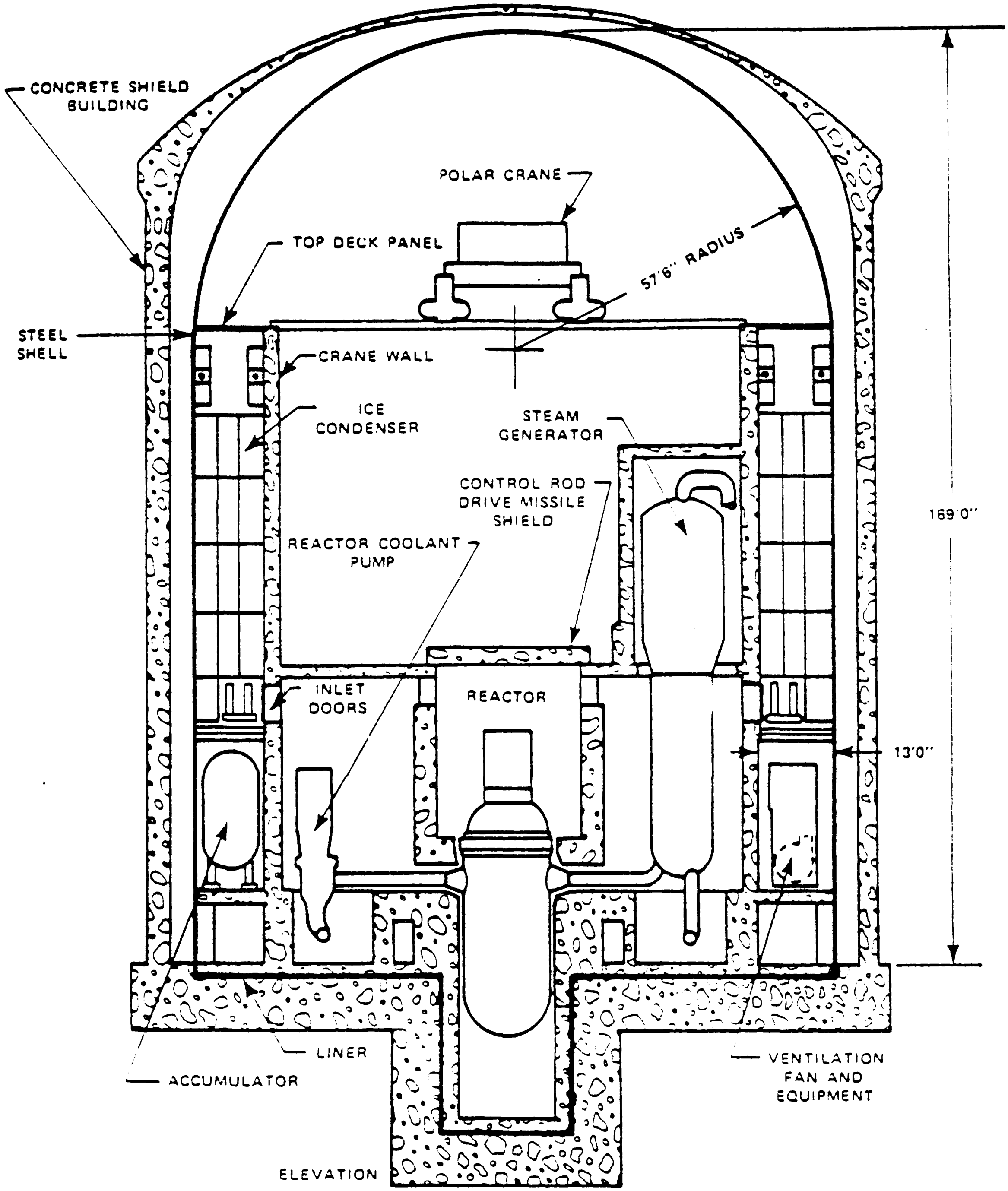


Figure **7.5** CROSS-SECTION OF A PWR CONTAINMENT BUILDING.
The containment building has the entire primary system, as well as various safety systems, in its interior. The building itself is concrete, with a steel shell inside. The safety systems within the building include emergency core cooling systems (note the accumulator), pressure control systems (one form of which may be the ice condenser indicated), and ventilation equipment. (Figure courtesy of Westinghouse Electric Corp.)

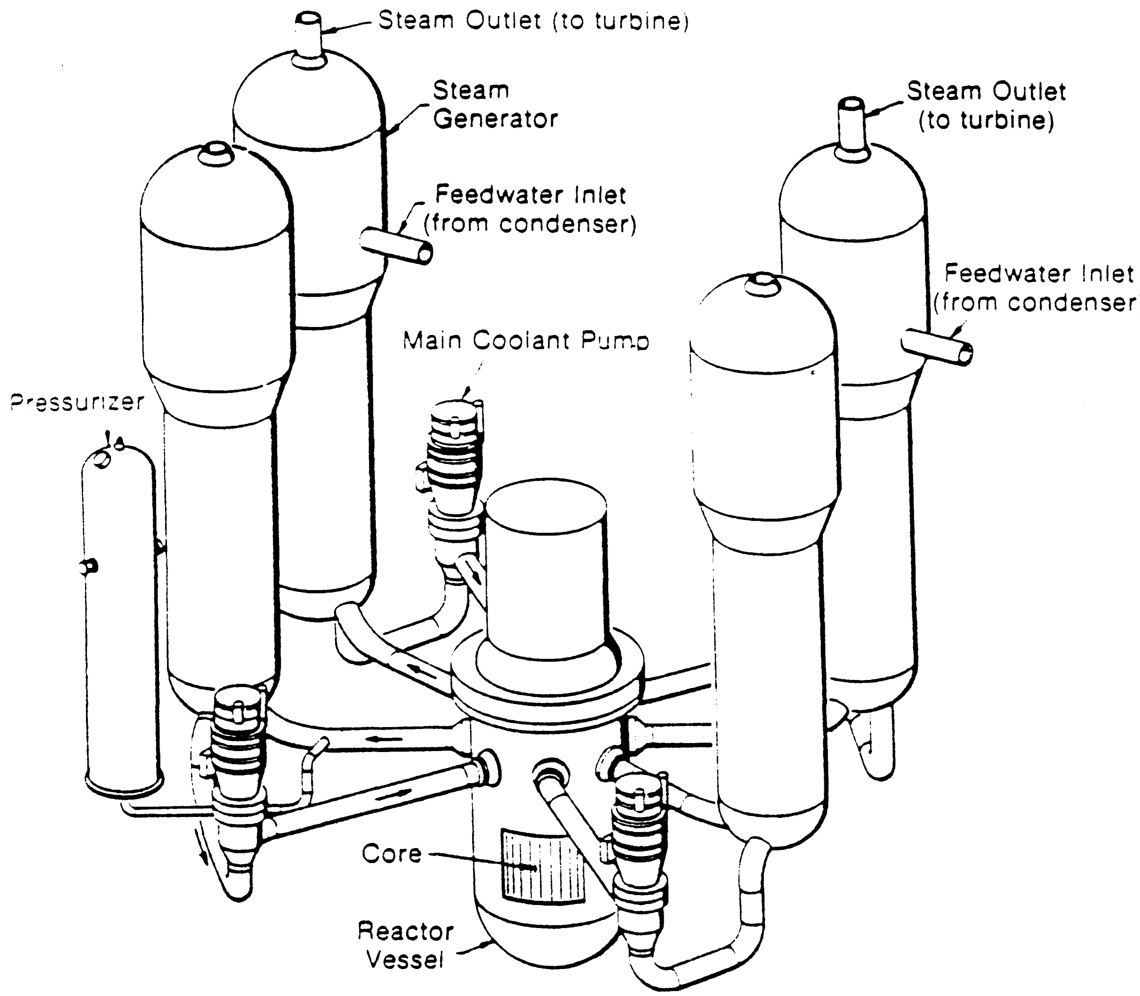


Figure 7, 6 ARRANGEMENT OF THE PRIMARY SYSTEM FOR A WESTINGHOUSE PWR. The primary system constitutes the nuclear steam supply system for a PWR plant. In the four-loop arrangement shown in the figure, each loop has its own steam generator and coolant pump. A pressurizer is connected to one of the loops. The primary coolant enters and leaves the steam generator from the bottom.
(Figure reproduced from WASH-1250.)

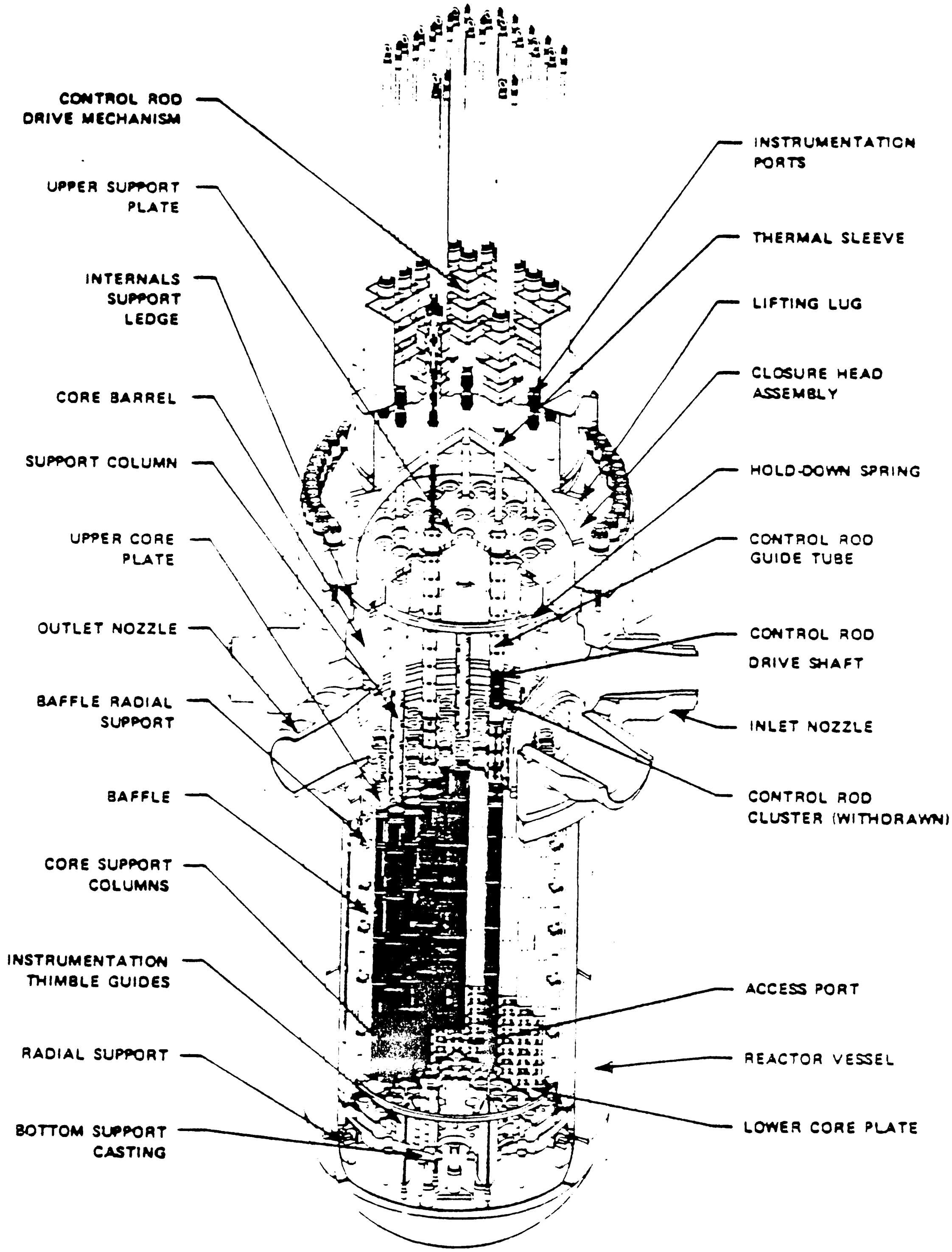
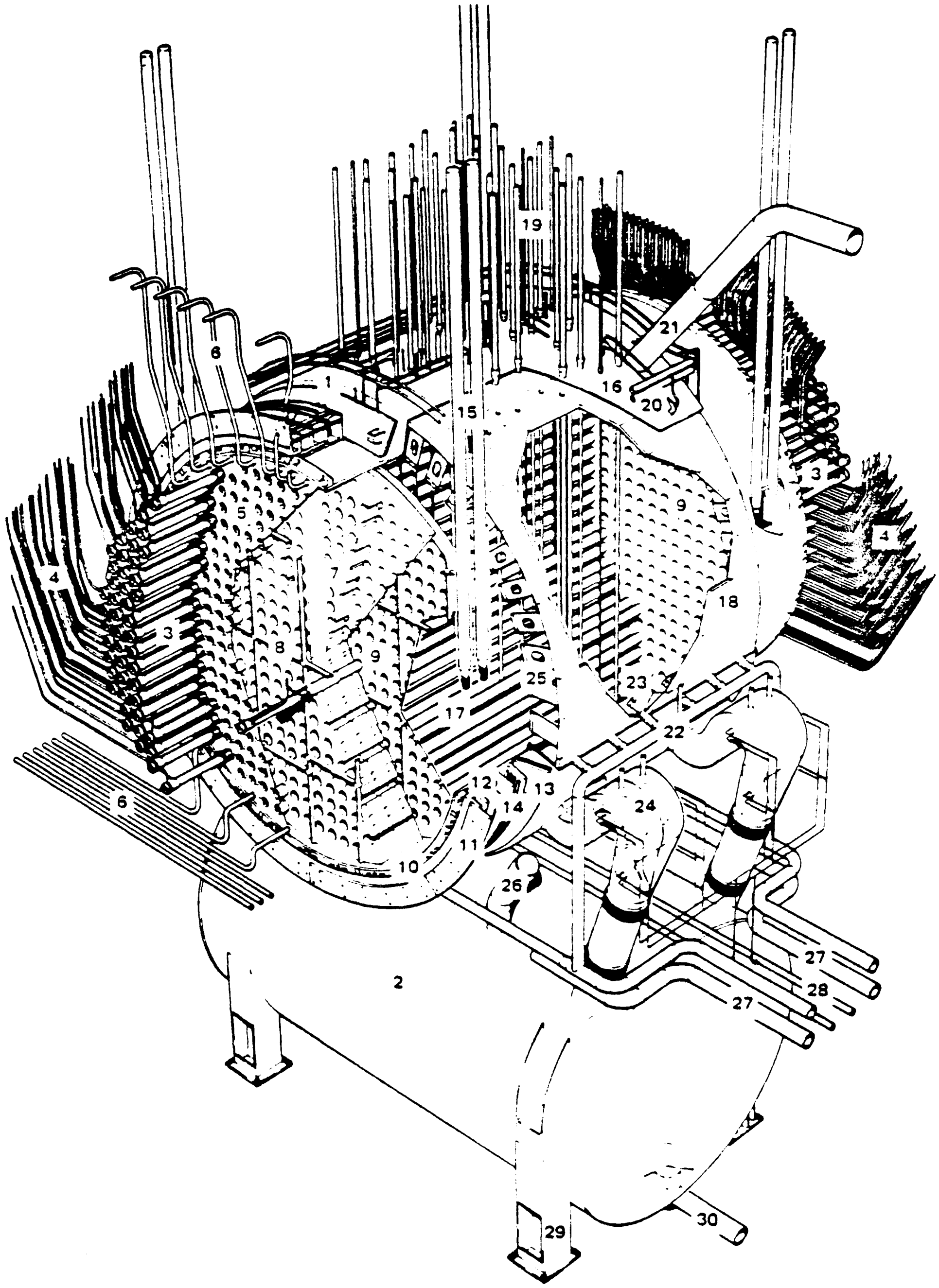


Figure 7.7 PRESSURIZED-WATER REACTOR VESSEL AND INTERNALS.
The core of a pressurized-water reactor is contained in a large steel vessel through which coolant flows. After passing into an inlet nozzle, the water flows down between the core barrel and the vessel wall, until it reaches the plenum beneath the core; there it turns upward to flow through the core and out one of the outlet nozzles to the steam generators. The top of the reactor vessel, which is removable for refueling, supports mechanisms for driving control rods. (Figure courtesy of Westinghouse Electric Corp.)



1. Calandria
2. Dump Tank
3. End Fittings
4. Feeders
5. End Shield Outer Tube Sheet
6. End Shield Cooling Inlets and Outlets
7. End Shield
8. Baffles
9. End Shield Inner Tube Sheet
10. End Shield Key Ring
11. Anchor Plate
12. End Shield Ring
13. Ring Thermal Shield
14. Cooling Pipes
15. Calandria Support Rods
16. Calandria Shell
17. Calandria Tubes
18. Calandria Shell Shields
19. Control and Shut-off Rods
20. D_2O Spray Cooling
21. Helium Balance and Blow Off Lines
22. D_2O Inlet Manifold
23. D_2O Inlet Nozzles
24. Dump Ports
25. Shell Shield Support Plates
26. Helium Balance Line
27. D_2O Outlet
28. Dump Port & Dump Tank Spray Cooling Lines
29. Dump Tank Supports
30. Dump Tank Drain Line

Figure 7.8 The CANDU Heavy-water-moderated and cooled reactor: core and some associated equipment. [From Atomic Energy of Canada Ltd Report AECL-5800 (1977), Fig. 4]

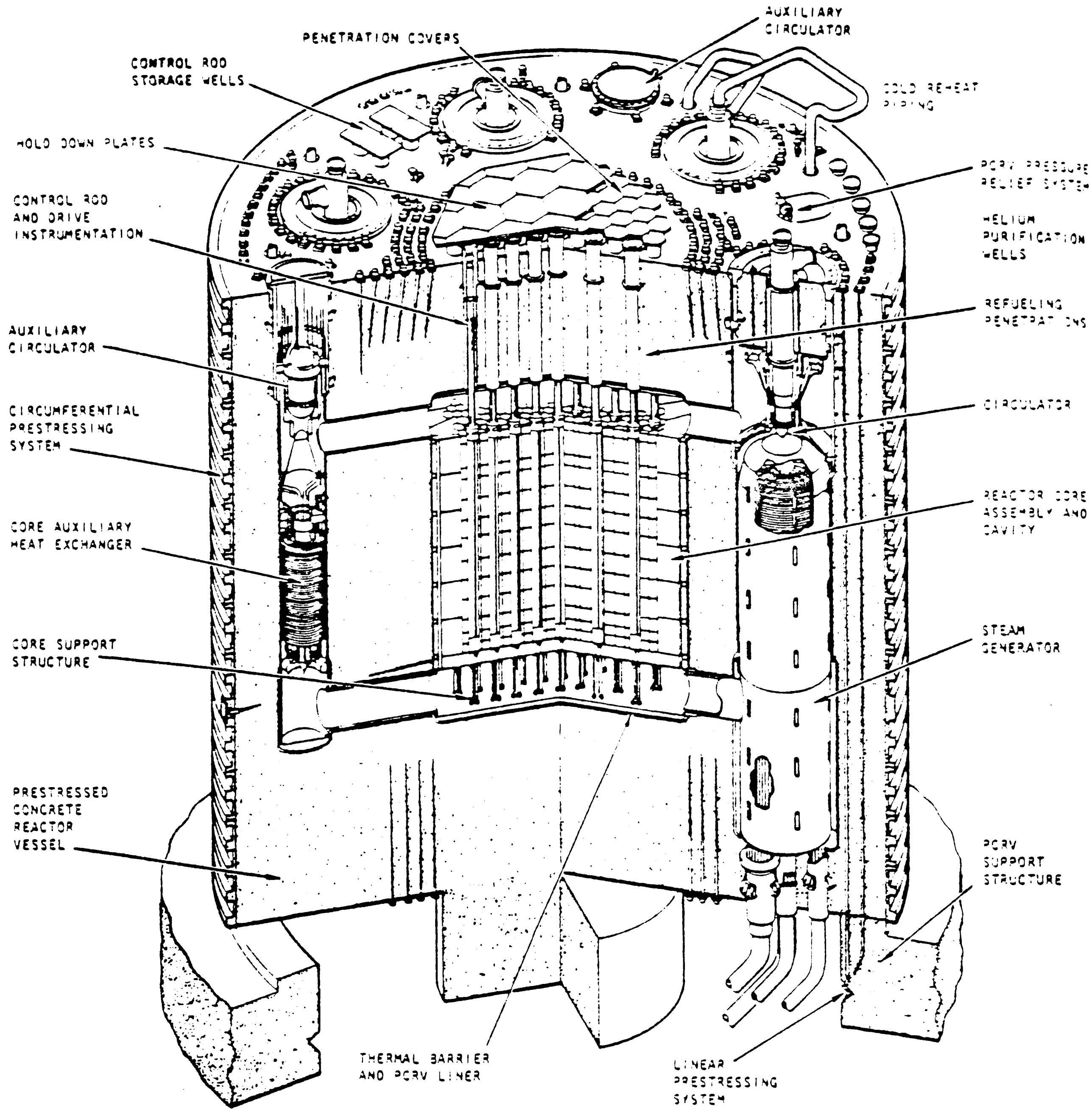
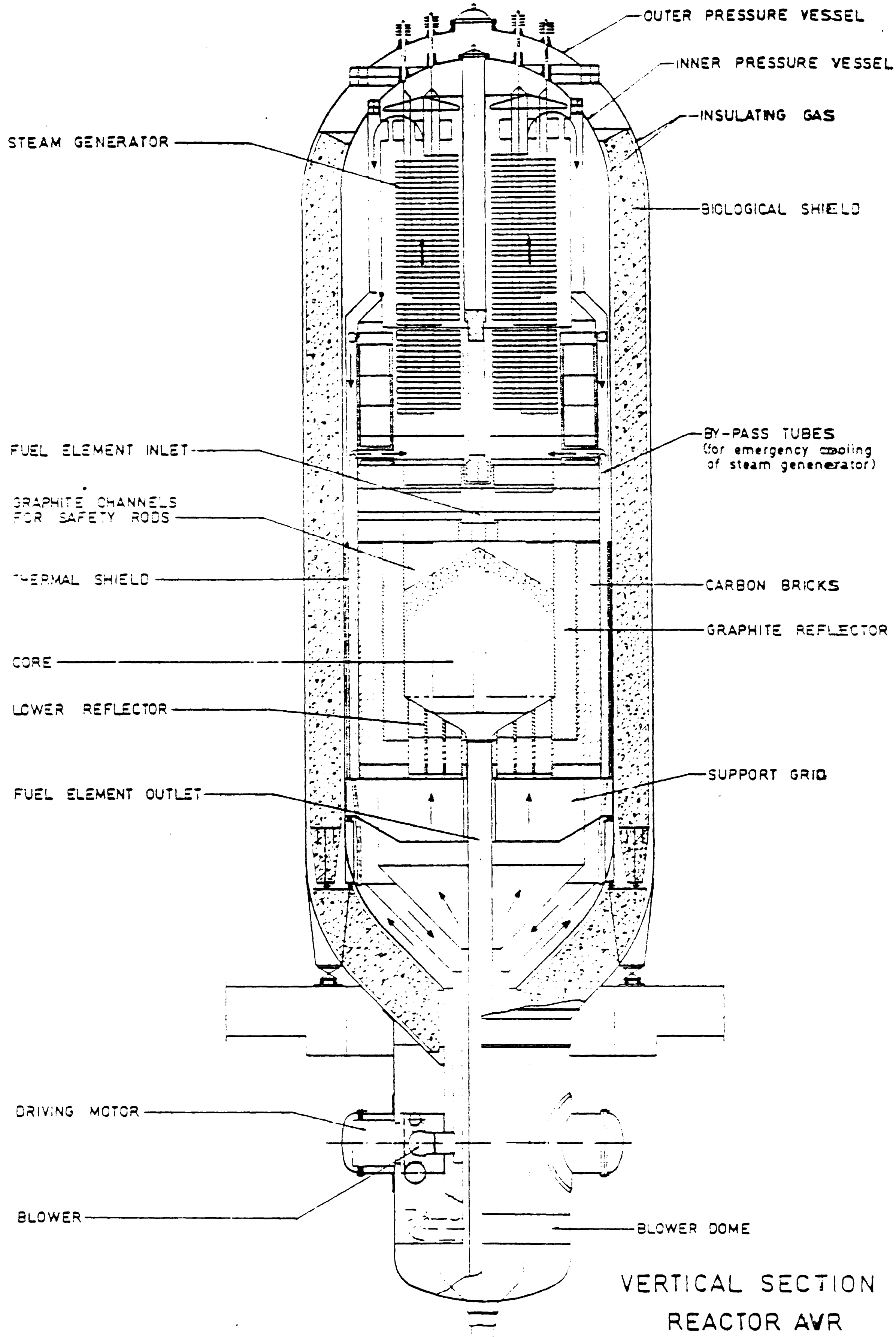


Figure 7.9 HTGR PRESTRESSED CONCRETE REACTOR VESSEL ARRANGEMENT. The primary system components are contained in a large cylinder of prestressed concrete. Penetrations exist for refueling, as well as for servicing (and even replacing) various pieces of equipment. Several primary coolant loops, as well as secondary cooling loops, are contained in the vessel. (Figure courtesy of General Atomic Co.)



VERTICAL SECTION
REACTOR AVR

Figure 7.10 The German Arbeitsgemeinschaft Versuchs-Reaktor (AVR), helium cooled. From Directory of Nuclear Reactors, Vol IV, Int'l Atomic Energy

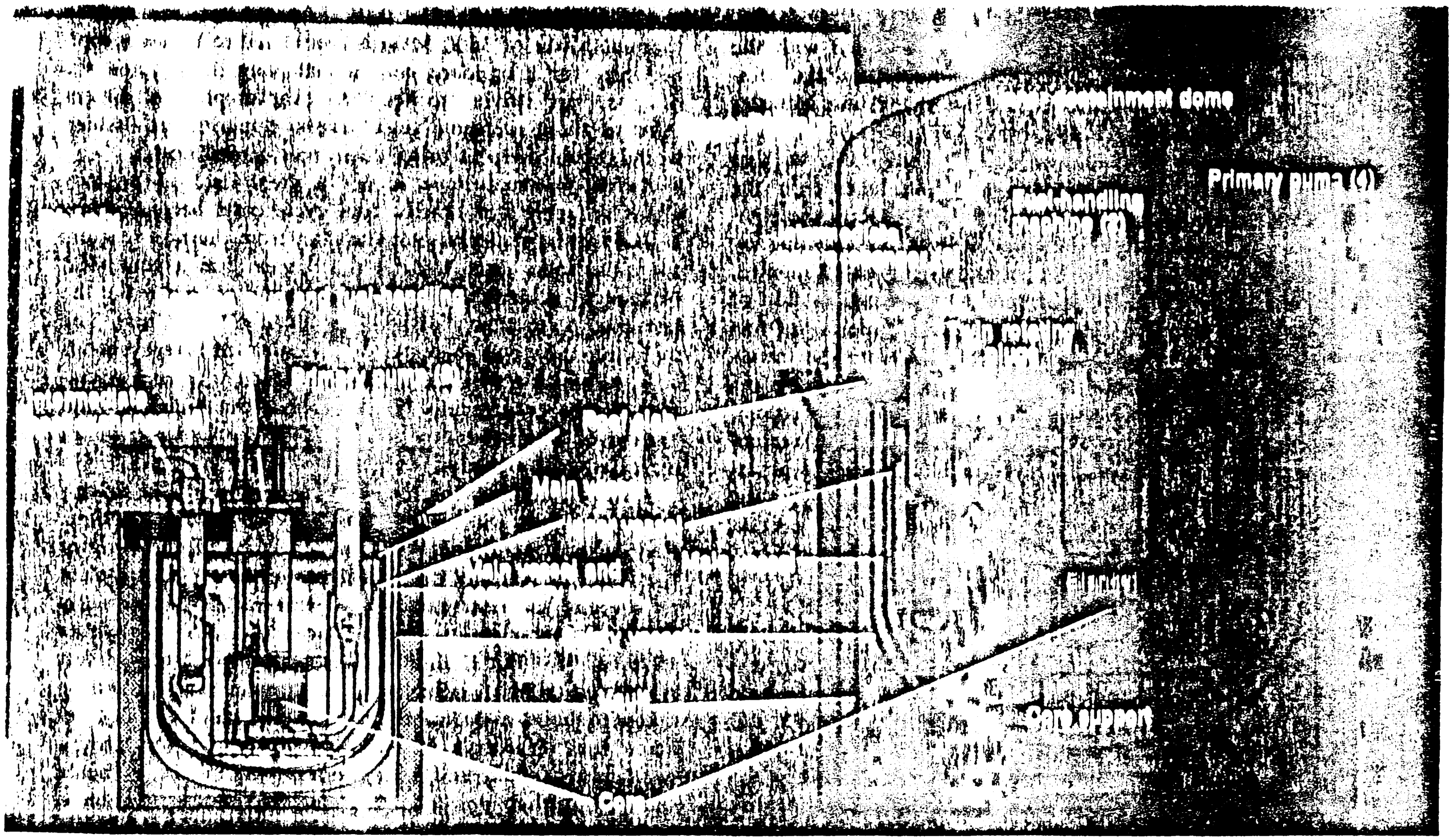
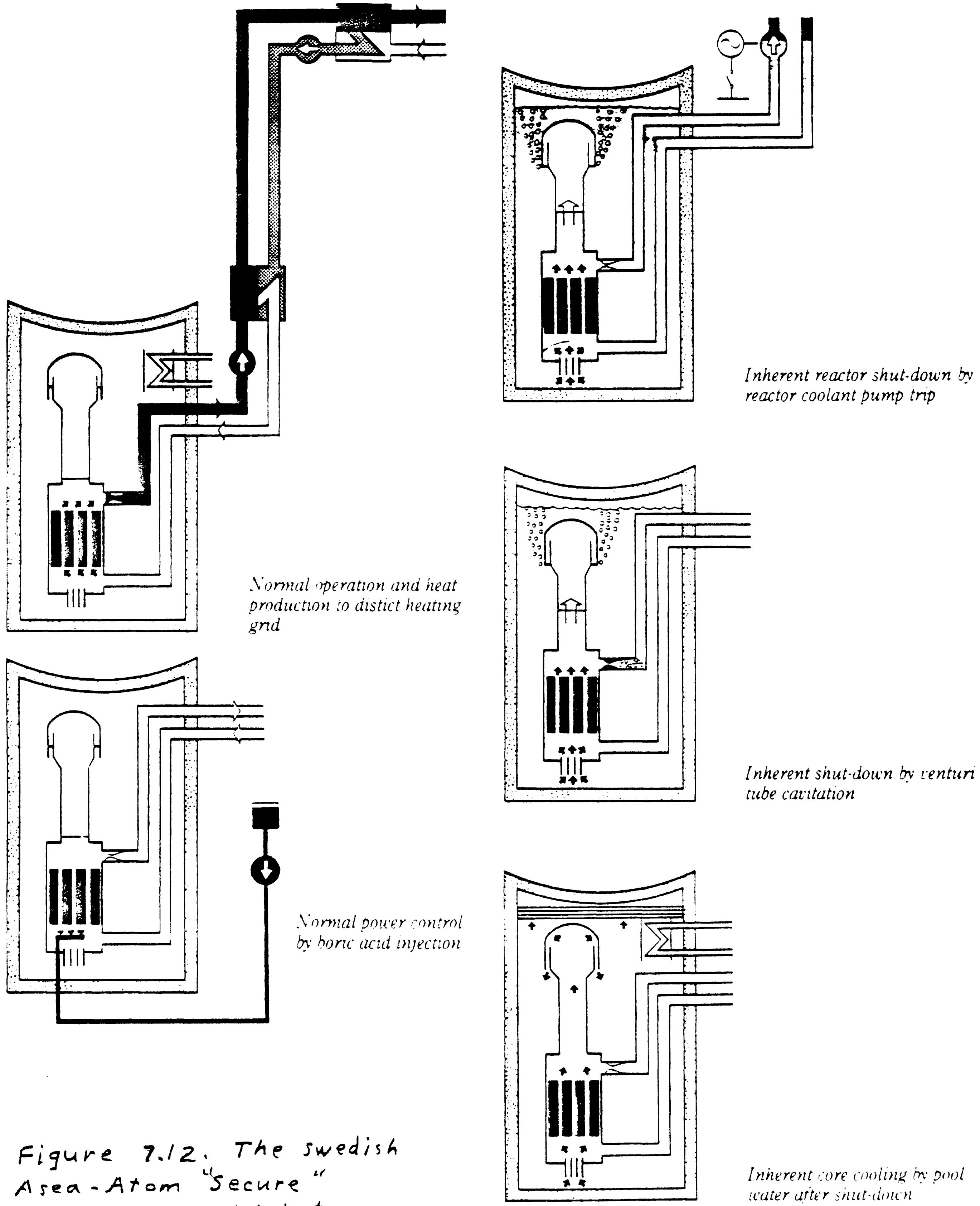


Figure 7.11 Diagrams of the Phénix and SuperPhénix Liquid Metal Fast Breeder Reactors, in France. The SuperPhénix reactor roof slab is 25 m diameter, weighs 800 tonnes. From Nuclear News March 1979 p. 67.



Normal operation and heat production to distict heating grid

Inherent reactor shut-down by reactor coolant pump trip

Normal power control by boric acid injection

Inherent shut-down by venturi tube cavitation

Inherent core cooling by pool water after shut-down

Figure 7.12. The swedish Asea-Atom "Secure" Reactor for district heating. see text for details.

— — Always Open Natural Circulation Circuit

1 Core
2 Riser, Coolant Density δ_2
3 Primary Recirculation Pump (Wet Motor)
4 Once Through Steam Generator
5 Down Comer
6 Lower Hot/Cold Interface
7 Upper Hot/Cold Interface
8 Cold (~ 120° F) Pool Water Containing ~ 2200 ppm Baron, Density δ_1
9 Steam Volume of Pressurizer
10 Prestressed Concrete Pressure Vessel
11 Feed Water to Steam Generator
12 Steam to Turbine
13 Steam Generator Tubes
14 Syphon Breaker Pipe
15 Water to Purification and Separation by Distillation
16 Temperature Sensors for Locating Hot/Cold Interface Level
17 Gas Lock Arrangement for Startup
18 Honeycomb Structure for Preventing Horizontal Flow
19 From Electrical Boiler
20 Pressure Relief Valves

$H \cdot g \cdot (\delta_1 - \delta_2) \sim \Delta p$ core

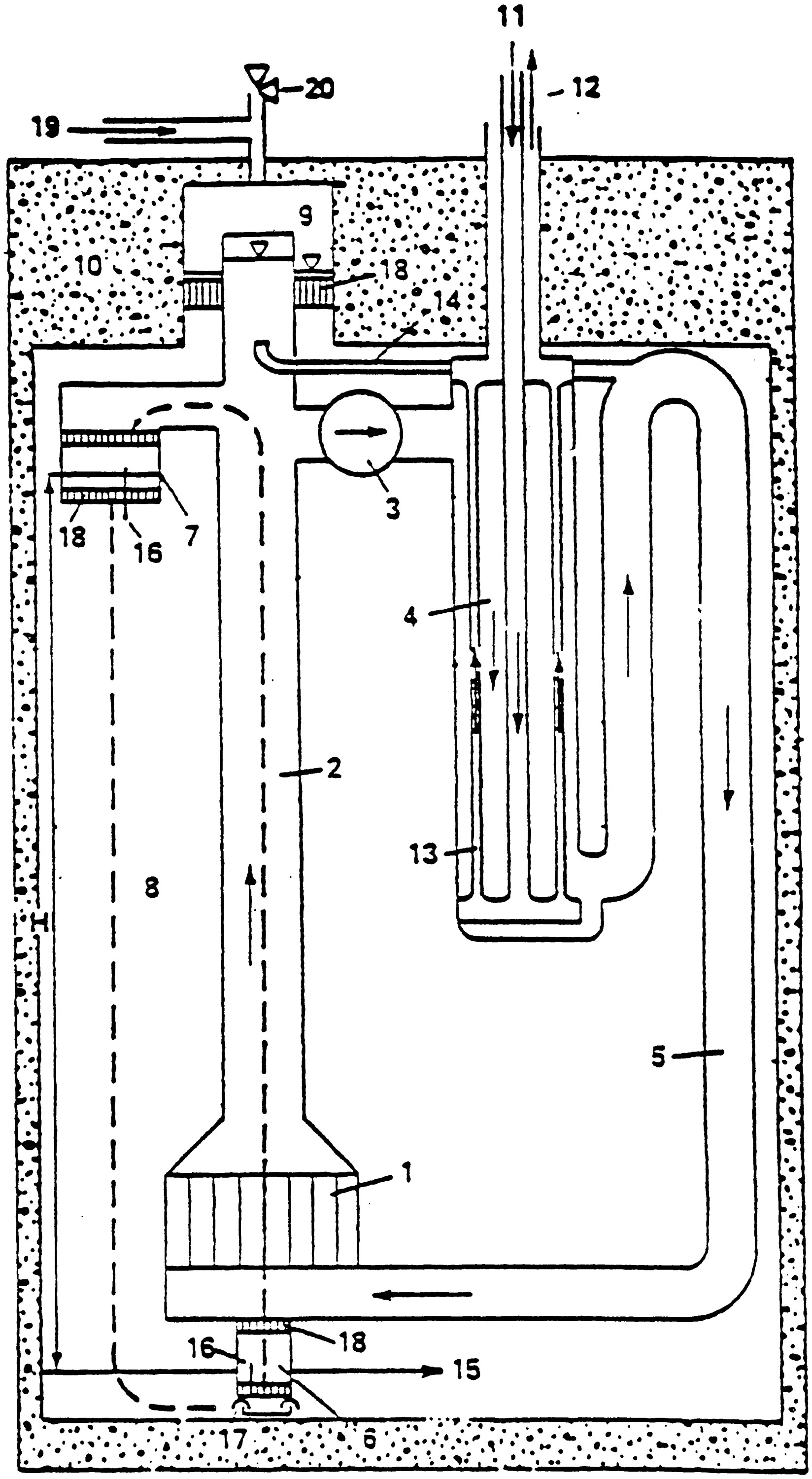


Figure 7.13 Schematic diagram of the proposed ASEA-ATOM "Intrinsically safe" light water reactor. Courtesy of Institute for Energy Analysis, Oak Ridge, Tennessee (Dwg. No. 82721

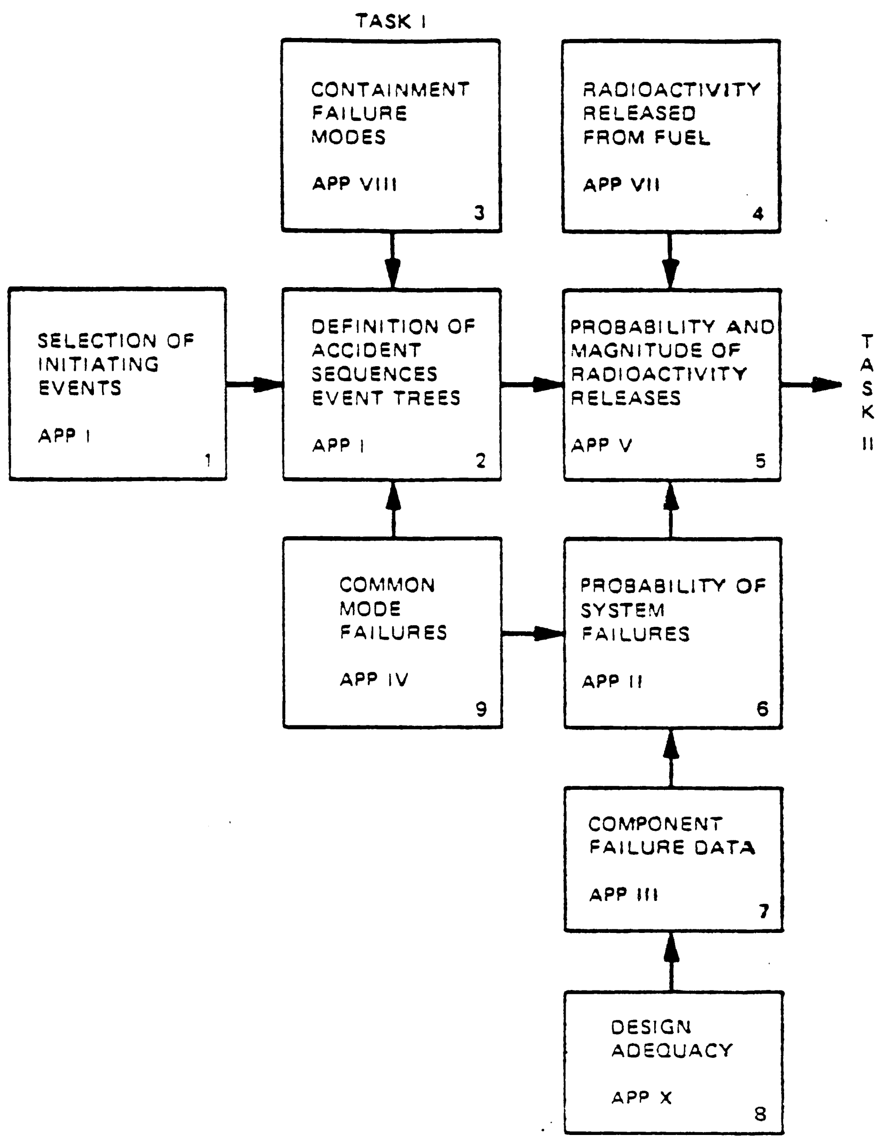


FIG. 7.14 PROBABILISTIC RISK ANALYSIS: SUBTASKS IN THE QUANTIFICATION OF RADIOACTIVE RELEASES FOLLOWING AN ACCIDENT IN A NUCLEAR REACTOR. (FROM REPORT WASH-1400, LOC. CIT. FIGURE 4.3)

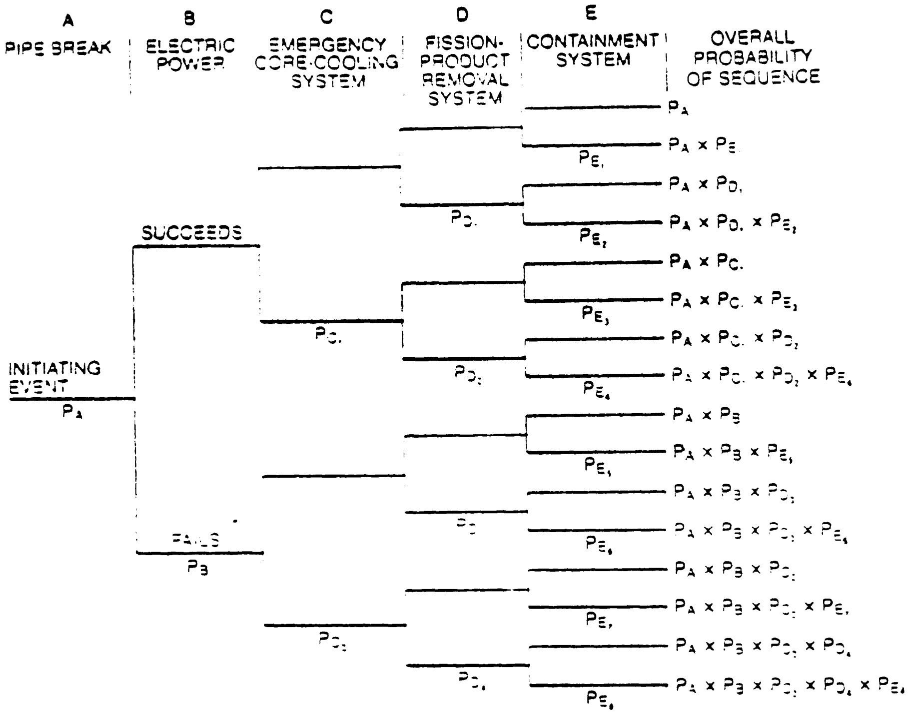


FIG. 7.15 SIMPLIFIED EVENT TREE FOR A LARGE LOSS-OF-COOLANT ACCIDENT IN A LIGHT WATER NUCLEAR POWER REACTOR. (FROM WASH-1400, LOC CIT, FIG. 4.4, ADAPTED AS IT APPEARS IN "THE SAFETY OF FISSION REACTORS" BY H.W. LEWIS, SCI. AMER VOL 242, p 53 MARCH 1980)

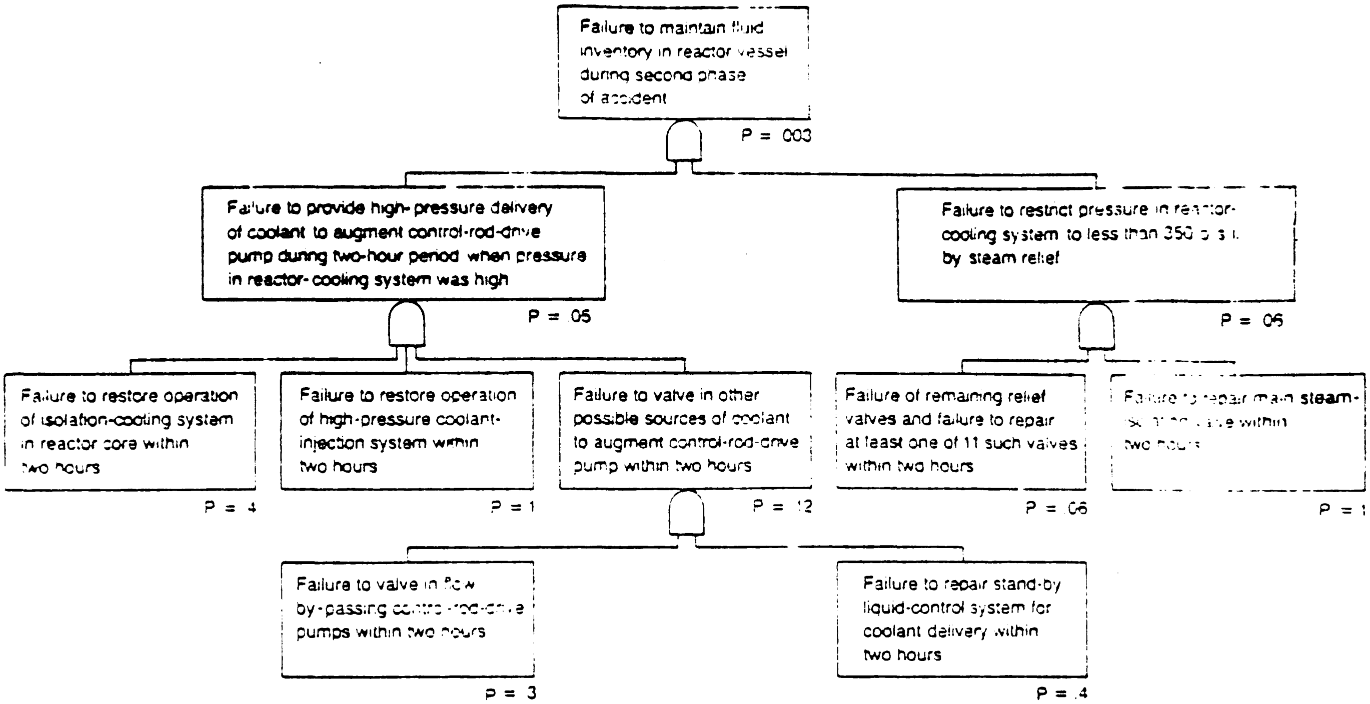
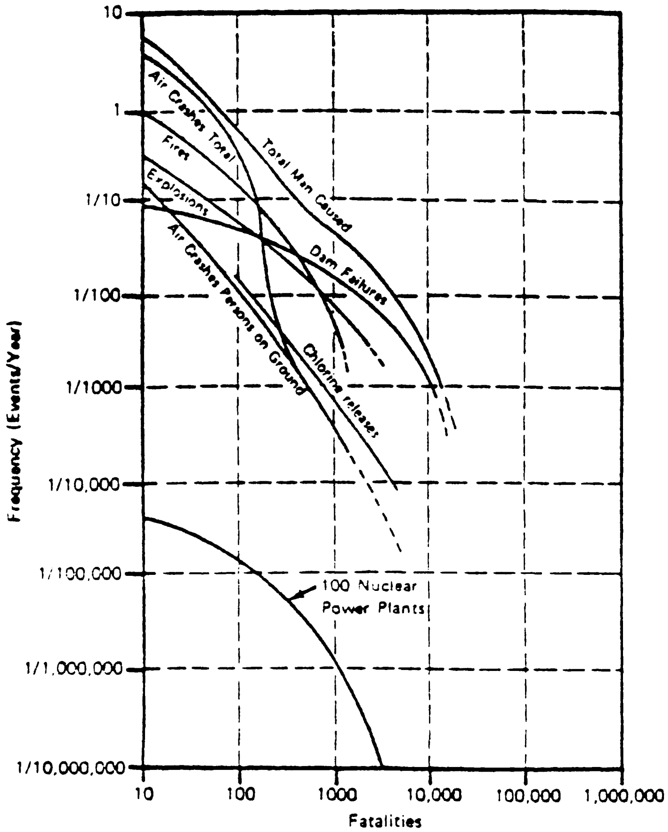
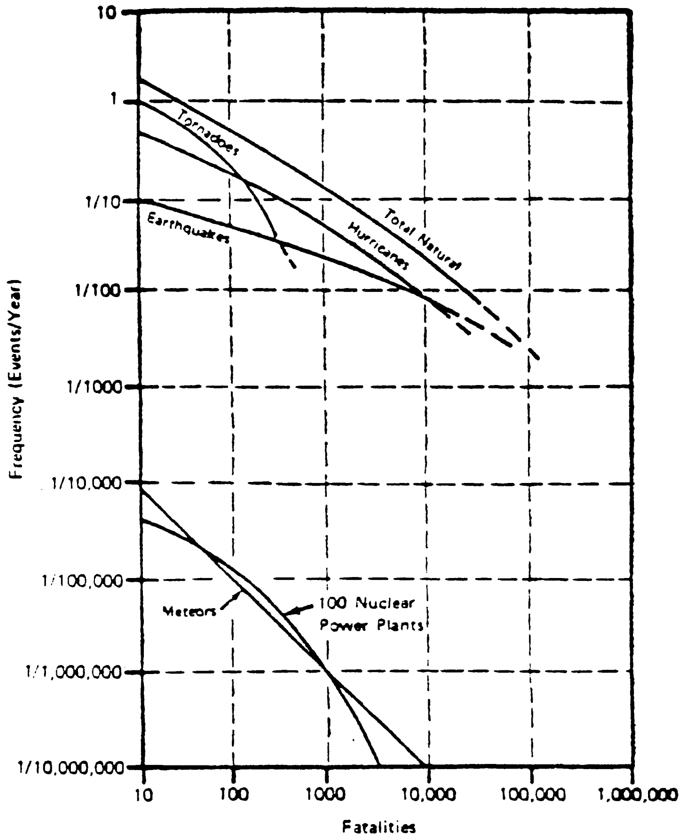


FIG 7.16 SIMPLIFIED FAULT-TREE FOR A PARTICULAR DEFECT IN A NUCLEAR POWER REACTOR, AND HOW IT COULD ARISE, WITH PROBABILITIES ASSIGNED. THIS ONE IS TAKEN FROM THE REACTOR SAFETY STUDY'S (LOC. CIT.) ANALYSIS OF THE 1975 BROWN'S FERRY ACCIDENT, AS SHOWN IN H.W. LEWIS "THE SAFETY OF FISSION REACTORS," (LOC. CIT.)



[redacted] Frequency of Fatalities due to Man-Caused Events

Notes:
1. Fatalities due to auto accidents are not shown because data are not available. Auto accidents cause about 50,000 fatalities per year.
2. Approximate uncertainties for nuclear events are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.
3. For natural and man caused occurrences the uncertainty in probability of largest recorded consequence magnitude is estimated to be represented by factors of 1/20 and 5. Smaller magnitudes have less uncertainty.



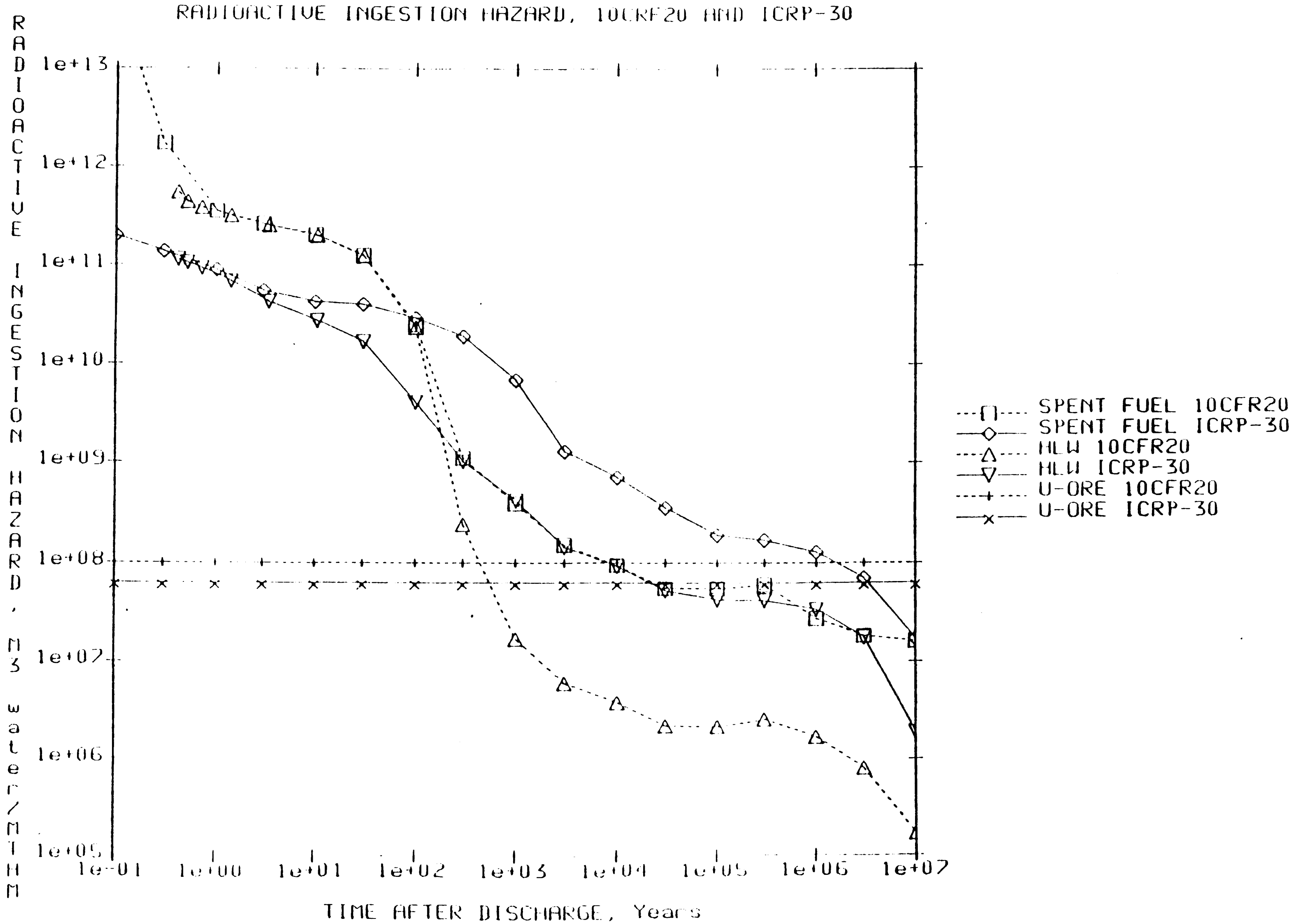
[redacted] Frequency of Fatalities due to Natural Events

Notes:
1. For natural and man caused occurrences the uncertainty in probability of largest recorded consequence magnitude is estimated to be represented by factors of 1/20 and 5. Smaller magnitudes have less uncertainty.
2. Approximate uncertainties for nuclear events are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

FIGURE 7.17

ESTIMATE OF FREQUENCY OF FATALITIES FROM NUCLEAR POWER PLANT~~S~~ ACCIDENTS, COMPARED TO [redacted] FATALITIES FROM OTHER CAUSES (FROM REACTOR SAFETY STUDY (LOC. CIT.), EXECTIVE SUMMARY FIGS 1.1 AND 1.2)

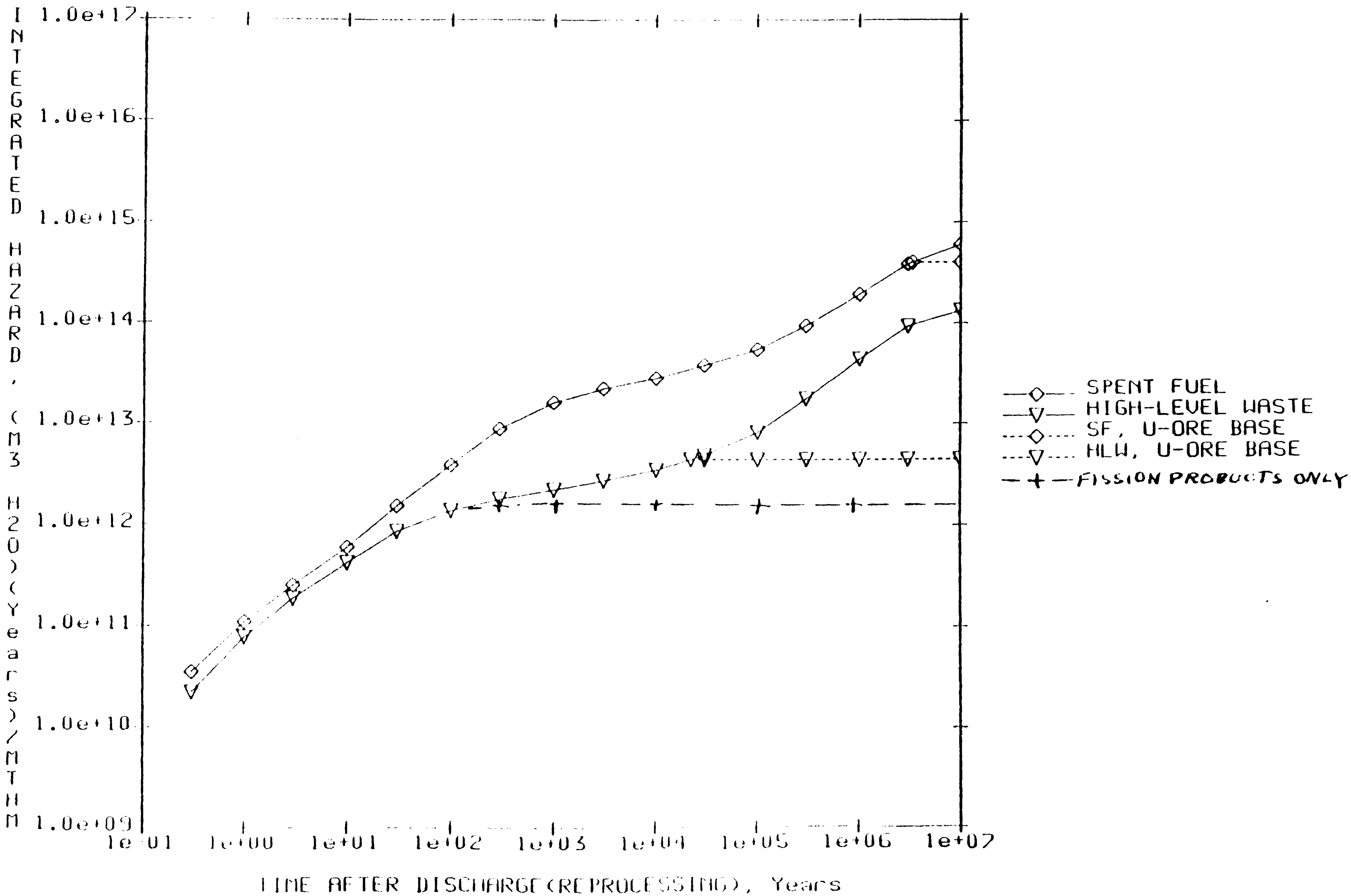
FIGURE 7.18



RADIOACTIVE INGESTION HAZARD, 10CRF20 AND ICRP-30
RADIOACTIVE INGESTION HAZARD, M3 water/MTHM
1e+13
1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
1e+05
1e-01
1e+00
1e+01
1e+02
1e+03
1e+04
1e+05
1e+06
1e+07
TIME AFTER DISCHARGE, Years
SPENT FUEL 10CFR20
SPENT FUEL ICRP-30
HLW 10CFR20
HLW ICRP-30
U-ORE 10CFR20
U-ORE ICRP-30

FIGURE 7.19

INTEGRATED RADIOACTIVE INGESTION HAZARD, ICRP-30



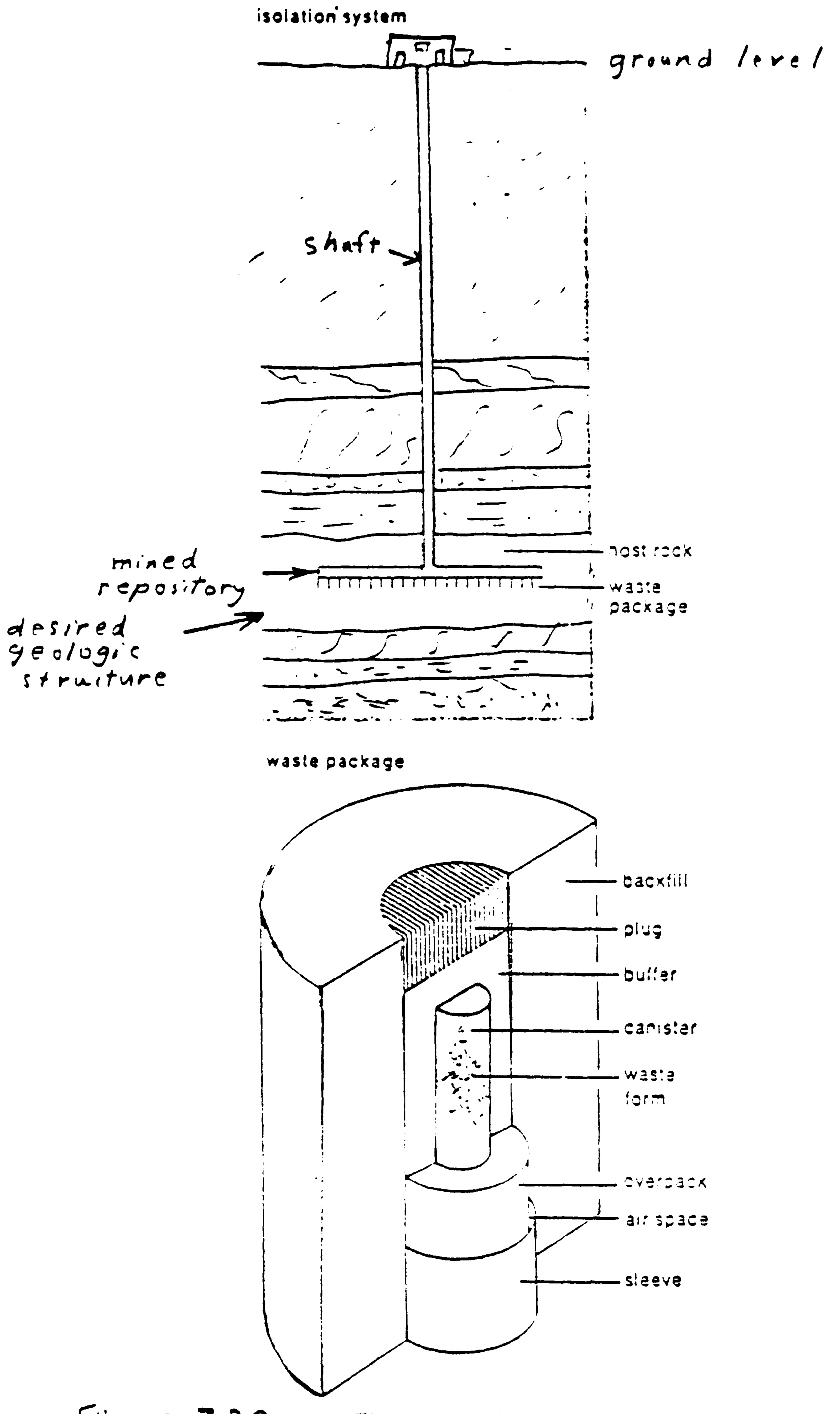


Figure 7.20 ~~2~~ The waste package, the components of which are depicted below, includes everything that is placed in the mined geologic repository. The position of the waste package within the isolation system is shown above.

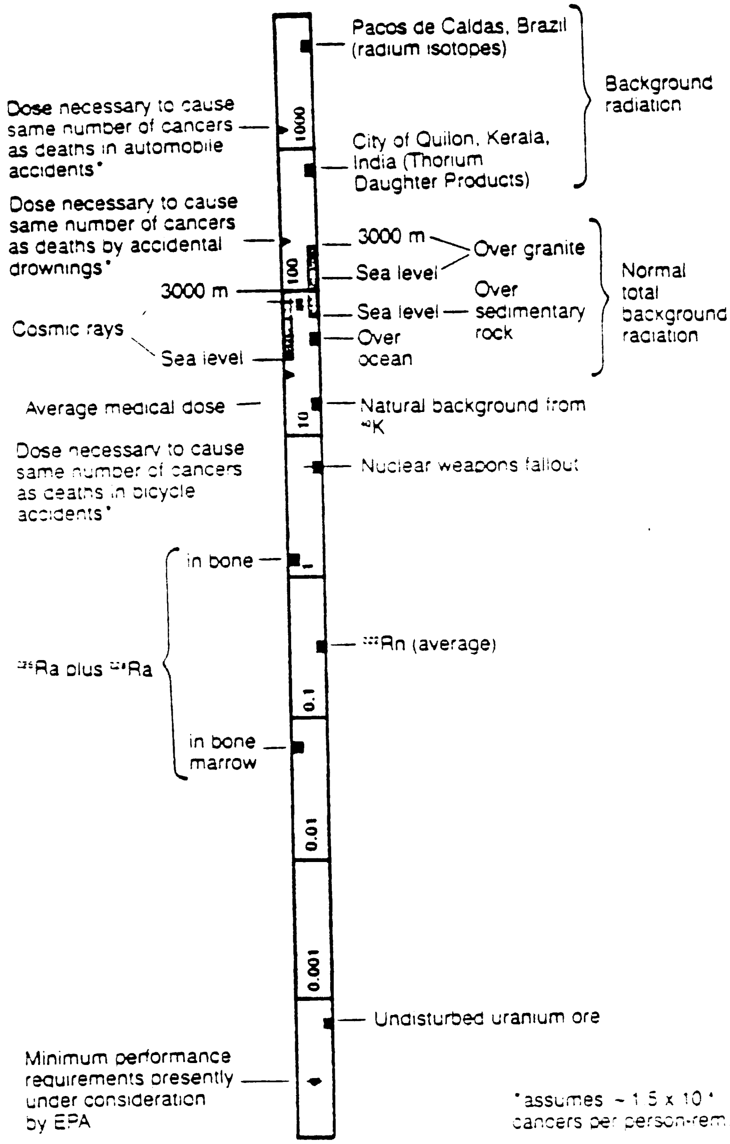


FIGURE 7.21

Doses from various radiation sources (m rem per year)[a]

[a] Radiation levels implied by performance criteria presently under consideration by EPA for high-level nuclear waste repositories, compared to other sources of radiation exposure

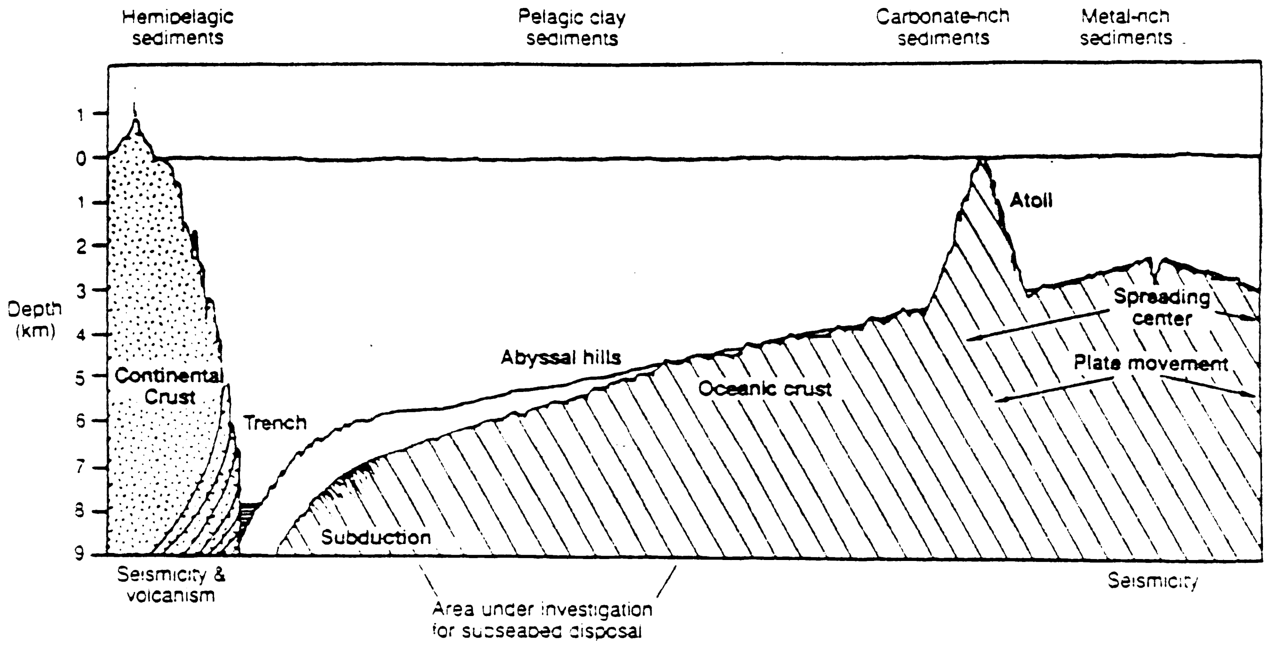


Figure 7.22 Mid-latitude profile of the North Pacific Ocean. From Hinga et. al. loc cit (Their Fig 3A)

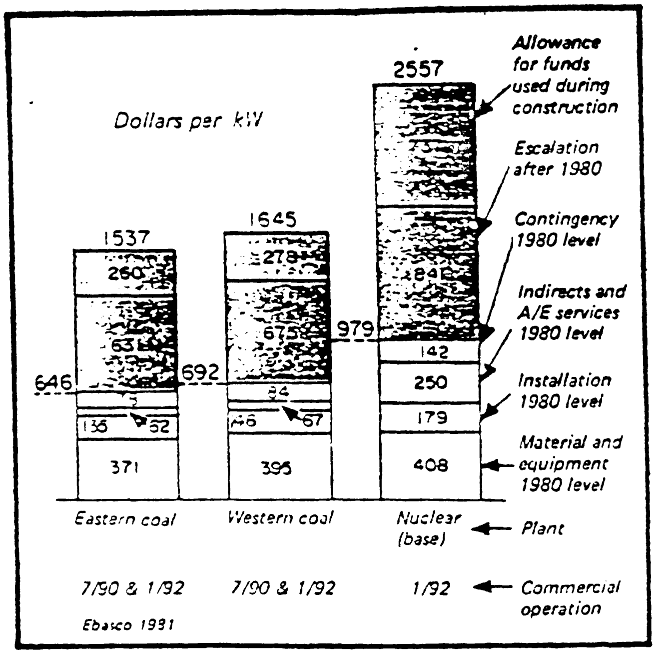


Figure 7.23 Cost projections for nuclear and coal units coming into commercial operation in ~~[illegible]~~ 1992. The base costs refer to 1980, used by Ebasco Services Inc. Escalation during construction was assumed to be 8%/yr, and Allowance for funds during construction (formerly called interest during construction was based on money being available at 9.5%/yr. For the nuclear plant, the base cost represents only 38% of the total. After F.C. Olds, loc. cit.

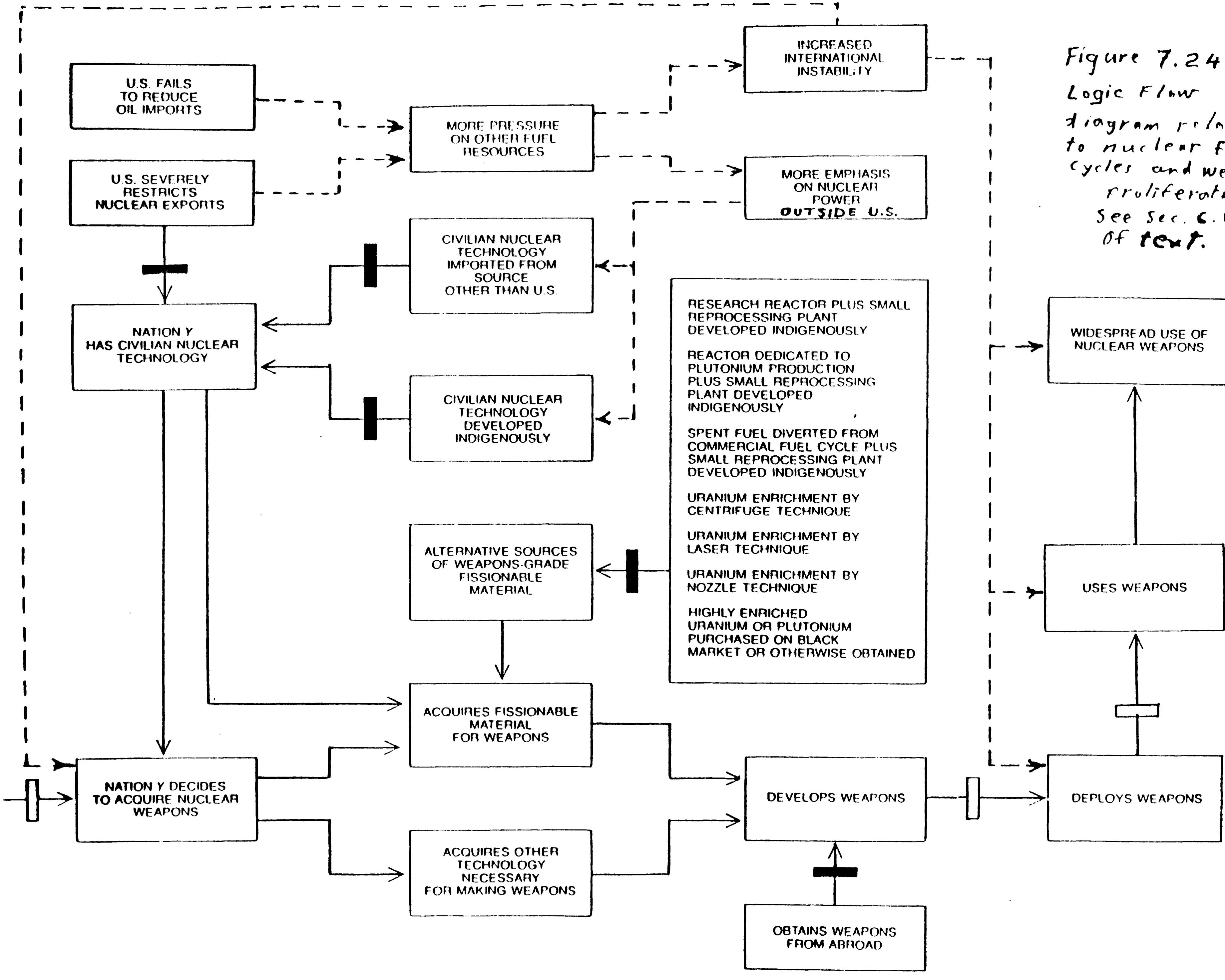


Figure 7.24
Logic Flow diagram related to nuclear fuel cycles and weapons proliferation.
See Sec. C.VII of text.

Table V.1

EXHIBIT III-D-23
MAXIMUM ACCIDENTAL RADIATION DOSES AND HEALTH EFFECTS AT SITE BOUNDARY[1]

Accident Class	Accident Type	Maximum Individual Dose (REM) at Radius of 2,130 Feet (Exclusion Area Boundary on Landward Side)		Probability of Effect to Exposed Individual (Events in One Billion)	
		Whole Body	**Thyroid**	**Mortality**	**Genetic Effect**
3	Equipment Leakage or Malfunction	2.91×10^{-4}	1.64×10^{-3}	57	75
3	Carbon Delay Bed Rupture	8.94×10^{-5}	Negligible	11	23
3	Drain Tank Spill	1.02×10^{-5}	1.54×10^{-4}	33	2.6
5	Off-Design Transients	1.08×10^{-4}	5.45×10^{-7}	13	28
5	S/G Tube Rupture	6.26×10^{-5}	9.29×10^{-7}	7.6	5.8
6	Fuel Bundle Drop	1.08×10^{-3}	3.70×10^{-5}	132	279
6	Heavy Object Drop	2.42×10^{-2}	7.48×10^{-4}	2,953	6,244
7	Fuel Assembly Drop	2.68×10^{-3}	3.05×10^{-4}	330	691
7	Heavy Object Drop	2.60×10^{-3}	6.54×10^{-4}	325	671
7	Fuel Cask Drop	5.10×10^{-4}	Negligible	62	132
8	Small Pipe Break	3.45×10^{-6}	2.11×10^{-5}	0.7	0.9
8	Large Pipe Break	1.89×10^{-2}	1.52×10^{0}	22,670	4,876
8	Rod Ejection	1.89×10^{-3}	1.52×10^{-2}	434	488
8	Steam Line Break	9.33×10^{-6}	1.23×10^{-3}	18	2.5

[1] Doses at EAB are analyzed for duration of accident except Class 8 events, which are considered as Design Basis Accidents. 0-2 hour doses are reported for Class 8 events.

Source: New England Power Company, Environmental Report NEP 1+2 . . .

Table 7.2

EXHIBIT III-D-25
TOTAL ACCIDENTAL DOSE COMMITMENT TO
MAXIMUM POPULATION EXPECTED WITHIN 50-MILE RADIUS
(Evaluated in 2020)

Accident Class	Accident Type	Population Dose (Person-REM)		Total Health Effect	
		Whole Body	**Thyroid**	**Mortality**	**Genetic Effect**
3	Equipment Leakage or Malfunction	4.06×10^{-2}	3.15×10^{-1}	9.16×10^{-6}	1.05×10^{-5}
3	Carbon Delay Bed Rupture	1.24×10^{-2}	Negligible	1.51×10^{-6}	3.20×10^{-6}
3	Drain Tank Spill	1.95×10^{-3}	3.01×10^{-2}	6.40×10^{-7}	5.03×10^{-7}
5	Off-Design Transients	2.96×10^{-2}	3.70×10^{-4}	3.60×10^{-6}	7.64×10^{-6}
5	S/G Tube Rupture	8.47×10^{-3}	1.80×10^{-4}	1.03×10^{-6}	2.19×10^{-6}
6	Fuel Bundle Drop	1.13×10^{-1}	8.43×10^{-3}	1.39×10^{-5}	2.92×10^{-5}
6	Heavy Object Drop	2.55	1.71×10^{-1}	3.12×10^{-4}	6.58×10^{-4}
7	Fuel Assembly Drop	8.84×10^{-1}	1.00×10^{-1}	1.09×10^{-4}	2.28×10^{-4}
7	Heavy Object Drop	8.47×10^{-1}	2.15×10^{-1}	1.06×10^{-4}	2.19×10^{-4}
7	Fuel Cask Drop	1.16×10^{-1}	Negligible	1.41×10^{-5}	3.00×10^{-5}
8	Small Pipe Break	2.24×10^{-3}	2.45×10^{-2}	1.47×10^{-5}	5.80×10^{-7}
8	Large Pipe Break	7.18	1.55×10^{2}	2.95×10^{-3}	1.85×10^{-3}
8	Rod Ejection	5.69×10^{-1}	1.57×10^{1}	2.80×10^{-4}	1.47×10^{-4}
8	Steam Line Break	2.01×10^{-3}	4.04×10^{-1}	5.66×10^{-6}	2.19×10^{-7}

Source: New England Power Company, Environmental Report NEP 1 & 2 . . .

TABLE 7.3

Nuclear Waste Inventories: Present and Projected[a]

	Present inventory	*Annual production rate (1980)*	*Projected inventory (2000)*
High-level wastes (m^3)			
DOE	288,000	~3,800	320,000
Commercial	2,200	—	
Spent fuel (MT)	7,000	1,500	73,000
Transuranic wastes (m^3)			
DOE	388,000	n/a	482,000
Commercial	363,000	1,300	n/a
Low-level wastes (m^3)			
DOE			
Defense and R & D	1,358,200	69,000	2,744,000
Remedial action	—	n/a	850,000
Commercial			
Nuclear power	668,000	50,000	4,800,000
Non-fuel cycle		44,000	
Mill tailings (MT)	125,000,000	6,000,000	615,000,000

[a] Sources: U. S. Department of Energy, *Spent Fuel and Waste Inventories and Projections*, ORO-778, Oak Ridge Operations Office, Oak Ridge, TN, August 1980; A. Ghovanlou *et al.*, *Analysis of Nuclear Waste Disposal and Strategies for Facilities Deployment*, MTR-80W00088, Mitre Corporation, McLean, VA, April 1980.

From R. K. Lester (1982) Loc. cit.

TABLE 7.4

FUEL COSTS FOR ELECTRIC POWER

Fuel	Cost/Unit	Gj thermal output/unit	$/kwh(th)	Conversion efficiency %	Fuel Cost of Electricity $/kwe
Uranium 3% enriched	$1000/kg*	2840/kg*	.00127	32	.004
coal	$40/tonne	25/tonne	.0058	37	.016
oil	$32/bbl	6.1/bbl	.0189	40	.047

* Figured on burnup of 33 Megawatt-days/kg, and enrichment losses described earlier.

Table 7.5 Commonwealth Edison Company, Chicago, Illinois. Historic comparisons of busbar costs for 6 big nuclear and 6 big coal-fired units, 1977-1980 (mills/kWh) Ref. Gordon Corey, Loc cit.

	Fuel	Total	Adjusted to 60% capacity factor
1977			
Nuclear	4.5	14.1	14.2
Coal	10.1	20.9	19.0
Nuclear advantage	5.6	6.8	4.8
1978			
Nuclear	4.7	13.6	15.1
Coal	14.0	25.3	22.7
Nuclear advantage	9.3	11.7	7.6
1979			
Nuclear	5.2	16.9	16.8
Coal	18.0	30.2	27.3
Nuclear advantage	12.8	13.3	10.5
1980			
Nuclear	5.6	18.0	18.2
Coal	21.2	36.1	33.7
Nuclear advantage	15.6	18.1	15.5

Table 7.5

Estimated costs for future nuclear and coal-fired units, 1100 mwe, ordered 1980, for 1991 operation[a] (Adapted from G. Corey, loc. cit.).

	Installed cost $/kw	Total carrying charges[b] mills/kwh	
		First ten years	Full service life
Zero escalation			
nuclear	1149	--	--
coal	785	--	--
difference	364		
6%/yr escalation			
nuclear	1816	78	68
coal	1458	59	49
difference	358	19	19
7½%/yr escalation			
nuclear	2035	87	76
coal	1695	68	57
difference	340	19	19
10%/yr escalation			
nuclear	2458	105	91
coal	2172	87	73
difference	286	18	18

a. Land and terminal costs excluded, as similar in all cases.

b. Money costs: 10% for debt, 10.5% preferred stock, 18% common equity; composite corporate income tax rate 49.45%; Illinois invested capital tax rate 0.3%; resulting present-value discount rate 10.31%, assuming 50% debt, 15% preferred, 35% common equity.

Table 6.7 Estimated total busbar costs—future nuclear and coal-fired units uniform carrying charge rates (mills per kWh)[a, b] From Gordon Corey, loc cit.

	First ten years		Full service life	
	Nuclear	Coal	Nuclear	Coal
With 6% annual escalation				
Carrying charges	78	59	68	49
Fuel and O & M	21	54	29	80
Cleaning and decommissioning	2	—	2	—
Backfitting	3	3	9	7
Total	104	116	108	136
Nuclear advantage	12 (10%)		28 (21%)	
With 7½% annual escalation				
Carrying charges	87	68	76	57
Fuel and O & M	26	68	40	114
Cleaning and decommissioning	2	—	2	—
Backfitting	4	3	13	11
Total	119	139	131	182
Nuclear advantage	20 (14%)		51 (28%)	
With 10% annual escalation				
Carrying charges	105	37	91	73
Fuel and O & M	37	99	72	213
Cleaning and decommissioning	5	—	5	—
Backfitting	5	5	23	21
Total	152	191	191	307
Nuclear advantage	39 (20%)		116 (38%)	

[a] These are level-premium averages expressed in current dollars for the periods indicated. Money cost and present-value discount rate assumptions are set forth in Table 6.2

[b] Expressed in constant 1980 dollars, the estimated per kWh full-service life nuclear advantage is 4.8 mills for the 6% scenario, 8.8 mills for 7½%, and 20.4 mills for 10%. The percentage advantages are 19%, 26%, and 35%, respectively—roughly comparable to the percentages shown above.

Table 7.8

Surveillance and Accountability: Features

	Containment and Surveillance	Materials Accountability
Detect Unforseen Diversion Routes?	✗	✓
Detect all diversion attempts within purview?	✓	✗
Capability for prompt detection?	✓	✗
Not limited by measurement accuracy?	✓	✗
Gives overall materials balance?	✗	✓

Table 7.9

Nuclear Reactors in Japan: Sources

MWe /TYPE	DATE OF OPERATION	WHO? REACTOR	GEN	A/E	CONSTR
159 GCR	66	UK	UK	UK	DOM*
340 BWR	70	US	US	US	DOM
320 PWR	70	US	DOM	JOINT	DOM
439 BWR	71	JOINT	JOINT	US	DOM
470 PWR	72	DOM	DOM	DOM	DOM
439 BWR	74	DOM	DOM	DOM	DOM
760 BWR	74	US	JOINT	US	DOM
780 PWR	74	US	DOM	JOINT	DOM
" "	76	DOM	DOM	DOM	DOM
2 x 529 PWR	75-81	DOM	DOM	DOM	DOM
780 PWR	76	DOM	DOM	DOM	DOM
2 x 1120 PWR	79	US	DOM	JOINT	DOM
1067 BWR	78	US	US	US	DOM
1067 BWR	79	US	JOINT	US	DOM
$\sum_{6}$ = 4150 BWR & PWR	76-78	ALL DOMESTIC			
$\sum_{11}$ = 9700 BWR & PWR	82-86	ALL DOMESTIC			

DOM ≡ DOMESTIC

Table V.10

Nuclear Reactors in Five Asian Countries: Sources

		WHO?			
MWe/TYPE	DATE OF OPERATION	REACTOR	GEN	A/E	CONSTR
KOREA					
564 PWR	78	US	UK	US	US
605 PWR	83	US	UK	US	US
2x900 "	84-85	US	UK	US	DOM
2x950 "	86-87	US	US	US	DOM
2x950 "	88-89	FRANCE	?	FRANCE	DOM
TAIWAN					
2x600 BWR	78-79	US	US	US	DOM
2x950 BWR	81-82	US	US	US	DOM
2x907 PWR	84-85	US	US	US	DOM
INDIA					
2x200 BWR	69	US	US	US	US
200 PHWR	73	CANADA	CANADA	CANADA	DOM
2x220 "	82-84	DOM	DOM	DOM	CANADA
2x220 "	86-87	DOM	DOM	DOM	DOM
PAKISTAN					
125	72	CANADA	JAPAN	CANADA	CANADA
PHILIPPINES					
620	85?	US	US	US	US

TABLE 7.11

1990 Projected LDC Installed Electrical Capacities and Small Reactor Market Potential Assuming 10% Maximum Unit Size Criterion*

Adapted from J. Egan, "Small Power Reactors in Less Developed Countries" Loc. Cit.

	Country		1979-1990 AVG %/YR GROWTH RATE	1990 Capacity (MWe)
1.	China (P.R.)†		N/A	N/A
2.	Brazil†		9.0	71,511
3.	India†		9.3	66,827
4.	Mexico†		9.0	43,333
5.	Yugoslavia†		9.3	33,853
6.	South Korea†		11.7	32,568
7.	Argentina†		6.4	30,063
8.	Romania†		6.4	28,055
9.	Taiwan†		11.2	25,408
10.	Venezuala		8.5	21,236
11.	Iran†		14.0	20,862
12.	North Korea		12.0	19,274
13.	Turkey†		11.3	15,478
14.	Indonesia		18.0	13,797
15.	Colombia		9.5	12,436
16.	Kuwait		16.6	11,731
17.	Thailand		10.3	10,156
18.	Egypt†		11.0	10,103
19.	Nigeria		16.0	10,017
20.	Philippines†		9.2	9,883
21.	Greece		6.8	9,791
22.	Portugal		7.9	9,771
23.	Vietnam		16.0	9,673
24.	Pakistan†		9.2	8,870
25.	Syria		16.0	7,797
26.	Hong Kong		8.0	6,995
27.	Libya†		21.0	6,966
28.	Saudi Arabia		15.8	6,811
29.	Chile		7.0	6,209
30.	Cuba†		8.6	5,801
31.	Peru		7.6	5,549
32.	U. Arab Emerites		15.8	5,540
33.	Ireland		6.8	5,494
34.	Israel		6.0	5,268
35.	Singapore		10.0	4,708
36.	Malaysia	440 MWe	10.2	4,646
37.	Algeria		12.6	4,375
38.	Iraq†		14.0	3,907
39.	Zaire		7.0	3,577
40.	Ecuador	300 MWe	11.6	3,491

TABLE 7.11 Continued

	Country		1979-1990 AVE. GROWTH RATE %/YR	1990 Capacity (MWe)
41.	Lebanon		13.5	2,644
42.	Qatar		16.0	2,638
43.	Dominican Rep.		10.0	2,611
44.	Zimbabwe		7.0	2,478
45.	Morocco		8.2	2,459
46.	Zambia		2.5	2,413
47.	Bangladesh		8.0	2,290
48.	Tunisia	200 MWe	11.8	2,116
49.	Mozambique		2.0	1,865
50.	Jordan		18.0	1,808
51.	Angola		10.0	1,712
52.	Bahrain		12.0	1,668
53.	El Salvador		10.3	1,510
54.	Jamaica		6.7	1,480
55.	Oman		19.0	1,403
56.	Ivory Coast		9.6	1,362
57.	Ghana		3.7	1,345
58.	Uruguay		5.8	1,313
59.	Guatemala	125 MWe	8.6	1,275
60.	Kenya		8.6	1,234
61.	Burma		9.5	1,232
62.	Panama		7.0	1,158
63.	Paraguay		11.1	1,144
64.	Costa Rica		7.6	1,140
65.	Papua New Guinea		12.0	1,113
66.	Sri Lanka		9.1	1,096
67.	Bolivia		8.5	1,095
68.	Nicaragua		10.0	1,050
69.	Afghanistan		9.1	986
70.	Suriname		8.0	952
71.	Mongolia		8.8	908
72.	Trinidad & Tobago		6.0	862
73.	Tanzania		9.6	707
74.	Cyprus		8.0	637
75.	Sudan		9.5	595
76.	Cameroon		5.0	580
77.	Ethiopia		3.0	457
78.	Liberia		3.0	422

* For data sources, see text.
† Nuclear power projects operating, underway, or being planned.

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Chapter 8

SOLAR POWER

8.1 Introduction

An observer from a distant star, if asked to describe the energy balance of the earth, would do so almost entirely in terms of sunlight incident, absorbed and reflected, and finally re-radiated to outer space at much longer wavelengths, in the infrared. The major terrestrial energy flows proceed through oceans, atmosphere, and the upper few meters of the continental lithosphere, and much less through the biosphere. All human activity now contributes little but, as shown in the analysis of global CO_2 effects, it could potentially upset the reflective and re-emissive properties of the earth enough so that the sun itself could drive the earth into a significantly different equilibrium.

Sørensen (1979), has written an excellent scientific text on renewable energy, and some of what follows finds its origin there. Figure 8.1 is his picture of the global energy cycle, showing the 172,500 TW of incident solar radiation described in some detail near the beginning of section 3.4 of chapter 3. Recall the discussion there, Fig. 3.4, and the conclusion that the mid-latitude insolation is about 250 w/m² in cloudless regions. Figure 8.2 from Melvin Calvin (1974), shows the annual average for the US, including the effects of cloud cover; 200 w/m² is a useful approximation for the US as a whole.

Returning now to Figure 8.1, note that:

- By far the largest accessible energy source is sunlight itself, which makes direct collection and utilization via photovoltaic devices, thermal collectors, etc. environmentally and ubiquitously attractive, and potentially important and technologically dominant. Thus photovoltaic devices, with their relatively high conversion efficiency have a prominent place in this chapter. Direct solar-thermal systems receive some attention here, augmented by material elsewhere, for example in chapter 4.

- About 1% of the incoming solar flux goes to drive the winds, about 1200 TW according to the figure. Thus windpower, used since medieval times in small amounts, appears attractive at favorable sites, and a section of the chapter deals with the state of the art.

- About 133 TW go into the biosphere; other estimates place it as low as 100 TW. About 30 TW drive all the oceanic life, and 65-100 TW goes into terrestrial biomass--trees, grasses, agricultural crops. Only a very small part of this, 1 or 2 TW perhaps, seems likely to be harvestable for energy without causing severe long-term environmental and ecological damage. The delusion persists that much more can be easily obtained; thus biomass becomes an urgent topic here, partly because it is locally and regionally convenient and important, and partly in order to describe the limitations.

Figure 8.1 shows several other minor sources and sinks. The natural input to replenishing coal, and other fossil hydrocarbons is about 10^{-5} TW, compared to a present extraction rate of about 8 TW. The entire geothermal flow amounts to an average of 60 milliwatts/m^2 over the earth's surface, making geothermal energy a local specialty, with probable total global potential of several tens of gigawatts. The world's rivers dissipate about 5 TW, not shown in the figure; this amount, though small, is potentially useful because of its natural concentration. Perhaps 1 TW could be conveniently and safely obtained from hydropower; most of the large undeveloped sources are in the Asian high mountains (particularly), South America, and Africa.

The 3 TW of tidal power (lunar power in fact) is largely untappable, except for modest amounts in special places.

Many simplistic views exist about the possibilities of using solar power, some to the effect that it is cheap and simple, some to the effect that vast installations must and should be built forthwith, and others of intermediate degree. Some of these views are conditionally correct, some totally wrong, and a final section in the chapter deals with a few notorious high-technology mistakes, plus some reflections on why such schemes, which pre-date the major US solar program, received so much early support, and appeared for so long impervious to criticism. If good results are to come, we must look at these and other schemes realistically, and not through sun-glasses.

Figure 3.4 of chapter 3 is particularly useful for the photovoltaic discussion. Note that the atmosphere absorbs ultraviolet radiation ($h\nu > 3.2$ ev, or $\lambda < 0.38$ um) strongly, and almost completely for $h\nu > 4$ ev, mainly because of ozone absorption in the high stratosphere. Other interesting features were taken up in chapters 3 and 4.

8.2 Photovoltaic Conversion: Principles and Problems

The science and technology become more attractive with time. Multi-megawatt experimental photovoltaic systems were connected to California power grids in 1982, 1983 and 1984, despite total system cost exceeding $10 per peak watt ($\$/W_p$ is the usual symbol). If properly built and installed, they require almost no maintenance. But to compete with other systems in bulk, without developmental or tax subsidies, PV system cost must decline by a factor of 10 or more, unless other overriding circumstances supervene. Much has been written on both the promise and problems; a short annotated bibliography is appended to section 8.3.

The same physical principles underlie both solar cells and solid state devices such as transistors. In some cases outstanding scientific problems persist, and in all cases technological and manufacturing problems remain. The technology is closer to the science than is the case in some other areas, so a simple description of the solid state physical principles, while not absolutely essential, aids recognition of the possibilities and limits.

Figure 8.3 shows a basic feature of all solid materials useful in this application. First, consider an electrical insulator (e.g., glass). Its constituent atoms have many electrons, yet they do not move. Why? By the rules of quantum theory, all electrons do not have the same energy in the solid, but each its own. This quantization leads to discrete and precise singular energy levels in isolated atoms (hence sharp spectral lines arising from electronic transitions between them in a partly ionized gas). In a solid, the lines blur into bands, the uppermost of which (i.e., highest electron energy) is the conduction band. Electrons in it are free to move, and their presence there would signify electric conductivity. The next lower band is the so-called valence band; others below that exist, but they do not enter this story. In an insulator, the valence band is completely filled with electrons. They cannot move in any organized way, because that would imply net velocity, which implies more energy, and the next higher energy states are in the quantum-mechanically forbidden gap. At the same time, there are no electrons in the conduction band. Thus it is an insulator. In good conductors, for example copper, the valence and conduction bands overlap, so there is no forbidden gap.

Semiconductors are insulators with a usefully small, but not too small, forbidden gap. At $0^{\circ}K$, they are all insulators, but at room temperature (say) some electrons will be thermally excited into the conduction band; very roughly, the fraction in the valence band that will be so excited into the conduction band is given by the Boltzmann factor

$$\exp(-eV_b/kT) .$$

For $T = 300^{\circ}K$ and $V_b = 1.0$ volt, $eV/kT = 38.6$ and the exponential is 1.7×10^{-17}. But with (say) 10^{23} electrons/cm^3 in the valence band, this gives a density of about $10^6/cm^3$ in the conduction band; it conducts electricity weakly. But at 320°, the electron density in the conduction band approaches 2×10^7; the weak conductivity of these semiconductors in their pure state rises rapidly with increasing temperature.

Most semiconductors are in column IV of the periodic table (Ge, Si particularly) or are alloys of III and V elements (Ga + As, Ga + P, In + Sb, etc.) with average valence of 4. Now let us introduce a very small amount of one of the valence-V elements (or a little bit extra of it) into the otherwise "intrinsic" semiconductor. The extra electron cannot be accommodated in the valence band, so it occupies a discrete level just below the conduction band. This is indicated in Fig. 8.3

Such a "doped" semiconductor is called n-type (for negative electrons); for electrons in these donor levels, the Boltzmann factor is small, and these electrons are easily excited at room temperature into the conduction band; the conductivity increases with more doping.

Now inspect Fig. 8.4 On the right appears such an n-type semiconductor. The donated electrons in the conduction band can move and carry current; the residual positively-charged ions (here phosphorus) are immobile and keep the crystal macroscopically neutral. On the left a lower-Z impurity (e.g., indium) dopes the hitherto-intrinsic semiconductor. The indium takes an electron from the valence band into an acceptor level created by the impurity atom. Thus a hole appears in the valence band, which can move as if it were a positive electron (hence p-type semiconductors). Of course, the electrons actually move to create the effect, exactly as a gap moves backward in a line of automobile traffic as cars move forward successively to fill it.

Now let the two pieces of semiconductor be joined (in reality, the single crystal of semiconductor is doped differently in adjacent layers) to form an n-p junction. Mobile electrons and holes will flow across the junction to recombine. This flow leaves a net positive charge from the residual ions in the n-region, and a net negative charge in the p-region. The flow stops when enough charge has built up to inhibit further net flow, leading to the situation of Fig. 8.5.

The ratio of electron densities N_1 and N_2 in the conduction bands of the n-region and p-regions respectively is set by the requirement that no net current must flow, i.e. $J_1 = J_2$ in the figure. Thus

$$\frac{J_1}{J_2} = 1 = \frac{N_1}{N_2} e^{-eV_o/RT}$$

arising from the fact that the few electrons N_2 in the p-region come from thermal excitation of electrons in the N_1 group and diffusion across the gap. Similar circumstances apply to the hole currents, not shown.

The solar cell is now complete, except for how it works. It is also (and in its original invention) a rectifying diode, as follows. If the left side in Fig. 8.5 is made relatively more negative, the barrier against electrons in the N_1 population being thermally excited to the N_2 group becomes even higher, and the already-low density N_2 declines even further. Each charge species, electrons and holes, is kept from crossing the barrier. However, if the left side is made relatively less negative, with a so-called forward-bias applied voltage, the junction potential decreases. This forward-bias voltage increases the flow of majority carriers across the junction (electrons in N_1 to the p-side and similarly holes to the n-side). The net current density across the junction is

$$J = J_o \exp\left[\frac{eV_{ext}}{kT} - 1\right]$$

where J_o is the small reverse-saturation current density that flows when a large reverse-bias voltage is applied.

Now to the solar cell; see Fig. 8.6. Let the p-region (for example) be very thin, and exposable to light. With no illumination, the internal voltage generated in the junction can do no work; no current flows, and that internal potential is exactly cancelled by the various contact potentials around the circuit. Now let light shine on it, with photons of energy $h\nu > eV_b$; some electrons will be excited from the valence to the conduction band, as shown, and an equal number of holes also appears. But the electrons appear where the population N_2 was very small, and the new holes constitute a negligible perturbation to the majority hole population $P_1 \approx N_1$. Thus if these photoelectrons can reach the junction, the J_1-J_2 current balance is upset, and J_2 becomes large. These electrons flow around the circuit, can produce a voltage across an external load comparable to a substantial fraction of V_b, and deliver power. If the exposed surface had been n-type instead of p-type, electrons and holes would be produced in it, but the current would be carried by the holes.

Several requirements for successful solar cells appear from this analysis:

- A band gap potential V_b appropriate to utilizing solar photons. For silicon, V_b = 1.1 ev, and for GaAs, V_b = 1.5 ev. The peak intensity in the solar spectrum is close to $h\nu$ = 1.5 ev. See Fig. 3.4.
- Materials with closely controlled purity. A concentration of 10^{-6} atomic fraction of the wrong impurity can provide $10^{17}/cm^3$ of unwanted conduction electrons or holes, making the device useless. Also, impurities impede diffusion of electrons and holes toward the junction, and provide sites for electron and hole trapping or recombination.
- Temperature control (or at least avoiding excessively high temperature), to minimize thermal excitation and efficiency loss. Silicon becomes useless at 200°C, and GaAs at 300°C.
- An appropriately thin layer between the junction and the sun-facing surface. In silicon, about half the useful photons (i.e., $h\nu$ > 1.1 ev) are absorbed in the first 5 μm, but about 100 μm is needed to absorb virtually all, because the absorption coefficient depends on photon energy. To a first approximation, it does not matter whether the photons are absorbed on the sunward (p-region of Fig. 3.6)

or the shadeward (n-region in Fig. 8.7) side, provided the photons can diffuse to the junction before being trapped or recombining. Electrons will flow to the right, as described earlier, and holes made in the n-region would flow to the left. Thus for silicon, a junction 3-10 μm below the front surface, followed by a 100-200 μm back region is about right.

For GaAs, the photon absorption depths are an order of magnitude less, so the solar cell can be very much thinner (e.g., 5-10 μm total thickness.

- Good lateral conductivity on the front surfaces. At the back, there is no problem, but pickup conductor strips compete with active cell surface, and should be limited to (say) 5% of the front area. This suggests how the cells should be made: the whole cell originally moderately n-type, for example, then a heavy p-type doping on the front, both to create the junction at the proper depth and form a relatively highly conducting front surface.
- An anti-reflection coating. The index of refraction of these semiconductors is high, and in the absence of any coating, about 30% of the photons will be reflected. SiO on silicon makes a good coating, fortunately; such surface layers are usually combined with others to protect the cell from the outer environment.
- Arrangement of the cells in series and parallel to give useful voltages (e.g., 150-200 volts for residential use) and current. This is done by internal connections inside the array of cells in a solar panel.
- Also internal to the panel, protective diodes, for example to

prevent one inadvertently short-circuited cell from draining the power from others connected in parallel.

- Power conditioning equipment to turn the dc power (which varies not only with angle of the sun, but with cloud cover and other external stimuli) into a form usable by the electric load, which in residential and larger applications will almost always require ac power.
- As high efficiency as economically and technologically possible, because covering area with anything costs money. 20% efficiency at 250 W/m^2 average insolation gives 50 W/m^2 average output, an optimistically high and perhaps unrealizable goal.
- Doing all this, including power conditioning, at a cost of $\$1/W_p$ if possible, and preferably less. If 50% of the cost is for the cell assemblies, this comes to $\$25/m^2$ for very sophisticated devices, a cost per unit area about equal to that of billboards.

Satisfying this last requirement, in view of all the others, will be very difficult, but in 1982 good hope existed for success in one or two decades, but probably not sooner. Solar cells that cost $\$30/W_p$ in 1975 cost $\$6\text{-}7/W_p$ in 1982.

Single crystal silicon cells are the most highly developed and reliable; their technology benefits from years of development of solid state electronics, and of solar panels for space. Metallurgical grade silicon costs \$1-2/kg, but semiconductor grade silicon cost \$80/kg in the early 1980's; reduction to \$14/kg would make the crystal cost marginally acceptable, with 20 wafers/cm cut from it (250 μm wafer, 250 μm for the saw cut).

These thicknesses can now be achieved. This silicon is usually purified by decomposition of trichlorosilane ($SiHCl_3$) gas, and the crystals, 8-10 cm diameter and 50-100 cm long, are grown from the molten silicon by dipping in a seed crystal, then gradually pulling it out (the "Czochralski" process, named after its developer). In another method, a thin single crystal ribbon is pulled up from the melt through a die. Wafers, after forming by growing or slicing, are etched to remove surface defects, doped (usually by vapor deposition and diffusion), and surface treated to form a grid of electrodes, protective covering, and so forth. In 1982, the energy payback time (years in the sun to capture the energy used in manufacture) was about 4 years; efficiency of solar conversion was 10-15%, with good reliability.

These expensive techniques lead naturally to thoughts of concentrating the sunlight; even mediocre quality Fresnel lenses will give a concentration of 50-100 suns (the present terminology); but now the devices must be sun-following, the lenses are not cheap, plastic lenses tend to degrade, and the PV cells themselves must be cooled. Some commercial/industrial uses for both electricity and heat have been envisaged, but the size of such a combined market is probably not large.

The expenses associated with single crystal silicon invite attention to alternative materials. Multicrystalline silicon, grown as a solid block from the melt, can be handled like single crystal ingots, is cheaper, and has slightly lower efficiency and reliability. Furthermore, different crystal directions and grain boundaries begin to complicate the elegantly simple physical pictures of Figs. 8.3-8.6 Grain boundaries trap electrons and holes and introduce other problems, and require passivating.

Evaporated amorphous silicon (a-Si) made by deposition of silane (SiH_4) gas is cheaper yet, but its physics is less understood -- the hydrogen appears to play an important role, and the idea of a precise band gap becomes only amorphously clear. Conversion efficiency approaches 10% on developmental devices.

The strongest competitors to silicon in 1982 are GaAs and InP; both are expensive. Consider GaAs; its elements are toxic, but only a 5-10 μm thick film is needed. Its 1.5 ev band gap promotes good conversion efficiency, with 17-20% hoped for in single crystals, and perhaps 15% in polycrystalline material.

Other promising solar cell combinations are Cu_2S/CdS, $Cu_2S/(Cd,Zn)S$, $CuInSe_2/CdS$, $CuInSe_2/(Cd,Zn)S$. All of these have been used to produce experimental cells with 9-10% conversion efficiency, and nearly all can be grown as thin films from the vapor phase.

Texturing the sunward surface can increase the efficiency by reducing specular reflection. So too, in principle, could stacked arrays, consisting of two (or more) layers with different band gaps and separate p-n junctions. The larger gap material on the sunward side absorbs only higher energy photons to produce current at a higher voltage V_1; lower energy photons cannot excite photo-electrons there, so pass virtually without loss to the second lower gap material below, where they produce current at a voltage $V_2 < V_1$. The solar spectrum is used more effectively this way, and could in principle yield efficiencies of 30%, but at increased cost and complexity.

Related to photovoltaic devices but different are photocatalytic electrodes in aqueous conductors, the art and science of which are much more primitive. Doped semiconductor electrodes form a diode which, when suspended in the liquid and illuminated, produce hydrogen photochemically. Reference was made to such systems in 1978 (American Phys. Soc. 1979). A report in Science (Maugh 1982) describes iron oxide doped with silicon dioxide and magnesium oxide respectively to make n- and p-type semiconductors, in a Na_2SO_4 or NaOH solution, that gave an overall energy conversion efficiency from sunlight to hydrogen of 0.05%--a very low number, but indicative of new and interesting science.

Even modest success, say 1% conversion efficiency from sunlight to hydrogen would be technologically and economically interesting, because a principal obstacle in the way of establishing hydrogen as a more common energy source is the high cost of conventional electrolysis. The prognosis remains hopeful but guarded.

8.3 Some Cost Projections and Trends

Where will all this lead, and what is the best direction to go?

If solar PV power is to be a major global energy option (i.e., at the terawatt level), it will consist in the main of multi-megawatt solar PV farms tied to local or regional power utilities. Several reasons exist for this. First is the increased electrification of the world (as described elsewhere) which is happening, solar PV or not. Second, is the increased ability of electric utility grids to accept energy from decentralized sources. Third, the operation and maintenance (O&M) costs associated with small stand-alone systems are estimated to be very large. In this last context, the SCI report (see bibliography) estimates O&M costs of 3.5 mills/kwh (1979 dollars) for 10 MWe systems, rising sharply for smaller installations. (These estimates are based on experience with diesels, batteries, fuel cells, etc.: the specific technology seemed less dominant in determining costs than were issues such as the need for travel time between sites because of lack of permanent personnel (SCI 1980). Note that 10 MWe systems are still capable of capturing many of the benefits of reduced transmission and even some distribution (T&D) costs and losses. Such systems are still "small" by most electric utility standards. 1983 plans for multi-megawatt systems described below supported this view. Various tax incentives can favor either the end-user or the utility; this is a redistributional problem, of secondary importance here.

Focussing on these "large" systems simplifies the arguments to follow. The driving force for development and cost reduction of both modules and balance of system (BOS) will come via such systems; in any event, whatever smaller systems that eventually develop will benefit from the spinoff. Kilowatt-size systems will be limited to remote locations and some special needs, and not to the roofs of the world's houses. Regarding this latter application: (1) the need for keeping the temperature low and the efficiency high conflicts with the usual schemes for saving energy in the home by insulated roofs; (2) a PV-covered roof gets dirty, and cannot be safely walked on; (3) despite claims by some PV enthusiasts that people will delight in caring for their own energy systems, most do not now service their own appliances or (usually) cars; this is related to the fact that efficient and reliable PV modules will be made in large (centralized) factories, from which will naturally flow the capability of service; (4) the capital cost is higher, in addition to O&M.

Sales and contracts for solar PV systems have grown by a factor of 2 or more in each of the past several years; from 1.5 to 2 million dollar installations in Colombia and North Africa in 1980-81 (Haq 1981) to $10 million and larger projects in service today. The largest and most advanced of these are in California, stimulated by a combination of Federal and State support, tax incentives, more public receptivity, relatively cloud-free sites, etc. Table 8.1 summarizes most recent information about these California installations.

According to Solar Age, April 1982, the market share of the three major US photovoltaic suppliers was:

Solarex (AMOCO, etc.)	38%
ARCO-SOLAR	26%
Solar Power (Exxon)	15%

ARCO-SOLAR has now overtaken Solarex, at least temporarily.

Regarding cost projections, the Department of Energy 1978 forecasts of $\$.50/W_p$ (in 1978 dollars) in 1986 will not be met. In the 1978-83 period, improvements seem to have come at about half the 1978-expected rate. Discussions in 1982 and 1983 with senior Jet Propulsion Laboratory personnel (Daniel et al. 1982-83) confirmed the view that modules, probably polycrystalline silicon, would be available for 1985 delivery at \$4-5/Wp. If all the technology available in the US were put under one factory roof, finished modules could probably be supplied at a price of \$2.70/W_p in 1980 dollars. Advances now foreseen and very probable would bring this down to an asymptotic \$1.50/W_p. For multi-megawatt systems, the power conditioning is expected to be only 10-15% of the module cost at most.

What might be a rock-bottom ultimate cost? A reasonable backing for any panels is expected to cost about 60¢/ft^2, or 6¢/W_p at 10% efficiency. This and other costs leads to an estimate of about 30¢/W_p (1980 dollars) for modules alone. That gives a factor of 5 between the extremes for asymptotic module cost. If past experience is any guide, the balance of the system (not including storage) will approximately double these costs (see SMUD phases I-III), although some of the engineering design and other costs will be non-recurrent. Taking factor 2 as a guide, we have \$.60 and \$3.00/W_p for entire systems.

What does this amount to in electric energy cost? At 20% capacity factor, a good day-night-summer-winter average, we have \$3000-\$15,000/kwe, on a continuous basis. At 15%/year rate of return on investment, this comes to 5.1¢-25.5¢/kwh, or \$14.3-\$73.3/GJ. The higher number would make solar PV prohibitively expensive except for special purposes, hence unfeasible for large-scale penetration. The lower one would allow solar PV to compete very well for daytime intermediate and peaking power. But intermittent electricity at a generation cost of 5.1¢/kwh is still much too expensive to be stored (in batteries, for example) for off-peak use, provided either coal or nuclear power are available. Any solar PV system which costs much in excess of this lower asymptote will face severe problems in adoption, without either large incentives and/or subsidies, or prohibitions of both coal and nuclear power, and perhaps even on oil. Furthermore, this lower asymptote seems far enough away that significant penetration of PV is unlikely this century; however, utilization of these technologies on a small scale is well-suited to current paths of low growth in electricity demand.

The path to improved and cheaper PV (and wind) systems could be in some ways smoother than the path to developing new nuclear reactors or (especially) controlled nuclear fusion. Very importantly, both solar PV and wind can be developed technically with relatively small units, hence without the necessity of constructing billion-dollar or even more costly proof-of-principle experiments.

The low costs of PV modules needed to permit their entry into the bulk electric market must come via substantial technological and perhaps scientific advances. Principal considerations are these:

(a) Sawn single or polycrystalline silicon will probably not do, because of the cost, as discussed earlier. But the various technologies to grow silicon ribbon from melt look more promising (Deb 1982). A ribbon thickness of 0.2 mm with small material waste would be adequately frugal of silicon use, even at \$16/kg (6.4c/W_p).

Much research has gone into development of amorphous silicon made by the silane process (a-Si:H) or by sputtering. The band-gap can be modified somewhat by inclusion of appropriate impurities. Efficiencies up to 8% have been reported, but the work is not nearly so far advanced as single- or poly-crystalline silicon.

(b) Thin films look promising. These can be a-Si, as mentioned above, or possibly other materials. The attractiveness of thin films lies principally in the hope that very cheap automated techniques can be developed to make them. Here, a high photon absorption coefficient, as in GaAs, is a great advantage, because of the thinness. Ingenious methods are being developed to grow it even in very thin single crystals. For example, the CLEFT technique developed by Fan and co-workers (Fan 1981, 1982a) of growing micron-thick crystals of 5-10 cm^2 area epitaxially on a reusable substrate, then cleaving them off without damage, is a remarkable accomplishment, and gives hope for even more future advances. Extensive use of arsenic raises significant environment/health problems. Supplies of gallium are not well known, but are certainly relatively small.

Elaborations of these film techniques are being tried to develop stacked multilayer, multigap cells, for higher total conversion efficiency, as described in the previous section. Work is still in an early stage, and the possibility of 30% conversion efficiency exists (Fan 1982b).

(c) Concentrators versus flat plates. It is still a horse race, with possibly a decade to go before we see if there is even a clear winner. New technology for concentrators (e.g., new plastic Fresnel lenses) will bring the cost down, but the solar cells live in a very severe and changing environment. The choice between flat plates and concentrators depends on:

- cost of concentrators vs. cost of flat cells.
- cost of flat one-sun cells vs. cost of highly sophisticated cooled cells with maximum efficiency.
- costs of reliable trackers.
- cost and availability of PV material--silicon is (or can be made) plentiful, but GaAs, CuInSe, etc., cannot be so plentiful.
- the environment--for example, flat plates still give about 40% reception on hazy or overcast days, but the efficiency of concentrators drops drastically under such conditions. For example, at Barstow, California, 100 miles ENE of California, Los Angeles smog decreases total reception by 15% (Mackin 1982).

(d) Aggressive and competent development. There is some worry that the U.S. solar PV industry is less than optimally structured. One worry is whether companies with the ability to produce the cells have the ability to sell them. Vice versa, do small companies with aggressive sales policies have the competence to produce them? Some other countries, expecially Japan and now Taiwan, are working very hard; according to some observers Japan is in the lead in much solar cell R&D, for example a-Si (Maycock 1982). Any large solar PV future is bound to take a long time to develop. It would be too massive for rapid movement. However, the entire solar and energy program in the U.S. has too-short time perspectives and there are few incentives to do any different. For example, there are few incentives at the moment to spend $30 - $50 million of capital expense to turn out about 50 MW/year of PV output (a 1982 estimate of the cost of factories). Nevertheless, PV is much easier than nuclear reactors in many ways, because there is only about a two-year lag in the factory investment before obtaining a return on capital, instead of a decade or more.

Brief Annotated Bibliography

Electricity from Sunlight: The Future of Photovoltaics, by Christopher Flavin. Worldwatch Paper No. 52, December 1982. A very readable 63-page summary of large and small projects, cost reduction trends, national programs. Also 82 references. Points out that this renewable technology did not develop so much with the "environmentalists" (as did wind, OTEC, biomass, etc.) but as part of science, technology and industry. This can be some advantage, and Flavin favors the technology.

Basic Photovoltaic Principles and Methods, Report SERI/SP-290-1448, February 1982, published by Technical Information Office, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401. A nice semi-technical overview.

Solar Photovoltaic Energy Conversion (Principal Conclusions of the American Physical Society Study Group, H. Ehrenreich, Chairman), published by American Physical Society, 335 EAst 45th Street, New York, NY 10017. An excellent review of the basic science and progress up to late 1978.

Photovoltaics as a Terrestrial Energy Source: Vol. I, Introduction; Vol. II, System Value; Vol. III, An Overview; by Jeffrey L. Smith, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1980. An excellent review, especially with respect to the problems of systems integration, incentives, cost projections, etc. A summary of this is "photovoltaics," by the same author, Science 212 1472-1478 (1981).

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Decentralized Energy Technology Integration Assessment Study, Systems Control, Inc. Report, SCI Project 5278, December 1980 (1801 Page Mill Road, Palo Alto, CA 94304). Most of the examples and calculations apply to solar PV and wind.

"Solar Cells: Plugging into the Sun," J.C.C. Fan, Technology Review, Vol. 80, No. 8, August/September 1978. Good description of principles and techniques as of that date; still good reading. 18 pages.

8.4 Wind

Most of the approximately 1200 TW of solar power that drives the winds (Fig. 8.1) returns to the air as frictional heat, either at the surface of land and sea, or via mid-air turbulence. The winds are stronger high above the ground and (generally) over the open ocean, so good wind-power sites are not common. However, even at modest heights above the ground, such as 20-40 meters, the wind can be considerably stronger and steadier than at ground level. This vertical change in wind speed profile is determined mainly be surface roughness, and the vertical temperature gradient (Sørensen 1979, pp. 237-240).

The technology is becoming well developed and applications totalling many GW can reliably be foreseen. Depending on competition from other solar-derived sources, the degree of decentralization of future electric power systems and cost, the eventual applications could be much larger, but much less than 1TW (which would require several percent of the world's land surface dedicated to wind farms). As with many other medium or high-technology solar applications, most of the power output will be electric, because sites with both good wind and large local mechanical loads are scarce.

Many good brief popular reviews exist (Sørensen 1981; Merriam 1977; EPRI 1980); of those listed here,, Sørensens's is best.

Simple calculations show both some of the possibilities and also the limitations. Consider first the available power. At a few hundred meters altitude, the air density $\rho \approx 1.2$ kg/m^3, a value assumed for convenience in all the calculations to follow. The kinetic energy per unit volume at wind speed v is $\rho v^2/2$, and the rate at which this energy crosses a unit area normal to the wind is $\rho v^3/2$. Thus the wind power available increases as the cube of the wind speed; substantial, steady and persistent wind speed characterizes good sites. This suggests locations where the trade winds or mid-latitude westerlies blow steadily, and where natural geologic features tend to channel the flow and increase the speed.

Figure 8.7 shows measured data on speed and duration of wind at Kahuku, on the Island of Oahu in the Hawaiian Islands; the trade winds are particularly steady and stronger than average at this location, the site proposed for a large wind-farm. It is one of the world's best, and serves as a good example to develop the topic.

The wind machine should be designed to capture as much of the area under the power curve as is economically practicable. The power below 3 or 4 m/sec is small and so (at this site) are the number of hours. It is uneconomical to design the power and conditioning equipment (to control voltage, frequency, etc.) for so little benefit, so the windmill might be designed to cut in at 3 m/sec, as shown. It is uneconomic to design the machine for full power operation at the highest expected wind speed, because it will be grossly over-designed and over-built for operation most of the time. Thus it should produce full power at a usefully high but intermediate wind speed, here chosen as 9 m/sec (20 mph). At higher wind speed, the power remains constant, usually either by adjusting the blade pitch or (in most modern designs) adjusting the pitch of outer segments of the blades, either to feather them or to act as wind brakes. Finally, at dangerously high wind speed, large systems will be designed to shut down completely, as shown somewhat schematically near the left margin of the figure. The shaded area under the power curve is potentially available to this machine, but not the part lying above 437 W/m^2. That shaded area corresponds to a power density of 240 W/m^2 averaged over the year, representing an effective capacity factor 240/437 = 55%, excellent for a wind machine, attesting to the excellence of the site.

However, the wind machine cannot use all the energy in the shaded part of Figure 8.7. To do so would require the wind speed downstream to be zero; even an ideal machine can only use 16/27 of the total, a fraction derivable as follows. Observe Fig. 8.8, showing the wind incident from the left, with density ρ, speed v_{in}, and leaving with the same density ρ but lower speed v_{out}. Well to the left and right, the pressures will also be the same, ensured by slow lateral flow, but across the wind machine itself an effective pressure drop will exist. Bernoulli's law states that the specific energy will be constant along a streamline. Both gravity and lateral flow energies can be neglected compared to the axial flow effects; thus per unit area

$$\frac{1}{2}\rho v_{in}^2 + p_{in} = \frac{1}{2}\rho v_{out}^2 + p_{out} \tag{1}$$

or

$$\Delta p = \rho(v_{in}^2 - v_{out}^2)/2 \; . \tag{2}$$

The average speed through the machine is

$$\langle v \rangle = (v_{in} + v_{out})/2 \; . \tag{3}$$

Now let

$$v_{out} = v_{in}(1 - b) \tag{4}$$

where b is an effective interference factor. The power per unit area becomes, after trivial algebra,

$$\text{Power/area} = \langle v \rangle \Delta p = \frac{\rho v_{in}^3}{2}\left[(b/2)(2-b)^2\right] \; . \tag{5}$$

This power is a maximum when the factor in the square brackets is a maximum; i.e., when b = 2/3, and the factor is 16/27, q.e.d. The downstream area crossed by the streamlines is enlarged, to accommodate the lower speed, as shown.

Now the achievable peak power of the machine in Fig. 8.7 becomes 259 W/m^2, and the average over the year becomes 142 W/m^2. A real wind machine like this will generally deliver about 60% of the maximum of Eq. 5, in this case 155 W/m^2 at 9 m/sec, and 85 W/m^2 averaged over the year at the optimistic but sometimes achievable 55% capacity factor.

How well do real wind machines perform? At the Kahuku, Hawaii site described in Fig. 8.7 the MOD-OA 200 kw experimental machine was installed, with rotor blade span 38.1 m (125 ft), which at its rated wind speed of 7.7 m/sec suggests a theoretical maximum of 0.27 kw/m^2, or 308 kw. Its conversion efficiency was therefore about 0.65. It operated for one year with average capacity factor about 0.5, comparable to the 55% derived earlier on the basis of the wind duration curves. A similar but smaller two-blade machine (Energy Sciences Inc. ESI-54) with 16.45 m rotor span delivered 31 kw at 9 m/sec wind speed, corresponding to a conversion efficiency 56% of the maximum achievable, on Molokai Island, Hawaii in June 1981.

In order to achieve such efficiency and give trouble-free service, the machine must be well-designed mechanically and aerodynamically. The wind is often different at the top and bottom of a large machine. The support tower can introduce unwanted impulses as a blade passes it; thus it is usually better to put the blades of a propeller-type rotor upstream of the support tower.

The system can fail dramatically if the support tower is not rigid enough, and a qualitative derivation of that difficulty shows not only the degree of design sophistication required, but also what can happen in real life. Figure 8.9 shows a 4-blade rotor (for simplicity of explanation—any other number would behave the same). The upper three figures show the rotor in three views: a side view on the left, a front view in the center, and an oblique view on the right. The wind blows as shown, the rotor turns clockwise as seen from the front, and the drag on each blade is the same, shown by the four equal-size dots on the blades.

Now suppose the support is flexible, so the mount and rotor axis can tilt. Let the axis tilt upward as shown in the lower three figures. The top and bottom rotors still present similar angles to the wind, so the drag on them remains much as before. But the left blade, because of its pitch, now faces the wind more bluntly, and the drag on it has increased; similarly, the right blade appears more feathered. Thus the rotor mount experiences a torque tending to twist it about the axis AA as shown in the lower right oblique view, and the shaft axis tends to precess as shown in the lower right, in the direction opposite to the rotor rotation.

If the mount is not rigid enough, this precession can increase in amplitude; the blades shake back and forth and eventually break off, if the mount itself does not break beforehand.

This instability can arise whether the rotor acts as a windmill or as a propeller. In the 1950's a series of mysterious and tragic crashes of the Lockheed Electra passenger airplane were eventually traced to this simple mode; the motor mounts were not stiff enough; after they were redesigned, the airplane enjoyed many years of trouble-free service.

So far in this description, the wind machine has been described as a propeller-like device, which indeed most of them are. This is not necessarily so. Figure 8.10 shows two vertical axis machines. The Darrius rotor appears symmetric for rotation either way, but it is not; it consists of two airfoils that have low drag for wind in one direction and high drag the other way. Thus it rotates to produce power. Variants of small Savonius rotors have been used for centuries. Their principal advantage is that the heavy electric generator (or pump) can be put in the base, instead of high in the air. Against this, the devices require a sturdy bearing at the top, instead of only about halfway up, as in a horizontal-axis rotor. Also, it is hard to mount these devices completely off the ground, and thus get their active parts out of the low-wind-speed, high-wind-shear region near the surface. As a result, horizontal-axis rotors are generally favored.

8.5 Wind: Applications, Costs, Trends

Because the wind blows somewhat unpredictably even at the best of sites, windpower (as also solar PV) has limited capability of displacing more conventional (and dispatchable) installations that must respond reliably to demand. That is, the capacity credit is likely to be modest, less than the fuel credit.

A simple calculation establishes some of these points, particularly the fuel credit. Suppose the electric power demand is P_1 (kilowatts) for 0.7 of every day, and P_2 ($>P_1$) during the remaining 0.3; this corresponds roughly to daily periods of normal and peak loads. Suppose also that the wind blows at optimally usable speed a fraction f of the time., and not at all during the remainder (1-f); the times are unpredictable. This two-level windspeed is not a bad approximation for our purpose, because the v^3 dependence of wind-power on speed makes slow winds almost valueless, and at high wind-speed, most machines limit the output, in order to avoid failure. Suppose also that oil-burning power stations are available at $500/kwe capital cost, oil costs $5/GJ ($30.50/bbl), the oil plant has 40% thermal efficiency, the annual cost of capital is 10%, and all systems have 90% technical availability.

What can we afford to pay for the wind-farm, assuming that transmission costs of the two systems are the same?

First, consider no energy storage (e.g. pumped hydro), and (for the moment) no capacity credit. Then we require that the entire demand be met by oil if necessary. The fuel cost of electricity is $5/0.4 = $12.50/GJ, and the wind cost must be less than this. To replace continuous power P_1, we have a wind capacity factor of 0.9f, and it can be easily checked that the annual output of the wind-farm is 28.4f GJ/year per kwe of name-plate capacity. The saving is therefore $355f/year-kwe, and with money at 10%, we can afford to spend $3350f/kwe for the complete windfarm.

If f = 0.5, corresponding to the best sites, the break-even comes at $1775/kwe; if wind farms are available for less than this, we should buy them up to the capacity P_1, unless other circumstances intervene, based on a fuel calculation alone.

What about building beyond P_1, to replace some peaking power as well? Now the additional windmills operate only 0.3 as often as the others, so their cost must not exceed $1183f/kwe or only $591 if f = 0.5.

Several important considerations have been omitted in this simple example.

1. Capacity Credit. The combined system is less likely to be inadequate to supply any given load than was the oil-only one. Therefore on a reliability (i.e. loss-of-load-probability) basis, some fraction of the installed wind capacity can be applied to reducing the base-load plants. Just how much depends on detailed calculations of the joint probability of the demand exceeding any given amount, and the wind not blowing optimally. This topic will be examined in chapter 9.

2. Spinning Reserve. Here, especially if the system penetration of windmills is greater than a few percent, a negative credit may apply. The reason is that the wind may not blow, in an unpredictable way, and the load may have to be picked up rapidly. Again, the detailed nature of wind fluctuations and calm periods will determine the outcome, to be discussed in chapter 9.

3. Operation and Maintenance. It is liable to be high for small isolated windmills, giving the advantage to substantial windfarms.

Now suppose that the wind-energy system of this example had retrievable-on-demand storage for more than one day, but for a shorter time than the maximum windless periods. In that case, we replace fuel at all times and can afford \$3350f/kwe up to maximum power P_2. If storage time exceeds the maximum windless time, then the whole oil system could profitably be replaced, if it cost less than \$3350f + 500 per kwe, or \$2275/kwe in our example with f = 0.5. But note the continuing caveats about spinning reserve (if the storage will not deliver in time), and O&M.

The wind parameters and postulated system in that example were close to the best available. If the alternatives had been nuclear, coal or cheap solar PV, the wind system could not have fared well, both because of its unreliability and the competition with cheap (or free) fuel. Energy storage overcomes that drawback, one might claim. That is so, but the same energy storage systems would turn daytime solar PV into night-time lights, and cheap off-peak (night-time) nuclear power into peaking power, as discussed at greater length, also in the next chapter.

From this simple example, one can see why windpower is attractive in:

. Scandinavia, where:

.. the winds are good, especially in Denmark and Southern Sweden;

.. hydropwer is available, especially in Norway; the two systems are complementary as detailed calculations have shown. See chapter 9 on energy storage for more details.

.. the skies are often cloudy;

.. traditional dependence on oil is high;

.. there is no cheap coal.

. California and some other continental U.S. sites, where:

.. favorable winds blow;

.. tax incentives and other subsidies, plus PURPA, make it attractive;

.. surplus power can be sold to electric utility companies;

.. there is high dependence on oil;

.. good winds blow at selected locations;

.. there are impediments to use of nuclear or coal.

. Hawaii, where:

.. almost all the California advantages apply;

.. trade winds are exceptionally reliable 9 to 10 months of the year.

Both publicly-funded development of multi-megawatt machines (up to 7.5 MWe) and private installation of many smaller units proceed briskly. About 120 MWe of total capacity were in place in mid-1983, much of it in California, but with three 2.5 MWe units in the state of Washington, 4 mwe units in Wyoming and Denmark, etc. Prices range from $1200/kwe at the factory to $2000/kwe and up for complete installations; quality is variable.

As with other systems, a tradeoff exists between economies of scale arising from larger size (e.g. transmission lines, central systems) and economies arising from mass production of many small units. If wind-power is to play any substantial role in our electric future, it will be with windmills in the megawatt range: at 0.5 capacity factor, 2000 one-megawatt machines are required per GWe, surely enough to capture the principal economies of mass production. One important advantage of large machines is the increasing strength and steadiness of wind with increasing height above ground.

The present price of about $2000/kwe installed will drop with time, advances coming in engineering and manufacturing, not in applied science. Therefore, prospects for cost reduction by a factor 2-3 seem bright, but beyond that it is hard to say. At about $1800/kwe it will and does replace oil marginally in good locations. At about $700/kwe it would replace coal similarly except for problems of system integration, taken up in chapter 9.

The Pacific Gas and Electric Company and Southern California Edison Company programs are largest. Compare these costs with those derived in the initial example. With present tax incentives, an effective capacity factor as low as $f = 0.25$ would still represent an attractive investment.

Material requirements are not nearly so large as for solar PV. Initial experimental machines weighed 100-200 kg/kw; 50 kw-size production machines contain 20-30 kg metal/kw. Material costs themselves decline, for example from $110/kg for special helicopter-quality rotor blades used for but not required for early experimental models, to $5/kg for aluminum alloy extrusions, to similar or even lower costs for laminated wood.

Alghough the average wind dissipation over the earth is very low per unit area ($\approx 2.4 w/m^2$ summed over all heights above the surface), the land requirements need not be prohibitive. First, one chooses favorable sites. Referring again to the excellent Kahuku site in Hawaii, the area with wind power density exceeding 500 W/m^2 at 50 m elevation is about 250 km^2 (HNEI 1982). With the approximate rule that the wind speed recovers at about 20 rotor diameters downwind, the average windpower output from that area, with 50 m rotors could be about 1.0 GW. Second, the specifically dedicated area need not be large. Consider for example 3 MWe units 100 m high, 80 m blade diameter, sited with a density of $7.8/km^2$, giving an average 20 rotor diameter recovery distance. At an average capacity factor of 0.33, this gives an average yield of 7.8 w/m^2, worse than solar PV. However, unlike solar PV, most of the surface is available for many low-rise purposes, for example agriculture. If the actual exclusion area is only 2000 m^2 at each unit, the power rises to 500 W/m^2 of acually excluded land. That is much less than the land disturbance attributable to operating a coal-burning plant plus its coalmines over the plant lifetime.

Can the vagaries of wind-power be overcome by combining it with some other source? Fossil fuels could be used; so could hydropower, which has the advantage of long-term storage and power on demand, features that are constructively complementary to windpower.

The wind-plus-solar-photovoltaic combination is not so promising. To be sure, locations exist where the wind is stronger in the winter than the summer; Kahn (1979) reports such a situation at College Station, Texas, where both average monthly wind and solar power vary by a factor of more than 2 during the year, yet the total varies by less than a factor of 1.5. But this is not good enough for most purposes; the daily variation will usually be more important. Unfortunately, the strongest winds often occur in the afternoon, when the sun has caused maximum (uneven) heating of the terrain. Figure 8.11 shows this for Molokai, Hawaii, and shows also the care needed to choose specific windmill locations, even within a generally favorable region.

8.6 Biomass

The IIASA analyses show a total photosynthetic potential on land of about 62 TW (1800 quads/yr), at the lower end of the range given in Section 8.1. The precise number is less important than the conclusion that the practical limit to prudent extraction may not exceed 2 TW, and justifying that approximate limit is a principal objective of this section. Despite that seemingly pessimistic lower limit, biomass is and will be important, for the obvious reasons that it is relatively ubiquitous, relatively available and extractable at low cost, and in many of its forms it grows by itself with little care. As implied in Chapter 1 and confirmed by others (Openshaw 1978), about 40-50% of the world's people rely "soley or greatly" on wood for heating and cooking. It is very useful, but endangered in many parts of the world--especially where it has been the traditional source--by overuse. This common resource failed in the Mediterranean region in the times of the classic-empires, in China, and elsewhere, and it will fail more drastically and completely in other regions, especially the tropics, if not properly attended.

Smil (1983) has given an excellent and very extensive account of all this, plus other shorter readable summaries, all well documented (Smil 1979a,b), and some of the material comes from those sources.

The differences between gross and net primary productivity, and sustainable yield are important here. The larger numbers, e.g. 60-80 TW, refer to the total energy content of all that is grown, that is the power obtainable if every bit of it were oxidized as fast as it grew. The net primary productivity is the net addition rate, and is by definition almost zero in a climax forest. The sustainable yeild describes the rate at which the biomass resource can be safely cropped.

The world land area is 1.33×10^8 km^2, or 13.3×10^9 hectares, or 1.33×10^{14} m^2, all of which units are variously useful (one hectare equals 2.47 acres). Almost one-half of this land surface is relatively unproductive: desert, mountains or rocky areas, Antarctic ice, Arctic or sub-Arctic tundra, submarginal steppes, and so forth. The figure 80 TW of gross primary productivity (GPP) suggests a solar conversion efficiency of about 0.12% over the productive part, a number to be compared to 1% for some managed high-yield crops. Of the relatively productive half, almost two-thirds is forest or woodland, leaving about one-sixth as potential or actual cropland. For example, the US area planted in crops is about 1.4×10^8 hectares ≈ 350 million acres (330×10^6 in 1970, according to US Department of Agriculture Stat. Bull. No. 233, 1972); that is little more than one-sixth of the total land area of the contiguous 48 states, and the US is agriculturally better-favored than most countries.

Conventional agriculture and forestry blend into one another, as both fall increasingly under control. However, it is both convenient and useful to consider the two categories separately, principally because the degree of control and the departure from natural ecosystems are usually very different in the two cases.

8.6.1 Agriculture

Some of the following material is taken from Calvin (1974), from Lipinsky (1978), or from Burwell (1978), besides the sources already quoted.

It has been estimated that intensive agricultural techniques could be used to produce about 25 metric tons/hectare-year (dry weight) of biomass. Some of this could be starchy (grains, for example), sugars (e.g., from sugar cane), but much of it will have a composition not much different from woody plants, e.g. 30-50% cellulose, 18-35% hemicellulose, and 15-25% lignin. The cellulosic materials are polysaccharides, and can be enzymatically hydrolyzed to sugars, which can in turn be fermented to alcohol. Alternatively, the biomass could be burned directly; also, the starchy or sugary food crops could be more-or-less directly fermented. Lignin itself has a three-dimensional molecular structure (unlike the celluloses, which are crystalline, made of long chains), and is more valued for plastics and other chemical products.

The energy content of this material averages about 16 Gj (approximately 15 million BTU) per dry tonne. That production rate comes to about 400 Gj/hectare year, corresponding to an overall efficiency of about 0.6% of the 200 W/m^2 annual average incident sunlight. At a fuel cost of $1.00/Gj (corresponding to the 1978 average price of coal) or $4.00/Gj (corresponding to petroleum in 1980), we find that this intensive agriculture and harvesting must be done for $400 or $1600 per hectare-year, respectively. This is a low economic yield for highly productive agricultural land. Growing food usually makes better use of the land, if it is agriculturally suitable. But some land is suitable only for growing trees, and surplus agricultural land exists in parts of the world; also some agricultural wastes can be used, so energy from biomass has remained a lively topic of study.

Some plants produce pure hydrocarbon compounds directly, i.e., with no oxygen incorporated in the molecules, and with available energies of 35-40 Gj/tonne—considerably in excess of coal, and 2-1/2 times what can be obtained from ordinary carbohydrates. Rubber is one such material; according to Calvin, the yield from Hevea rubber plant has increased from 450 pounds/hectare-year in 1945 to about 2.5 tons/hectare-year at present, with good prospects for further increases to perhaps 6-7 tons/ha-hr eventually. Such a yield would correspond to 0.7% efficient use of solar energy, better than sugar cane. *Hevea* does not grow in the US, but the domestic plant guayale does produce natural rubber; but Burwell points out that results so far are discouraging, despite an optimistic (but in my view incorrect) National Academy of Sciences report (NAS 1977).

Lipinsky and others have discussed the uses of corn stover (stalks, leaves, etc.) in the overall energy-food symbiosis. At present, about 2.6×10^7 hectares are planted in corn in the US, almost 20% of the total cropland. The yield of corn stover can be as high at 7 tons/ha-yr, but about half of it should be left to maintain the land's quality. Thus we potentially have about 90 million tons/year of corn stover at our disposal, whose total energy output (at 15 Gj/ton) slightly exceeds one quad/yr.

Rather than using this material as fuel, Lipinsky reminds us that cattle can digest cellulose materials directly, so we could use it preferably as cattle feed; two tons of stover replace one ton of grain, which can then be used directly as human food, fed to other animals, or converted to ethanol (leaving a stillage that also has some nutritive value to cattle). By this pattern of use, Lipinsky calculates that some 18 billion liters of ethanol (close to 0.5 quad) could be produced per year. But see the next section about alcohol and gasohol.

It requires energy to grow and harvest these and other materials. Burwell lists the gross and net energies potentially collectible from a variety of crops, and from silviculture and range-land; Table 8.2 gives his estimates.

Other examples come easily to mind: animal wastes, for instance (covered in a subsequent section). In reviewing all these possibilities for agricultural biomass, we should be struck by the modesty of their magnitudes.

Too-simple theoretical calculations, alas too often accepted uncritically, suggest large energy yield from intensive agricultural techniques applied to all available land. In practice the yield is much smaller--we see from calculations made to this point one or two quads from a revision of corn production, perhaps 2 quads in the US from grain and other agricultural residues. The yield, while not negligible, was limited by alternative and competing uses of land, nature of the agricultural products themselves, need for diverse crops, and the danger and expense of over-intensive cultivation.

Even this projected few quads per year from agricultural biomass in the US may be significantly inflated; sure enough, it exists out there on the fields, but how will it be gathered and used? Should it be left on the ground? At present, the soil erosion rate in the most productive corn-producing region is about 20 t/ha-yr, several times the rate allowable for sustainable agriculture. The crop residues provide essential nutrients and soil-conditioning matter to the fields, and the need for it has been estimated as 0.5 - 1.0 kg/ha-yr. If so, the 0.7t/ha-yr of GPP shrinks to a sustainable yield of almost zero. Even if only 50% of the corn stover is to be left on the fields, do we need new corn-harvesters that pick up half the stover along with the cobs themselves? To return later to the field with a special stover-picker may require even more effort. The problem seems somewhat comparable to growing, harvesting, baling and shipping hay, which presently requires significant fossil fuel energy to produce an agriculturally useful but relatively low-calorie material. These difficulties can be seen in a different way: the high present US farm productivity arises in part from substantial energy inputs, mainly fertilizers and fuel. That would be the very problem to avoid, in producing biomass for energy.

In addition to the difficulties already mentioned, changing even a modest fraction of general US agricultural practices so as to produce more useful biomass would take decades, timed to the normal slow charge of such practices.

Despite all this, some opportunities surely exist, and some energy can surely be gleaned at low environmental cost or even with environmental benefit: see the discussions on animal wastes and general urban wastes in later sections.

This discussion has focused mainly on the US, a particularly favored country for energy from biomass. In India, China and many other countries, the need to return agricultural wastes to the land is more urgent. (Smil 1981, 1983).

9.6.2 Alcohol and Gasohol

An egregious misunderstanding existed around 1980 to the effect that it would be a good idea to make large amounts of ethanol (or methanol), particularly in order to augment the gasoline supply. This idea can be good in some places, especially where there is an excess of biomass that has relatively low nutritive qualities, and can be easily fermented. However, the idea applied to the US was misdirected.

Sugarcane is one of the most favored approaches. Present yields of 10 tons/hectare can yield with little energy loss in the fermentation process about 5 tons of ethanol plus 1.2 tons of ethylene, at an overall solar efficiency of 0.23%. But the distillation of this alcohol requires substantial energy. The cellulose in the cane stalks, called bagasse, represents an equal amount of energy, so the total conversion efficiency is about 0.5%.

Both Calvin and Lipinsky think that making bulk ethanol and ethylene from sugar may be marginally economic now, but increasingly attractive in the future, but Hopkinson and Day (1980) give a brief and revealing contrary analysis. First, they point out that the average expected yield of alcohol from sugarcane grown in Louisiana would be 18.4 x 10^9 cal/ha-yr, or about 77Gj/ha-yr. Even at $4.00/Gj, this represents unattractive use of the land. It would have been better to have used sugar (or some other crop) for food than fuel.

But the matters are still worse. Hopkinson and Day point out that the mechanized growing of sugarcane requires 8.9 x 10^9 cal/ha-yr, mainly of petroleum-based fuels (or perhaps ethanol) and that the associated industrial structure took an additional 0.4 cal/ha-yr. Thus even if all distillation energy were supplied free of charge, the net yield of high-grade liquid fuel would be only 9.5 x 10^9 cal/ha-yr, or about 40 Gj/ha-yr, a very unencouraging prospect. Now we must distill the alcohol from the fermented mash, a task that takes (according to Hopkinton and Day) 10.4 x 10^9 cal/ha-yr, which exceeds the energy content of the net alcohol yield. If the distillation is done by fossil fuel, the yield from the whole process is negative: about 0.9 units out for each unit in.

To be sure, the bagasse has sufficient energy for the distillation if it is burned; but other uses for it may be more attractive, as a basic cellulosic material for fibreboard, etc. Alternatively, it could be hydrolyzed to produce more fermentable sugars.

Solar stills for the ethanol would restore the prior output/input ratio of 18.4/8.9 = 2.07 as determined by the agricultural energy input; but even here, we have lost almost half the naively expected output, at an uncertain but probably high capital and operating cost.

Alcohol can also be produced from sugar in sugar-beet, but the yield is only half as much, and the beets don't grow all year round.

The 1980-era idea of producing gasohol as a major gasoline extender in the US had many qualities of a hoax. The more common version was to ferment grain, then distill it. Automobiles in the US used about 10 quads of gasoline/year, and the idea was to replace about 10% of this with gasohol. Gasohol contains 10% alcohol, so we are concerned with replacing 1% of the gasoline by 0.1 quad of alcohol. How much alcohol is this, and from how much grain did it come? At about 12 million BTU/ton for the energy content of grain, one can find easily that 8 million tons of grain were needed; but the alcohol production is, as we have seen, at best about 50% efficient overall (with solar stills, etc.). Thus about 16 million tons of grain would be needed per year. At 2,000 kcal/person-day, this grain would feed about 66 million people.

The image projected to impoverished parts of the world, of the Americans using food sufficient to feed 66 million people, in order to replace one percent of their gasoline in their automobiles, did not go un-noticed.

Stauffer (1981) explains the early 1980's enthusiasm producing gasohol, partly as a response to remission of all Federal and some state taxes on the gasoline in the gasohol; 5c/gallon of gasohol translates to 50¢/gallon of the constituent ethanol. Other tax write-offs, subsidies (e.g., controlled natural gas prices which permitted lower fertilizer prices to the farmers) made the activity attractive, despite its actual energy and national economic disadvantages. Depending on particular circumstances, the total federal and state subsidies could range from 70c to $2.37 per gallon, of contained alcohol, according to Stauffer.

This scheme was enthusiastically supported by Commoner (1979), faded away in the early 1980's, but remains a good case study. We learn three things (at least) from this example:

1. Food is much more valuable than burnable biomass.

2. It is much more important to reduce the immense use of gasoline in automobiles by increasing their efficiency or reducing their number, than by trying to maintain the high consumption via turning food into fuel.

3. The politics of such activities can be self-serving, and in the long run destructive.

In Brazil, gasohol, even pure alcohol, is being extensively developed for motor fuel, and many acclaim it as a success. Goldemberg (1981) presents what could be interpreted as a more ambiguous view, as he describes an exquisite dilemma of costs and benefits--a dilemma of conflicting interests, goals, and time perspectives. The dilemma relates to the various costs, both economic and social, of ethanol production: the disruption of farming patterns and food supply, the problem attendant with monocultures, the inequity of benefits going mainly to minority elite groups, the exacerbation of income disparities, and so on. How big are these costs? How does one compare them with tbe benefits of reduced oil imports? Who decides? In his careful enumeration of the various pluses and minuses of the Brazilian sugarcane route, Goldemberg has laid a basis for similar consideration of using forest biomass.

Continuing this line of thought, Carioca and Arora (1982) give a comprehensive assessment of alcohol schemes for Brazil and elsewhere (and also of other biomass prospects) and emphasize the difficulties. The attached table 8.3 shows their opinion about alcohol distilleries and their impact on various sectors of society.

8.6.3 Forests and Woodlands

Most of the world's biomass consists of forests and woodlands, plus the humus in the soil beneath. Olsen, Pfuderer and Chan (1978) estimate a GPP of 84 Gt/yr, which at 16 Gj/tonne comes to 1.34×10^{22} J/yr or 43 TW, a value that falls in the mid-range of informed estimates. Persson (1974) estimated 28×10^8 ha of closed forest and later (Persson 1978) estimated a lower value of 26.6×10^8 ha, plus 15.8×10^8 ha of non-closed woodland. Smil (1983) estimates that the closed forest area declined to 25×10^8 ha in 1980. The FAO (1971) estimated that the total sawnwood could soon exceed 10^9 m^3/yr (7×10^8 tonnes), with about one-half used for housing: that amount, corresponding to about 1% of the global GPP, may already be exceeded.

These numbers correspond fairly well with other FAO data. Of the 13.3×10^9 ha of world land, it classifies 4.1×10^9 ha as forested, a third of the total, as stated in the introduction to this biomass section.

The total world annual recorded wood harvest is about 2×10^9 m^3/year, or 1.4×10^9 tonnes/year, figuring an average density of 0.7. About half this wood is now used for fuel, mainly in the tropical countries. At an energy content of 7500 BTU/lb or 1.6×10^7 Gj/tonne, we find some 11.6 quads of wood used annually worldwide for fuel, or about 0.4 TW. Non-commercial biomass, much of which is agricultural waste and casual collection of sticks and twigs, makes up the difference between these numbers and the generally agreed total of about 1.5 TW for all biomass energy.

Spurr (1979) gives a very readable summary of forest biomass and its use, estimates the GPP from forests as 40 TW, and that much more could be used for fuel than is used presently, but the difficulty is that the pattern of use is very uneven. For example, the present high cost of petroleum causes further deforesting in India, and an influx of visitors into Nepal (among other factors) brought selective local deforestation.

These limitations have been analyzed and stressed by many writers. Revelle (1980) analyzes the situation in the entire South and East Asia region, extending from Pakistan to Japan and Korea, including the large island states. Table 8.4 shows his estimate for the forest area available, taken mainly from FAO data. Using an annual yield of 3 dry tonnes/ha-yr, he arrives at 0.66 TW for forest biomass energy from this entire region.

The tropical and subtropical forests provide an excellent example of the difference between GPP and sustainable yield. The Amazon basin is particularly dramatic. Much of that region consists of oxisols: red-yellow soils of kaolinite, iron oxides, quartz, all very low in weatherable materials, with little nourishment value. Some of the ground is almost pure silica sand. Most of the minerals reside in the trees; as leaves, branches and whole trees fall, bacteria and animals turn their contents rapidly into materials that a dense network of ground-level roots quickly re-absorb, thus closing the nutrient cycle. Some of the most mineral-free and non-nutritious water in the world flows in some Amazon tributaries. The forest appears sturdy, but it is actually very fragile. It can be (and is) cut and burned over large areas, which releases minerals to fertilize the soil for a few years. After that, harvests fail, and the land becomes a semi-desert. Herrera et al (1981) describes this nutrient cycle, how its delicate balance is disturbed, and the nutrients irretrievably lost. The deforestation also causes increased flooding (Gentry and Lopez-Parodi 1980). The deforestation and other adverse consequences, including spread of diseases, arising from building the trans-Amazon Highway have been described by Smith (1981).

The difficulties are by no means confined to the Amazon. Myers (1981) describes how about 40% of the central American forests have been converted to pasture to produce cheap beef, at a rate of 20,000 km^2/yr (the global total of forests destroyed for all purposes is about 200,000 km^2/yr).

The sustainable yield from tropical forests thus appears quite limited. The temperate zone forests, being mostly grounded in more productive and less-leached soils, have more potential.

Let us examine the US forests in more detail. About one-third of the US is classified by the UN as forested (3.05×10^8 hectares), the same fraction as in South America and the USSR. Some of this forested land is marginally productive, and the US Forest Service classifies 2.02×10^8 hectares as commercial timberland, capable of producing at least 1.4 $meter^3$ of timber per hectare per year.

How much energy could be developed from these forest lands? Consider an extreme example: all the forests put under intensive coppicing--i.e., growing highly efficient photosynthesizers (e.g. sycamores) under intensive cultivation with frequent harvesting. It has been estimated that perhaps 20-30 tonnes/hectare year of dry plant material could be produced this way. Twenty-five tons/hectare is equivalent to 84 quads. This is, of course, a totally unacceptable (and impossible) procedure; the number calculated shows the impossibility of satisfying present US energy needs by biomass.

Let us consider less extreme circumstances. Spurr states that the present average growth rate of US forests is 2.7 $meter^3$ hectare-year, but if all forests were fully and optimally stocked, the production would double. In addition, with known techniques of intensive silviculture (selective thinning, genetic adjustment, use of fertilizers, and selective herbicides and pesticides), the yield could be doubled again, hence the US forest growth rate could be about 10 m^3/hectare-year. About half this total growth might be available for fuel (the other half being structural timber or a source of cellulose); thus we come to a somewhat more realistic upper limit of about 17 quads/year. Even this number is much too optimistic, because it assumes:

(1) all forest lands are intensively managed.

(2) the management goal is mainly to produce quick-growing softwoods.

(3) the forests can be chemically treated and severely cropped without damage to the ecosystem.

(4) the geographic location of the forests is everywhere favorable to such activities as using forest slash (branches, bark, etc.) to produce energy.

Again we should back off by a factor of at least 2-3, to allow for long-term ecological balance, other uses of forests, unfavorable geographic location, etc. We find a potential of 6-8 quads/year from the US forests, a number agreeing with other optimistic estimates. Both Burwell and Spurr note that the present <u>total</u> growth of the US forests is about 9 quads/year, a number that dramatizes both the optimism implicit in these estimates, and the silvicultural discipline that would be needed to realize them. The Congressional Office of Technology Assessment (<u>OTA 1980</u>) estimates that between 6 and 17 quads/yr might be produced from all sources, of which forest wood constituted 5 and 10 quads respectively. But more recently, the same OTA (<u>1983</u>) pointed out that (1) the value of wood for construction and as new material for paper and other products far surpasses the value of wood as fuel; (2) extended research and development on using wood and wood waste would make it even more valuable; (3) the long-term environmental impacts of intensive silviculture and other business production can be severe and are not well understood. Thus the conditions that could lead to substantially increased use of biomass in the United States for energy seem unlikely to be realized, and the lower estimates seem most plausible.

Hayes (1979) suggests that the present contribution of forest biomass is about 1.6 quads. He also quotes Tillman's (1978) estimate of 5.7 quads available by AD 2000 (4 from wood, 0.67 from agricultural wastes, 1.0 from municipal solid waste).

Considering that the forests can be harvested and replanted only on a time scale that ranges between 40 years (for pulp-wood) and 100 years (for commercial hardwoods and large timbers), we see the simple calculation made here of 6-8 quads potentially available is not far wrong, and even that number could be considerably reduced by increasing use of forest products as structural or chemical raw material.

Wood-burning has often been described as ecologically sound and benign. But (1) the accident rate in the forestry industry is higher than that in coal mining, per unit of energy in the respective products; (2) wood has a higher percentage of tars and other biologically hazardous hydrocarbons than do most coals (except for sulfur compounds). Small wood-stoves and coal stoves emit many of those pollutants, now treated in some cases by expensive catalytic converters in the stovepipes.

Wood (and dung, straw, etc)-burning in rural villages in South and East Asia villages presents a serious pervasive health hazard. The traditional "three-stone" cooking hearth, with sticks pushed in radically to make an open fire, creates levels of respirable particulates and biologically undesirable material up to a thousand times the US customary upper limits--that is up to many milligrams of such material/meter^3. This hazard to women (principally) now receives increasing attention by the Government of India (Smith 1982).

The ecological limits deserve further mention. When forest management was first introduced in Europe in the 19th Century, foresters discovered that the second and third crops gave lower yields than did the first one, particularly for lands planted with spruces. Analysis of such effects has led to the selection of species better matched to local conditions, but has led Switzerland (particularly) to adopt a naturalistic approach: maintaining a mixture of trees ecologically suited to the region, and cropping them lightly and often, so as to preserve a steady forest. The total yield of the naturalistic approach is considerably lower than the more intensive silviculture described earlier, but the forest survives in the long term.

Regarding the extensive use of fertilizers in silviculture, it was written (Rose et al 1970) in connection with a proposal to establish new national institutions (replacing and extending roles of various then- and presently-existing national laboratories):

> ". . . It must be able to measure things, as we have said: pollution of air, water, land; such things as transport of nutrients into and out of forests, to find in advance about what it really would mean to apply lots of fertilizers in silviculture . . ."

At that time, the idea of fertilizing forests was still largely speculative, and concern existed about: (a) accelerated eutrophication of streams, especially in the warm and relatively flatter Southeast US (as opposed to the cold and more rapidly running rivers in the Northwest); (b) long-term effects of fertilizing and cropping on the underlying land and humus; (c) the general tendency to focus on too-narrow objectives, usually to our later regret. That example in 1970 seemed surely far enough in the future to permit comprehensive and rational debate.

Apparently those issues are still not well resolved, but the forest products industry proceeds with fertilization and so forth nevertheless. Spurr writes in his closing paragraph

> " . . .not enough work has been done on a number of problems that have become major issues in the encounters between environmentalists and forest managers. How do forests of even age and uneven age . . . compare in productivity and loss of nutrients. How do pure and mixed stands compare on these matters and on relative vulnerability to insects, diseases and other hazards. . ."

In summary, perhaps 4-8 quads/year of energy could eventually be produced from forest biomass in the US, with careful management, the amount being limited by the onset of severe ecological damage and other factors. The opportunity exists to satisfy a larger fraction of the energy needs of some developing countries, not only because plants grow faster in the tropics (7 years to grow pulpwood-size eucalyptus in Brazil), but also because the total energy demand is lower in those countries. However, the peril exists of overcutting, because of (1) no other energy sources available, and (2) no well-established forest management.

Regarding forest management and reforestation, an FAO (1982) analysis of tropical forest resources points out that for every 10 hectares of forest land cleared, only about 1 hectare of plantation will be created. This 10% replacement rate is a global average for the tropical forest and masks the great variation from one region to another. For example, in tropical Asia, the replacement rate is about 25%, but in Africa it is less than 3%. Moreover, often reforestation is distant from the clearing areas. For example, in Brazil tree clearing occurs in the north, but the plantations are in the south. It is a good sign that plantations are being encouraged in many nations.

Notably, 40% of the total tropical forest plantations were planted in the 5 years from 1976-1980.

8.6.4 Urban Solid ~~/~~ and other Wastes

Three general motivations exist for processing urban wastes:

1. to recover the energy of it
2. to extract some valuable material from it
3. to prevent environmental damage by the unprocessed material.

Total urban solid wastes at present amount to about 140 million tons/year (3.5 lb/person-day). A typical composition is, by weight, dried (Burton and Bailie 1974):

	percent
paper products	48
plastics, rubber, leather	3
food wastes	12
other organics (grass, wood, etc.)	10
glass, stone, etc.	17
iron and steel	8
non-magnetic metals	1-2
TOTAL	100

Regarding motivation 1 (above), energy content runs typically 4500 BTU/lb; if fully utilized, urban waste could therefore provide 1.3 quad/year, not quite 2% of 1982 national energy needs. At $\$1.00/10^6$BTU, the waste would be worth $12/ton, minus all processing costs and losses.

Regarding motivation 2, at $40/ton for steel, $200/ton for aluminum, and $20/ton for scrap glass, the wastes yield $3, $2-4, and $3, respectively, in round numbers. The iron content is about 10% of the total US annual production.

The total of all these values is about $20/ton, less all processing costs; in general, net value is much lower. In summary to this point, urban wastes represent a minor energy resource, and/or a modest source of materials, chiefly paper, iron, and glass.

The strongest motivation seems to be number 3: environmental protection. While representing less than 2% of national fuels needs, the wastes are a very large source of free energy in the thermodynamic sense: energy available for causing alterations in the surroundings, sometimes over short time periods (e.g. open burning) and sometimes over much longer ones (activity in land-fill site). If the wastes were chemically inert, and could suffer no more change with time (e.g., glass and ceramics) then land-fill would be a reasonable solution, because re-processing costs have often equalled or exceeded the expected product benefits.

However, "sanitary" land-fill is not chemically sanitary and sometimes not biologically so either; landfill costs now run as high as $18/ton near congested cities, and many cities foresee no more land available. New York City burns garbage at sea.

The idea of minimizing the flow of free energy in processing materials is useful as a guiding principle, and has been discussed before (Rose et al 1972). It is the same idea, re-stated, as the one of conserving thermodynamic availability; rather than just energy, as taken up at length in Chapter 4.

For whatever reason, many urban centers--St. Louis, Missouri; Nashville, Tennessee; Lynn, Massachusetts; Bridgewater, Massachusetts; Baltimore, Maryland; San Diego, California are a few--build advanced waste treatment systems along these lines.

Three general methods exist to treat wastes.

(1) Recovery for recycle. Here, paper is the most profitable single constituent; Malina and Morgan (1972) calculate transfer and land-fill costs are more than offset by salvage revenue; land-fill site life is doubled. But while one is at this task, it seems only reasonable to go after other material as well, on general environmental principles; Malina and Morgan calculate these further benefits, deciding they are economically small. But the increased recovery of recyclable material doubles the life of land-fill site once more, and reduces chemical activity of the remainder.

(2) Energy from burning the wastes. Relatively pollution-free incinerators now exist, but it makes better sense to use the energy (Fife 1973; Singer and Mullen 1974), European systems were developed earlier, but now US designs start to take the lead, particularly for US conditions.

Utilizing the wastes in more conventional steam-electric power plants generally utilizes the energy at higher efficiency. A St. Louis, Missouri urban waste project was an outstanding example of both the promise and the pitfalls. There, the Union Electric Co., Combustion Engineering Co., and the Federal Government since 1969 ran a pilot project utilizing two 125 megawatt electric plants to burn up to 25% shredded refuse, the remainder being powdered coal. Based on this experience, Union Electric announced plans to use 8000 tons/day of municipal solid waste at one of their largest generation plants. However, in 1977 the company abandoned the project because of (a) rising costs, (b) failure to obtain electric power rate relief that they felt was relevant to the project, (c) failure to obtain permission to build a waste transfer station in the St. Louis suburbs. A happier outcome seems in store for Milwaukee, Wisconsin; there, the City, the

Wisconsin Electric, and the Americology Division of American Can Company are presently starting operation of a plant that would process 1600 tons/day of municipal solid waste, and use the relevant fractions as supplementary power plant fuel.

In 1978, about 15,000 tons/day of municipal solid waste--perhaps 3% of the total produced--was being productively incinerated. One difficulty with these schemes is variable feed quality, which results in off-optimum conditions in parts of the combustor (which increases corrosion). This and other problems are substantially ameliorated by waste pre-treatment: shredding, magnetic sorting, pneumatic sorting, for example. This not only yields by-products but also makes a more uniform feed, with lower ash. Even so, the presence of salts and acid (for example, hydrochloric acid from polyvinyl chloride plastics) exacerbates corrosion of conventional boiler materials; the wastes also contain nitrogenous materials and heavy metals that are hard to separate before combustion, all of which contribute to air pollution; however, the sulfur content of these wastes is usually low, an environmental advantage.

(3) Synthetic Fuel Generation. Here, the goal is again to recycle non-burnable material, and extract the energy content from the rest. However, the object is to produce fuel for consumption in a different device. Several major routes exist.

The first route is via pyrolysis, where a small fraction of the refuse is burned as all of it is heated--distilled, more or less--to produce fuel; a similar process was described in the coal chapter. Composition of the produce is adjustable within limits--oil or gas, with apparently about 60% of the original refuse energy appearing in the final output. Typical heating value of the gas is 400 BTU/ft^3, compared with methane at 1050 BTU. The lower heat value comes from more free hydrogen, and oxygen in CO and CO_2.

The second method is hydrogenation, as developed by the Bureau of Mines. It is a high pressure, high temperature reaction, in the presence of an alkaline catalyst; a heavy paraffinic oil comes out.

The third method under study is anaerobic digestion, more applicable to sewage, animal and vegetable wastes than to the usual mix of urban solid waste; the topic is included as item (4) below.

The preceding paragraphs concentrated primarily on the energy content of urban wastes, and only incidentally on its other putative treasures. The reason is simple: the wastes largely consist of combustible material; sorting is difficult. The future relative values of scrap paper and bulk heating fuel will help to determine whether one should recycle paper or not (note that much paper, plus almost all other organic material, is not recyclable in anything like its raw form; so using them for energy often makes good sense).

The municipal waste problem is one of social and political organization was well. The amount is large, but not overwhelmingly so in comparison with other materials: one-fifth the weight of the coal that is mined, for instance. The source is diffuse, and it has been handled almost as a cottage industry. Its value is substantial, but not immense; and the present microeconomic profit in doing much with it is small, after costs of collecting, sorting, shredding, combusting, or whatever, are included. Urban refuse departments have often been employers of last resort. Although social benefits of that kind of garbage policy may be substantial, the system has tended toward a condition where the debate and technological thought have been simplistic and short-range. Developing broad principles of recycling and disposal applicable to broad ranges of wastes, and responsive to long-range social problems does not come naturally, despite the best efforts by those involved.

(4) Sewage and Animal Wastes. Anderson (1972) estimated 12 million tons of municipal sewage annualy in the U.S.; presently it is buried, burned, sometimes used for fertilizer, rarely digested anerobically to extract methane and reduce its free energy. He also estimated 200 million tons per year of animal manure, which causes problems not often visible to academic bodies, but highly visible and troublesome to those living near feed-lots. The trend toward further mechanization of meat-, poultry-, and egg-raising exacerbates the waste problems that are already serious in Kansas, Missouri and elsewhere. The fraction at present that is readily collectible is much less than that pertaining to urban solid waste, but the need for something better than present practice is great.

Anerobic digestion is an excellent way to treat both these and many vegetable wastes in combination. It has several advantages, especially for wet materials. The installations can be technologically simple, suitable for small villages in China, India, etc. (but building and running them properly requires care and attention); they can also be large and complex, suitable for animal feedlots in the U.S. They accept a fairly wide range of organic material. Much of the free energy in the wastes appears in the clean biogas product, 60-70% methane and 30-40% CO_2 with traces of other gases that depend on the input material. Most original bacteria in the raw wastes are killed, so the process offers substantial environmental and health benefits. Sludge residue retains most of the organic nitrogen and makes a good fertilizer--

better than the original wastes in being less biologically active; however as with other organically-derived materials, it gives off ammonia when stored, hence loses nitrogen values. Smil (1983, Chapter 7.3) gives an excellent description of the process and the state of affairs worldwide.

The live digesting agents are methanogens, which have only recently been recognized as different from ordinary bacteria, and whose detailed working in digesters is not well enough known. Methanogens cannot live in the presence of oxygen, and appear to work best at 30-35°C. Thus community digesters in East Asia are built with a water-trap entrance for the waste, and below ground so that the modest heat of methanation keeps them warm. Typical residence times for conversion of animal manure is 10-15 days.

The total amount of methane producible in the U.S. from sewage and animal wastes might be 0.5-1 quad/year, small compared to present natural gas use of 20 quads/year in the U.S. but significant nevertheless; but as with urban solid waste, the greatest gain is environmental.

8.7 Hydropower

Figure 8.12 from the U.S. Department of Energy (DOE 1982, their Fig. 7.4) shows a world total of 1.766×10^{12} kwh developed in 1981, corresponding to an equivalent 201 GW operating full time. This is an increase of 30% over the 1973 amount. The United States had been the world's largest hydroelectric producer, but Canada, with very large projects principally in the provinces of British Columbia, Quebec and Newfoundland/Labrador, now matches the U.S. total, and exceeds it by a factor 10 on a per capita basis.

In the period 1973-81 U.S. total installed capacity grew from 63 to 77 GW, for a decline in actual utilization from 43.6% to 30.1%. These low numbers are typical of systems used to meet peak or seasonal loads. Brazil had the largest fractional increase in hydroelectric power production during that period, a factor of 2.2.

The distribution shown in Figure 8.12 does not correspond to the global hydropower potential. Vastly underrepresented are China, India, the Southeast Asia region in general, central Africa, and South America, leading to opinions that 2 TW average might be obtainable from all reasonably developable sources in the world, from an installed capacity of perhaps 4 TW.

Hydropower has the advantage of providing both storage and quick availability. The former quality is obvious: reservoirs and lakes behind dams. The latter is also fairly obvious, because the turbine-generators can be kept spinning at no load with a small water flow, then brought up to full load as rapidly as the valves can be opened and water flow smoothly increased. Regarding this latter point, the performance of a modern bulb-type hydroelectric project at the Grand Coulee Dam in Washington state has been described in detail (St. Onge, Harty, Click 1982). From a cold start, it can be synchronized in 90 seconds; if already spinning, it can go from zero to full load in 45 seconds.

Along with these advantages of storage, quick availability and free fuel come substantial disadvantages, mostly environmental. The CONAES study, for reasons described below, ranked it among the most environmentally destructive per unit of energy produced of all major supply systems. Some sites cause little trouble, but others cause much; most of the environmentally acceptable large sites in the U.S. plus other not so acceptable ones have already been developed.

El Hinnawi and Biswas (1981) give an account of these difficulties, the main points of which are:

- Siltation and erosion. The Yellow River in China carries about 38 kg/m^3 of silt, the Colorado River 17 kg/m^3, the Nile above Aswan 1.6 kg/m^3. A depletion of capacity 0.5-1.0%/year on this account is typical. The Sanmen Gorge Dam on the Yellow River started operation in 1960, but its capacity was reduced to less than half in a few years, and it required extensive modification. The Aswan High Dam will take 500 years to silt up, but some 10^8 tons/year of silt is no longer carried to the sea; the Nile Delta erodes 16×10^6 tons/yr. The annual floods that renewed the land with silt no longer do so. Fishing near the Nile Delta now languishes for lack of nutrients. Similar difficulties attend the Glen Canyon Dam on the Colorado River, the Grand Canyan downstream of it, and Lake Powell above it.

- Segmenting the riverine ecosystem. Although fishing in large reservoirs can exceed what can be done in the free-flowing river, the segmenting denies access to anadromous fish (like salmon, that breed in the streams, but live in the ocean) and catadromous fish (the other way around).

• Weeds. The Aswan High Dam loses 3×10^9 m^3 of water per year by evapotranspiration on this account, corresponding to about 150 MW of electric power if the water had flowed through the turbines.

• Disease. The still water beind the Aswan High Dam has increased the snail population, hence also schistosomiasis.

• Dam failures and related accidents. About one sizable dam per year fails. Most serious was the Vaiont Dam in Northern Italy, when part of a water-logged clay mountain behind it became thixotropic and slid suddenly into the reservoir. The dam itself held, but the wave over the top wiped out the village beneath and killed all 2,000 people, in the middle of the night.

8.8 Solar water heaters

Solar panels can heat water either for private houses or for some commercial or industrial enterprises. Domestic devices find increasing acceptance; their main problems have been economic (compared to using oil or natural gas, or electric heat pumps); unreliability, a problem in the 1970's, is reduced in the 1980's.

The economic problem is easy to outline. At 200 W/m^2 average insolation, and 70% conversion efficiency to hot water (an optimistic figure), the annual energy available to heat water is 4.4 Gj/m^2. Not all of this will be useful, because of frequent excess capacity, especially in the summer. Let us take 2.0 Gj/m^2 as a working number. That amount of heat could be delivered to hot water by about 0.5 barrels of oil burned in a 70% efficient hot water heater. In the early 1980's that oil would have cost the householder about $23.

The piping, storage, and emergency backup heater for the solar system cost more than the oil-fired water heater and storage tank; but ignoring that difference, let us calculate what would be the justifiable cost of a solar water heater, figured on the basis of fuel oil savings alone. Suppose mortgage money were available at about 14% annual interest, so in this rough approximation the householder can expect the two systems to be comparable if the solar collectors can be bought and installed for $164/m^2$. Installed collector units cost more than that, but tax incentives made them marginally attractive, especially in the sunbelt.

Some technological problems need resolving about such solar panels. Virtually all of them circulate a liquid through pipes embedded in a blackened surface, exposed to the sun through one or more sheets of transparent material (to minimize cooling of the collector surface). An inexpensive plastic with tailored transmission and absorption properties would be good to have. What is the "blackened" surface? Ideally it should be black to the visible spectrum, and not radiate in the infrared. Some (copper-oxide on copper) surfaces approximate this ideal behavior, but copper is expensive. What is the liquid? If it is the water that will be eventually used, the system must be protected against freezing on cold nights. If it is some nonfreezing liquid, an extra heat exchanger to the actual hot water will be needed.

Using such collectors for heating the house itself is presently quite unattractive; the demand is seasonal, at a time when the sunshine is weak. Solar home heating is however another matter, an attractive option discussed in chapter 4.

8.9 Solar Ponds

About 30% of the energy used by industrialized countries is in the form of heat at $T \leq 100°C$. To provide it, solar ponds look increasingly attractive in favorable locations, although it is too soon to say for sure. Lin (1982a,b) and Garg et al (1982) give comprehensive overviews of the state-of-the-art in the early 1980's. Whether these installations should be described as energy storage or solar converters is a matter of semantics and choice.

Solar ponds are bodies of saline water, typically 3-5 m deep, consisting of three distinct layers, as shown in Figure 8.13 At the bottom is a heavy convective zone of concentrated brine, typically with density of about 1.2, which may be 2-3 m deep. Above that lies a non-convective zone, in which the density decreases upward according to a carefully arranged profile, typically 1 m thick. On top is another zone 0.15 - 0.3 m thick, made convective by wind-induced mixing and the diurnal effects of heating and cooling.

The principle is simple but successful execution is not. The bottom layer absorbs sunlight (via a dark bottom of the pond), and heats up to a working temperature that can be as high as 80-85°C. The controlled density gradient above it leads naturally to a controlled temperature gradient also, so relatively little heat is lost by conduction. The saline water is transparent to visible radiation, and virtually opaque to infra-red radiation, so the bottom convective zone loses little heat by radiation also. The heat can be extracted by withdrawing hot brine (from one side, for example) and returning it (at the other side) after use; or cooling pipes can be run through it.

Success depends on several things:

1. Maintaining the non-convective zone. It must be carefully established, for example by carefully stacking thin layers of salt water of successively decreasing density on top of the bottom convective-storage layer. It must be maintained by periodic injection of salt at the appropriate density at the right level. This is the single most critical feature.

2. The salt must have high water solubility, low absorption of sunlight, be stable at elevated temperatures, and inexpensive. Sodium or magnesium chloride, sodium carbonate and sodium sulfate have been used successfully. The quantity of salt needed is large: 500-1000 kg/m^2 of pond; a pond of 100 ha may require a million tons of salt, a substantial expense.

3. The pond must be impervious to the salt solution, except perhaps in a few places on Earth where leakage of the concentrated brine causes no ill effects and replacement salt is cheap (e.g., near the Dead Sea in Israel).

4. The water must be kept clear; in particular, dirt or other light-absorbing material in the upper or gradient regions will not only reduce the efficiency of collection below, but can, via the absorptive heating, destroy the convective layer.

The principal cost of small solar ponds (e.g., less than 100 ha) goes to constructing the pond itself, and costs of such small ponds were estimated in 1980 to be \$5-6/m^2. This cost is not high compared with other devices that produce and/or store low temperature heat, so investing for maximum collection efficiency is not economic. On the other hand, test structures built in the early 1980's cost several times that much. With a mean solar flux of 200 W/m^2 at collection efficiency of 0.2, this comes to 40 W/m^2, or a pond cost of \$120-150 per thermal kilowatt, an attractive number.

Solar ponds of at least a few ha area make more sense than very small ones, because of the maintenance that must be performed on a pond of any size. Thus one can imagine a low temperature heat source of 400 kw/ha average, suitable for district heating or such low temperature industrial uses as drying crops or paper.

For electric power, solar ponds are not so attractive, but much superior to the Ocean Thermal Energy Conversion Scheme discussed briefly in Section 8.9. Here: (1) the ΔT is larger, because of an upper temperature near 100°C rather than (say) 25°C; (2) there are no storms at sea to worry about; (3) the site is accessible and delivering the power is much easier. But the temperature difference between the hot and cold sides, while greater than in OTEC, is still modest--say, 50-60°C, and a cold sink may be harder to find. Thus a net thermal-to-electric conversion efficiency exceeding 7% is unlikely, leading to total capital costs comparable to those of nuclear or advanced coal plants. Nevertheless, the idea is conditionally attractive, and a 5 MWe intermittent peak power plant on a 25 ha was to start up in Israel in 1983; larger plants deliverying a total of 2000 MWe have been advocated (French 1981). A 0.7 ha pond in Israel began operation in 1979, producing 35 kwe continuously or 150 kw intermittently; on a continuous basis, that corresponds to an incident-sunlight-to-electricity conversion efficiency of about 0.5%.

If a principal difficulty of the salt pond--maintaining the proper non-convective salt gradient--could be eased, the idea would become even more attractive. Wilkins et al (1982) state that they have developed a "Gel-Pond," in which the nonconvective zone is a viscous gel, with a thin pure water layer floating on top. The gel requirements are stringent:

transparent, stable under ultraviolet light and in the operating temperature range, nonbiodegradable, non-toxic, less dense than the saline solution beneath, easily prepared at low cost. The authors state that the composition and manufacture of their successful polymer gel are proprietary information, and it will be interesting to follow progress of the work.

8.9 Sun Dogs

The Ocean Thermal Energy Conversion scheme, the Power Tower and Solar Satellites all illustrate inappropriate applications of technology, and the development of client-sponsor self-protecting relationships that exploit popular but uncritical sentiment.

How such schemes came to be supported is more important than the technical details themselves; it went like this. In the late 1960's several events coincided. First, many research and development activities of the National Aeronautics and Space Administration were approaching completion, and other program terminations could be foreseen; thus many highly skilled and high-technology-focused NASA persons began to look for other occupations. Second, someone asked the question, "If we can get to the moon, why can't we (clean up Lake Erie, clean up the environment, cure cancer, etc.)" It is clear what the answer should have been: getting to the moon was the substantial but relatively straightforward task of executing a series of technological operations, for which most of the basic research and technology assessment had been done, and for which a broad social consensus existed. But for the seemingly mundane earth-bound tasks, no consensus existed at all about how they were to be accomplished, or indeed whether they should be undertaken , when compared with other technological and social options and priorities.

The third event was the National Science Foundation receiving Congressional advice to pay increased attention to problems relevant to social needs; the NSF started in 1964 a small activity with the rambling title "Interdisciplinary Research Relevant to Problems of Our Society (IRRPOS), and soon expanded it into a large program: Research applied to National Needs (RANN). The RANN program attracted a number of NASA personnel, and NASA-type project thinking soon influenced RANN's attitudes.

The fourth and final circumstance was that in the early 1970's, solar power received little attention; a 1972 evaluation of RANN's activities by a sub-committee of the National Academy of Sciences* suggested, inter alia, that RANN should play a much larger role in energy conservation, societal issues connected with energy, and solar power, for all of which there existed at that time neither an institutional home nor any appreciable programs.

So the NSF became the champions of solar power, and set the bias toward building large devices, often at the expense of developing more basic understanding, a bias that was to continue through the Energy Research and Development Administration, into the Department of Energy, into the early 1980's.

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* I was chairman of the panel concerned with RANN's energy program. The Fiscal Year 1974 budget (starting 1 July 1973) was the first opportunity for action, although some opportunity existed for shuffling money in FY'73. The solar energy R&D budgets became:

Fiscal Year	$ Amount (in millions)
1971	1.2
1972	1.7
1973	5.1
1974	17.3
1975	42
1976	115.
1977	290.

Sometimes it is possible to identify a fairly modest and straightforward test, which the proposed scheme should be able to pass, if it has the merits that its backers claim, before much money is spent on the idea. How the backers react to the suggested test gives some insight into their private attitudes. We shall see some examples here. These schemes were proposed as desirable alternatives both to some other solar power concepts, and to nuclear power, against which strong objections were being made, as decribed in Chapter 7.

8 .9.1 Solar Satellites

The idea was to put a solar collector many kilometers in extent into synchronomous orbit, 36,000 km. above the surface of the earth, and beam solar energy in some form down to a fixed receiving array on the surface. The idea was first put forward in 1968 by Glaser (See Glaser 1977), and strongly supported by NASA-oriented persons (Kraft 1979; DOE 1978)

A solar power satellite has the advantage of being in direct sunlight almost all the time; its disadvantages will appear anon. A simple array of mirrors focusing sunlight onto the earth will not work (apart from the problem of clouds), the reason for which is left to be developed in one of the problems at the end of the Chapter.

The solar satellite, as envisaged, would be about 50 km^2 area, use PV cells to generate electricity, then send the energy as microwaves from a 1 km^2 antenna on the satellite, onto a receiving array on the earth, which would also be about 50 km^2 in area. The beam would be kept on target by laser and other guiding signals, and a propulsion system on the satellite that would correct for various calculable orbit perturbations and for errors. The microwave beam would be programmed to defocus if it became misaligned.

Glaser estimated a total system cost of $1500/kWe, but this would depend on achieving many goals, for instance:

1. Reducing the cost of silicon or gallium arsenide photovoltaic devices to (at most) about $100/kWe, about a factor 100 below present costs.

2. Reducing the cost of launching heavy loads into high synchronous orbit by a factor 5-10 below those projected in the late 1970's for putting loads into low orbit with the space shuttle, which themselves turned out to be too optimistic.

3. Building the space station to weigh less than about 1 kg/m^2, including allowance for structural material, power connectors, guidance system, antenna, etc.

An additional difficulty with the concept is the estimated level of microwave power incident at the edge of the earth-side receiver: originally proposed to be the present U.S.-adapted standard of 100 $watts/meter^2$, but the U.S.S.R. standards are a factor 1000 lower (based on observations of sensory disturbances at higher power levels); the matter is still unresolved.

Clearly, power satellites are at best some years off. It would have been possible to have initiated a modest and relatively inexpensive program in (say) 1972 to determine the long-term effects of low level microwaves on some test animals; acceptibility of the concept depends very much on the outcome of such tests. Indeed, they were proposed at that time, but the solar satellite proponents gave them no support.

The solar power satellite scheme illustrated how groups gain strength by mutual support. The NASA space shuttle program cited the solar power satellite in support of NASA (Kraft 1979), and vice versa. The idea finally died in the early 1980's, after increasing criticism, culminating in a comprehensive report by the Congressional Office of Technology Assessment. (OTA 1981).

8 .9.2 Ocean Thermal Energy Conversion (OTEC)

In much of the tropics, water at the surface is 20°C warmer than it is 1000 meters down. A thermodynamically perfect engine operating between those hot and cold sources would be about 6% efficient, and the proponents of OTEC imagine that they could make a practical floating power system with an actual conversion efficiency (to electricity) of 2.5%.

William F. Whitmore, chief scientist of the Ocean Systems Organization of Lockheed Missiles and Space Co., Inc., a prime contractor and principal supporter for the OTEC system, described some of its qualities (Whitmore 1978):

> A general argument favoring OTEC is the "net energy assessment," pioneered by the State of Oregon. It is based on the fact that energy must be "organized" to be used and that the act of organizing requires the expenditure of energy--one way of looking at the Second Law of Thermodynamics. To produce 1000 calories of energy from more traditional sources, a fossil-fuel or a nuclear fission plant must be built, the mined and refined and then transported to the site where it will be used. When all these energy "costs" are added up 3,000 calories are usually expended to make available the 1,000 calories for useful work as output from the utility plant.
>
> An OTEC plant, on the other hand, derives its energy from a natural and uncontrollable nuclear fusion plant--the sun. Solar energy is supplied directly to the site, at no cost, by radiation. Thus, over a nominal life of 40 years or more, the only energy "investment" for OTEC is the construction, deployment, and operation of the plant itself.

> This is estimated to be about 700 calories for 1,000 calories output. So 700 calories expended to build and operate an OTEC plant can produce 1,000 calories of useful energy--a positive payback. Note that this payback is not directly related to "profit"--a nuclear fission plant may very well pay back its monetary cost in a short time, but it can never beat the Second Law of Thermodynamics by reducing the entropy of the thermodynamic process. The solar processes manage to do so locally (as do living organisms) because the sun is outside man's control and is, on the scale of human existence, inexhaustible.

The greatest difficulty could not have been stated more accurately, or in a more bizarre way: if these initial estimates of the cost of OTEC should be 30% low, a very likely circumstance, the system will never even pay back in energy output the energy cost that society must pay to construct it, let alone labor and development costs, or the cost of the vast amount of material necessary to build such an inefficient plant. Furthermore, even if Whitmore's optimistic assessment were to be true, both the social and economic returns on the investment would be intolerably delayed.

Whitmore's invocation of the second law of Thermodynamics in this context is misleading: using his formulation and in his context, any installation would be attractive just so long as it eventually captured more useful energy from a nondepletable source than was used to build it, irrespective of other considerations. Any other solar installation, nuclear fission breeder reactors or nuclear fusion reactors (with billion-year supplies or uranium and deuterium, respectively) would qualify as well.

In addition to the immense cost of such a large installation for the amount of electricity it produces, these additional difficulties exist, among others:

1. electricity appears out in the ocean, necessitating either an expensive undersea power cable many miles to shore, or a chemical conversion

plant on board, probably to produce hydrogen which must itself then be transported, but possibly by ship (with attendant hazards greatly exceeding those of shipping liquefied natural gas).

2. The large heat exchangers must be very efficient, because of the very small permitted temperature drops; but even a small amount of biofouling will spoil the heat transfer. Use of antifouling chemicals on such a scale presents further difficulties.

3. The cold water pipe (Whitmore avers) must be 600-1000 m deep, and large enough to carry at very low speed a flow of water equal to that of the Missouri River at Omaha. Higher speeds (and smaller pipes) are precluded by the need to minimize pumping power. Anchoring this device will be a problem. A 50 meter diameter pipe, 1000 meters long requires about 5×10^7 newtons (≈5000 tons) force to hold it against a 1 m/sec current. If the current at the surface and at 1000 meters are different, the support structure becomes very complex.

I suggested in 1971 a simple test of the idea. Many large power plants built on the seacoast will reject 1500-2000 megawatts of heat as warm sea-water, into the colder ocean; in the winter the temperature conditions match those envisioned for OTEC. This flow is adequate for a 20 megawatt electric experimental installation, which should logically be built anyway in the process of developing the concept. Advantages would have been:

1. The hot and cold sources are free, conveniently available, already in pipes.

2. If the scheme works, an electric power line exists on-site to take the power.

3. If the technology of such large low temperature turbines (probably operating with ammonia as the working fluid) and heat exchangers

promising after such a semi-scale development, one could look on OTEC more optimistically.

4. Alternately, if such a test showed the prospects were poor under such favorable circumstances, they would be a fortiori poor in the deep ocean, where conditions are worse.

5. In any event, such a test would help develop the useful technology of low-temperature vapor cycles, which could be applied to sea- or land-based power plants, even to energy-conserving co-generation schemes.

The OTEC advocates either ignored this suggestion or condemned it as a scheme to draw attention away from OTEC itself, which had to be developed by itself. In 1979-1980, a small pilot plant on a moored barge operated off the Island of Hawaii, producing 10 kw of power in the course of a $50 million developmental program that was terminated in the early 1980's.

This unwillingness to confront legitimate intellectual challenges leads some observers to think that supporters of such schemes want first to build a profitable base of financial support. It also reminds one of the Indian fakir who was quite willing to lie on a bed of 10,000 nails, but would not sit on one.

8.6.3 Power Towers

The principle is simple: a multiplicity of mirrors focus sunlight onto a boiler atop a high tower; the steam from it runs a conventional turbine and generates electricity. The most expensive single solar energy project to date: a 10 MWe plant near Barstow, California, for a pre-construction estimated cost of \$120-150 million, or \$12-15,000/Kwh.

Here too, the aerospace industry had been much involved: Martin Marietta, Honeywell, McDonnell-Douglas, Boeing; all four have their own concepts of steerable mirrors and boilers. In all four concepts, each mirror was 35-40 m^2 in area, either round or rectangular, slightly parabolic in figure, mounted on a pedestal embedded in concrete, and is aimed by sensors and/or computers onto the boiler with an accuracy of about 10^{-3} radions. A 100 MWe (peak power) commercial installation would require about 1 km^2 area covered with about 10,000 such mirrors, and a tower about 300 meters high; a lower tower would cause the mirrors to block each other's light unduly, higher towers become extraordinarily expensive.

Present costs of test mirror assemblies are about \$1000/m^2; some obvious difficulties are:

1. The power is peak, not average; an economically attractive system should cost no more than \$50-100/m^2, which is (it has been said) comparable to the price of billboards; but here the device is technologically sophisticated.

2. The poor prospects for significant cost reduction in major construction materials and components: concrete, steering pedestals, etc.

3. The boiler itself, which must be able to withstand large sudden thermal shock, as (for example) when clouds pass overhead. No conventional power plant boiler is designed to withstand such treatment.

4. Winds and dust in the most attractive siting area: The U.S. southwest desert. The force on a 37 m^2 panel facing a 100 km/hr. wind is about 30,000 n (3 tons), and the dust often carried by those winds in the springtime is very abrasive.

The project was completed in the early 1980's; no more will be built in the foreseeable future, and no local California utility company volunteered to take it over, even as a virtual gift.

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Table 8.1

MAJOR CALIFORNIA PHOTOVOLTAIC INSTALLATIONS

Site	Owner	PV Supplier	Size MW	Power Sold To	Year of Operation	Cost $million	Note
Hesperia, 60 mi. NE of Los Angeles	ARCO-Solar	ARCO-Solar	1	Southern California Edison	1982	Propri-etary	a
Carissa Plains I, between Bakersfield and San Luis Obispo	ARCO-Solar	ARCO-Solar	6	Pacific Gas & Electric	1984	Propri-etary	b
Carissa Plains II	ARCO-Solar	ARCO-Solar	16 total	Pacific Gas & Electric	?	Propri-etary	c
SMUD I	SMUD	ARCO-Solar	1 ac (1.2 dc)	SMUD	April 1984	11.4	d
SMUD II	SMUD	Several (?)	1 ac (1.2 dc)	SMUD	1986?	10.4	e
SMUD III	SMUD	?	5 ac	SMUD	?	40	f

NOTES

(a) 1' x 4' panels assembled to 30' x 30' single-axis tracking units.

(b) Robert E. Robertson, Manager of Engineering, ARCO-Solar Industries, Inc., private communication. Has side-mirrors in panels for non-focused concentration.

(c) Entire plant (640 acres) to operate unmanned, by remote control.

(d) Sacramento Municipal Utility District. $7 for modules ($5.80/W_p dc); 50c/W_p for support; power conditioning, $400,000; site construction $1.46 million; field engineering $1 million. Mostly Federal money. These data from E.S. "Ab" Davis, "Assessment of the Single-Axis Tracking Flat Plate Concept for SMUD PV PHase I," Jet Propulsion Laboratory Report 5250-15, August 9, 1982, also private communications. Mark Anderson, Project Manager, SMUD, private communications.

(e) Specifies only 8' x 16' arrays to match mechanical and electric interfaces. Bids asked mid-October 1983 for 900 kw dc from one supplier, 3 x 100 kw dc from others. SMUD offers to pay $3.6 million. Deflated to 1980 dollars (basis for original plan), this comes to $7.67 million total, with $2980/kw contributed by SMUD.

(f) Up from original 2 MW ac. Expect complete solar panels at $4.00/$W_p$ dc, SMUD pays 50% of costs.

Table 8.2 Potentially collectable net yield from U.S. biomass operations under present management practices (1974).

Activity	Gross energy yield (Q)	Collectible net energy yield* (Q)
Agriculture		
Corn	3.9 (1.9)**	3.0 (1.8)
Grains	3.2 (2.1)	2.9 (2.0)
Green crops	2.2	2.1
Oil seeds	1.2 (0.4)	1.1 (0.4)
Fruits and vegetables	0.2	0.2
Other***	0.7	0.6
Silviculture	9.3 (3.7)****	6.6 (1.2)*****
Pasture and range	7.0	0.7
Total	27.7 (8.1)	17.2 (5.4)

*Energy inputs valued at 1.5 times the value of the biomass energy.

**Residue values given in parentheses.

***Taken as 10 percent of the total for all agriculture excluding corn in order to account for minor crop acreages not included in Table 1.

****All residues.

*****Excludes tree leaves, small branches, and roots; includes stump, unmerchantable bole, and large branches.

From C.C. Burwell, <u>Science</u> <u>199</u>:1041 (1978).

TABLE 8.3

	Size of distillery		
	Micro[a]	*Mini*[b]	*Macro*[c]
Agricultural sector			
Cost of transport	low	reasonable	high
Risks associated with feedstock	small	reasonable	large
Mechanization	none	some	high
Investments	small	reasonable	large
Land use diversification possibilities	large	reasonable	small
Environmental constraints	none	few	many
Industrial sector			
Level of technology	simple	simple	sophisticated
Labor requirements	semi-specialized small	semi-specialized small	semi-specialized large
Management efficiency	high	high	low
Total investments	low	reasonable	high
Resistance to technological improvement	nonexistent	small	large
Possibilities of technology diffusion	many	many	few
Environmental constraints	none	few	many
Cost per liter			
Production	high	reasonable	low
Distribution	low	low	high
Social	negligible	low	high
Total	large	reasonable	large

Source: adapted from J. O. B. Carioca, H. L. Arora, and A. S. Khan, "Technological and Socio-Economic Aspects of Cassava-based Autonomous Minidistilleries in Brazil," to be published in *BIOMASS - An International Journal.*

[a]About 2,000 liters per day.

[b]About 20,000 liters per day.

[c]About 200,000 liters per day.

TABLE 8.4

Population, agricultural land, and forests in southern and eastern Asia.

Country	Population (× 10⁶) (38)	Area (× 10⁶ ha) Total (38)	Agricultural (39) Irrigated*	Agricultural (39) Total	Forests (39)	Hectares per person Cultivated	Hectares per person Forest
Bangladesh	85	14.4	1.2	9.1	1.5†	0.11	0.02
Burma	32	67.8	0.8	18.9	39.0	0.59	1.22
People's Republic of China	900	959.7	76.0	127.0	111.8	0.14	0.12
India	638	328.0	31.6	165.0	65.8	0.26	0.10
Indonesia	137	190.4	6.9	18.1	121.8	0.13	0.89
Japan	116	37.2	2.6	5.3	24.5	0.05	0.21
Korea	37	9.8	0.8	2.4	6.6	0.06	0.18
Malaysia	13	33.0	0.3	3.5	23.5	0.26	1.81
Nepal	13	14.1	0.2	2.0	4.5	0.15	0.32
Pakistan	77	80.4	14.0	19.4	2.6	0.25	0.03
Philippines	46	30.0	1.2	11.1	13.9	0.24	0.30
Sri Lanka	14	6.6	0.5	2.0	1.3†	0.18	0.09
China (Taiwan)	17	3.6		0.9‡		0.05	
Thailand	45	54.4	2.5	13.9	16.0†	0.31	0.36
Vietnam	50	33.0	0.6	5.3	13.5	0.11	0.27
Total	2220	1862.4	139.2	403.1	446.3	0.18	0.18
Percent of estimated world total	50	14		27	11		
Percent of world total, less China	30	7		19	8		

*Area irrigated about 1970. †See text. ‡Author's estimate.

REVELLE, ROGER (1980) LOC. CIT.

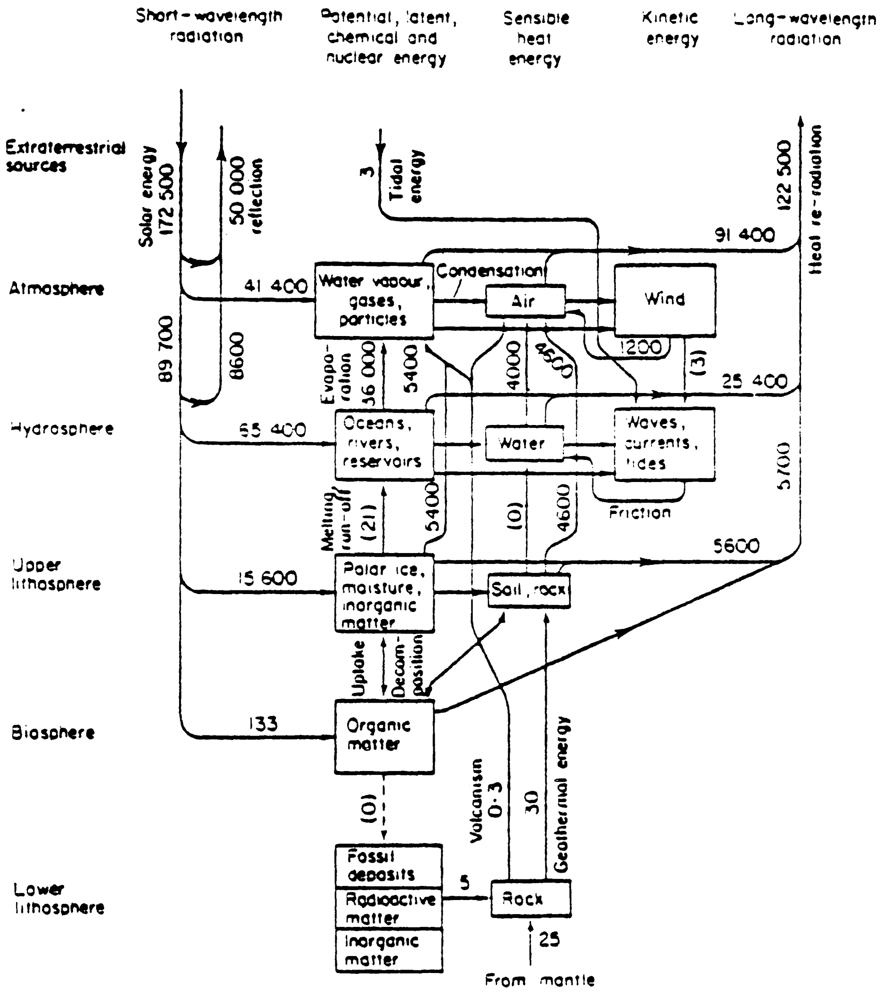


FIG. 8.1 SCHEMATIC ENERGY CYCLE WITHOUT ANTHROPOGENIC INTERFERENCE, WITH FLOWS IN TERAWATTS. FROM B. SØRENSEN, RENEWABLE ENERGY, LOC. CIT.

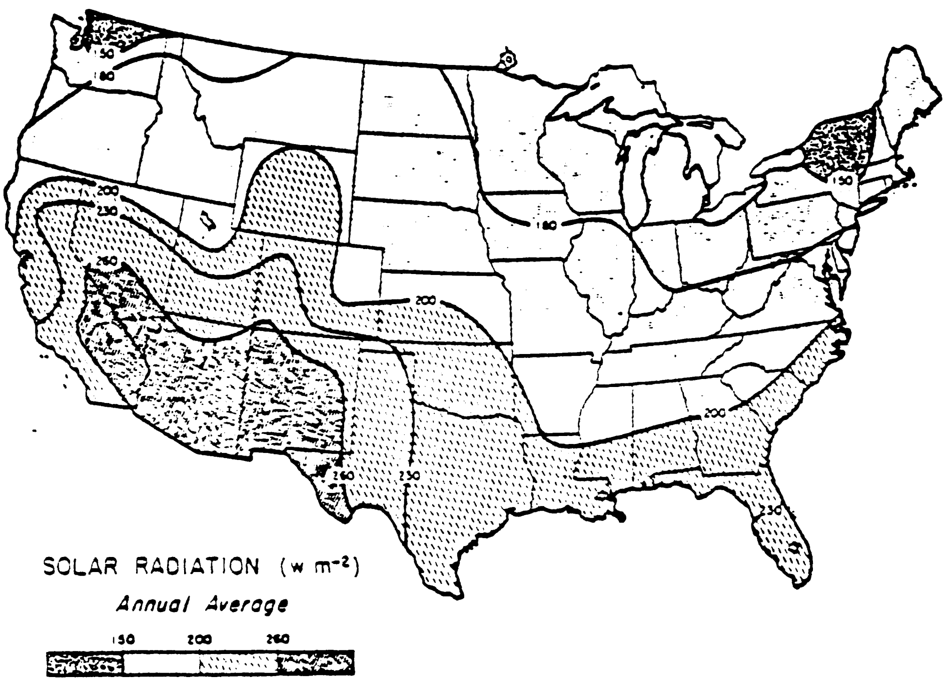


FIG. 8.2 ANNUAL INSOLATION IN THE UNITED STATES, FROM MELVIN CALVIN, "SOLAR ENERGY BY PHOTOSYNTHESIS," LOC. CIT.

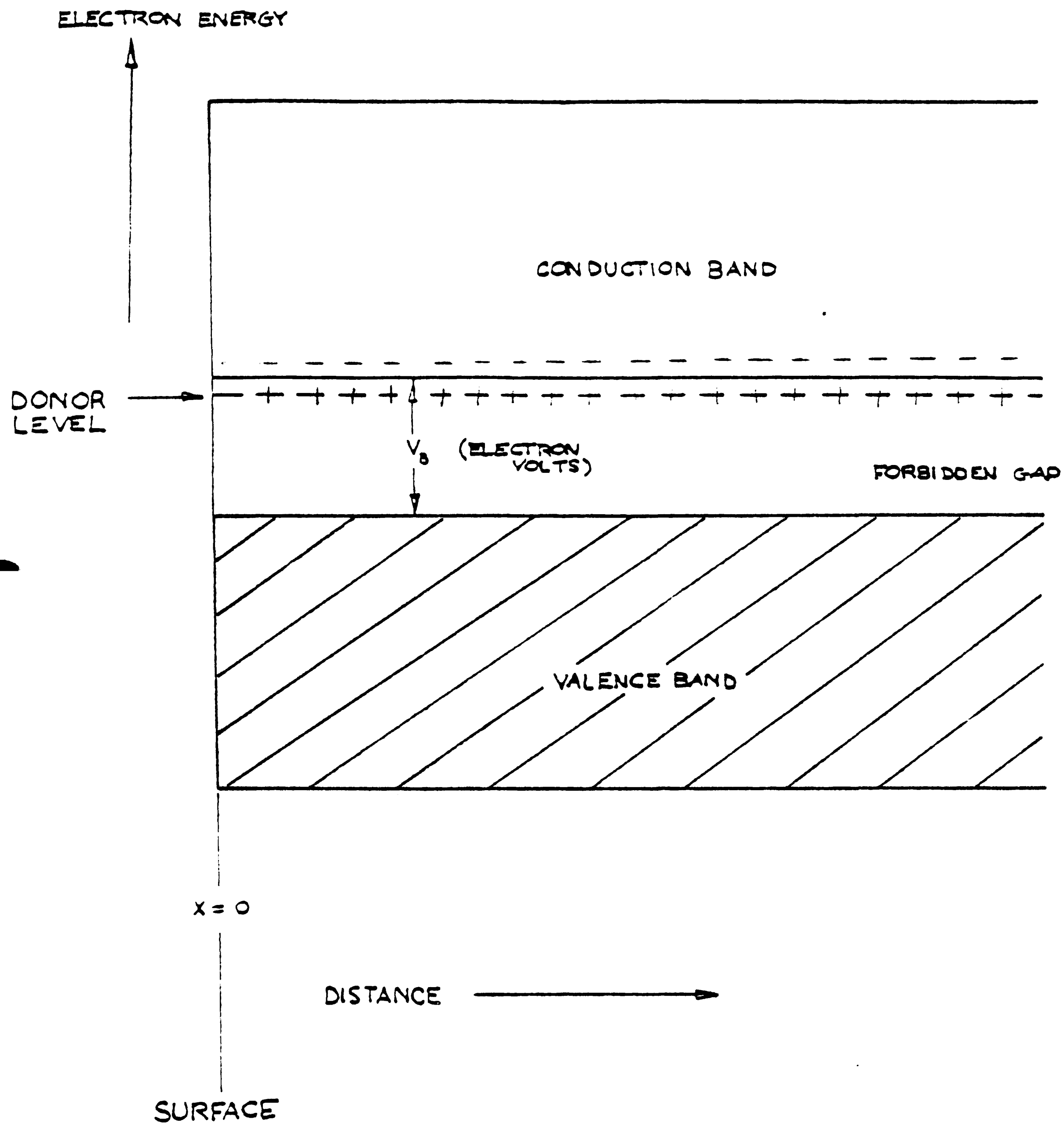


FIG. 8.3 ENERGY LEVELS IN A PURE SEMICONDUCTOR, AT 0°K.

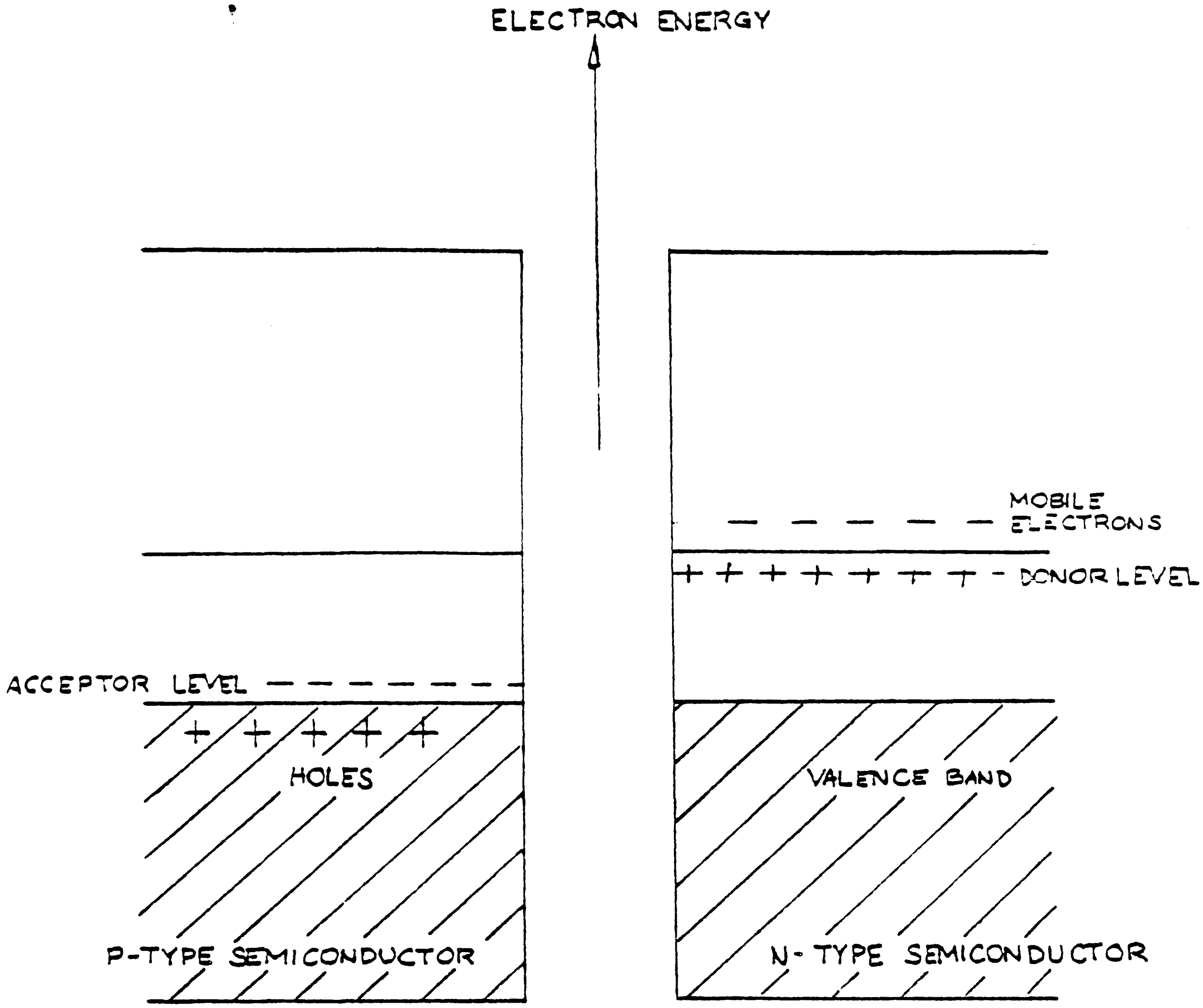


FIG. 8.4 N AND P TYPE SEMICONDUCTORS, DOPED FOR EXAMPLE WITH PHOSPHOROUS AND INDIUM RESPECTIVELY.

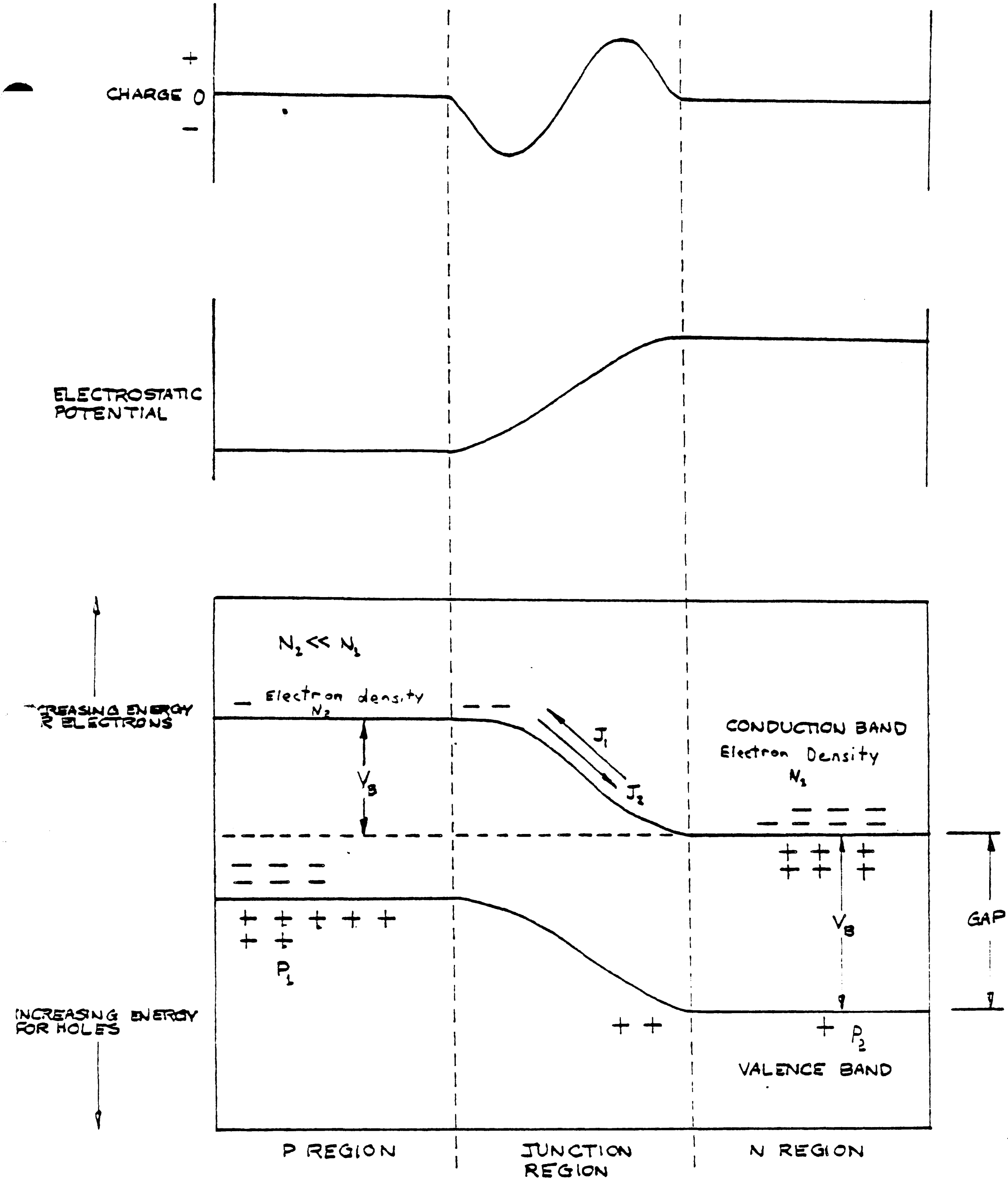


FIG. 9.5 CHARGE DENSITY, ELECTROSTATIC POTENTIAL, ELECTRON AND HOLE ENERGY STATES IN A P-N JUNCTION.

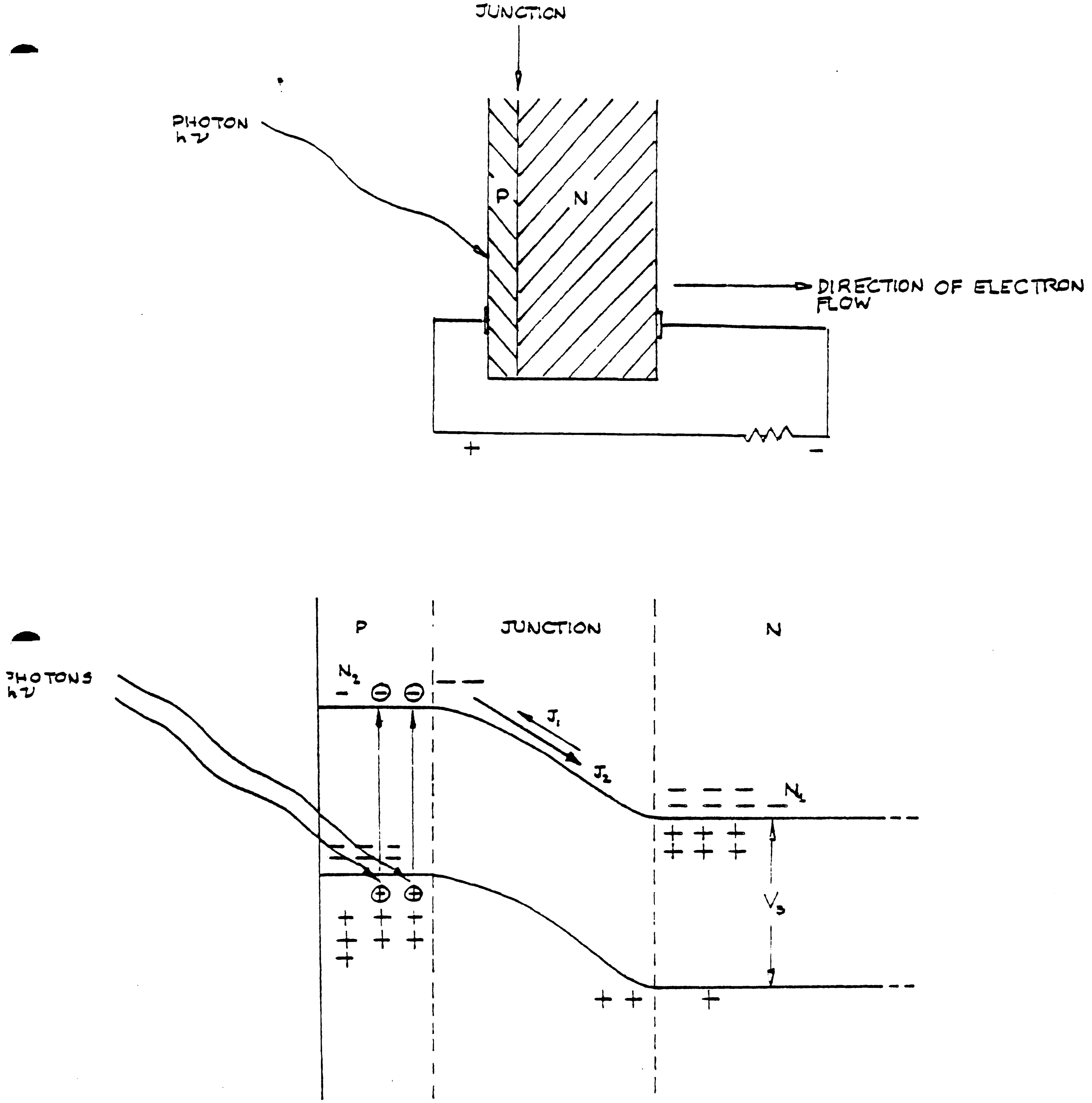
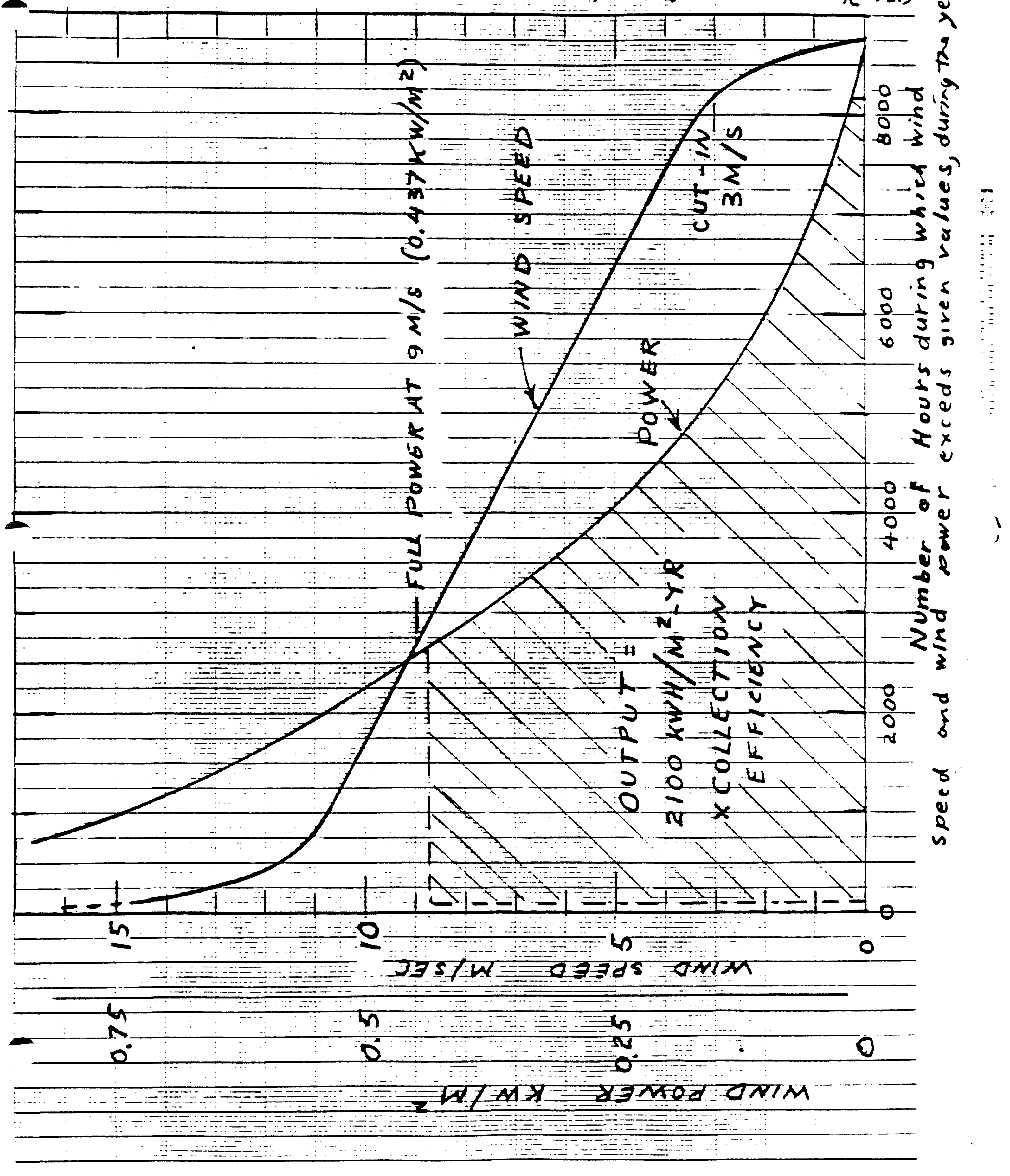


FIG. 8.6 A SOLAR CELL, PHYSICALLY (TOP) AND ELECTRONICALLY (BOTTOM).

FIG. 8.7 WIND AND POWER DURATION CURVES, FOR KAHUKU, HAWAII, WITH POSSIBLE APPLICATION DATA. ADAPTED FROM "GUIDEBOOK ON WIND ENERGY CONVERSION APPLICATIONS IN HAWAII" HAWAII NATURAL ENERGY INST, UNIV. OF HAWAII, (1981)



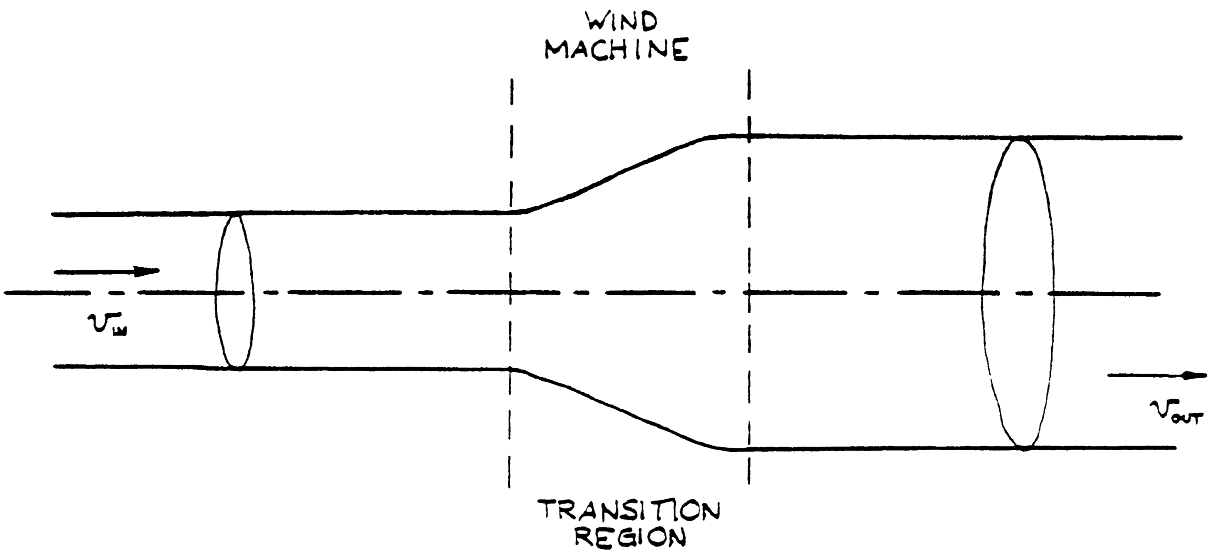


FIG. 8.8 FLOW THROUGH A WIND GENERATOR.

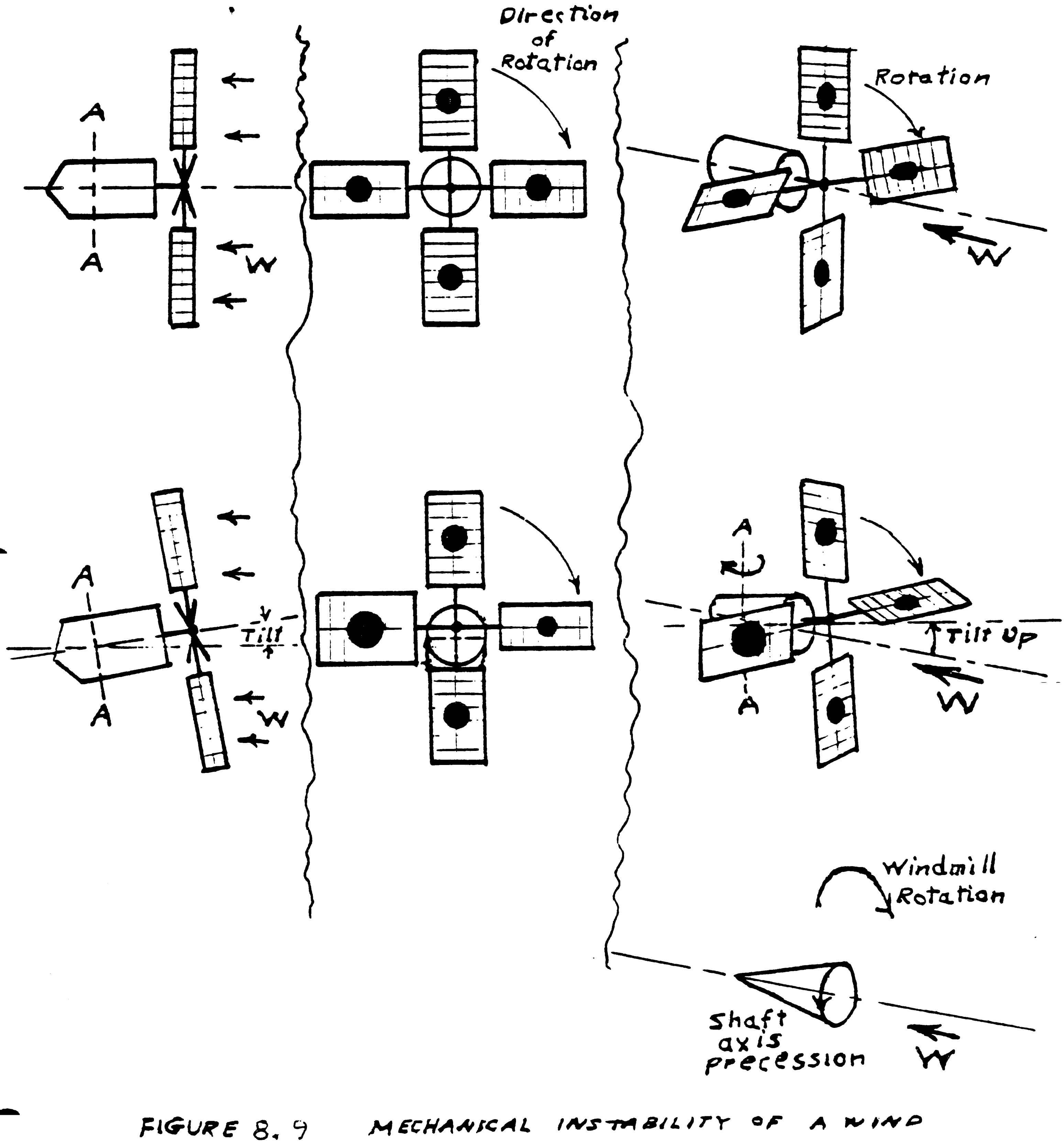
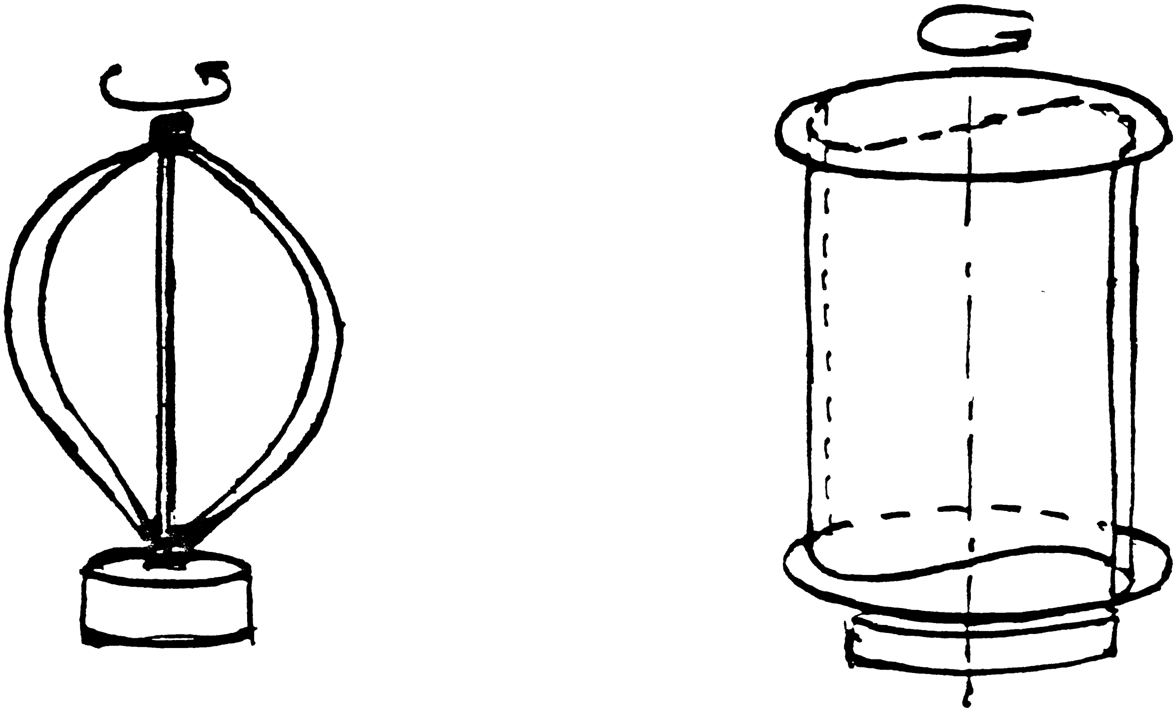


FIGURE 8.9 MECHANICAL INSTABILITY OF A WIND ROTOR OR PROPELLER WITH TOO-FLEXIBLE SUPPORT SEE TEXT FOR DESCRIPTION



DARRIUS ROTOR SAVONIUS ROTOR

FIG 8.10 THE DARRIUS AND SAVONIUS WIND ROTORS, RESPECTIVELY.

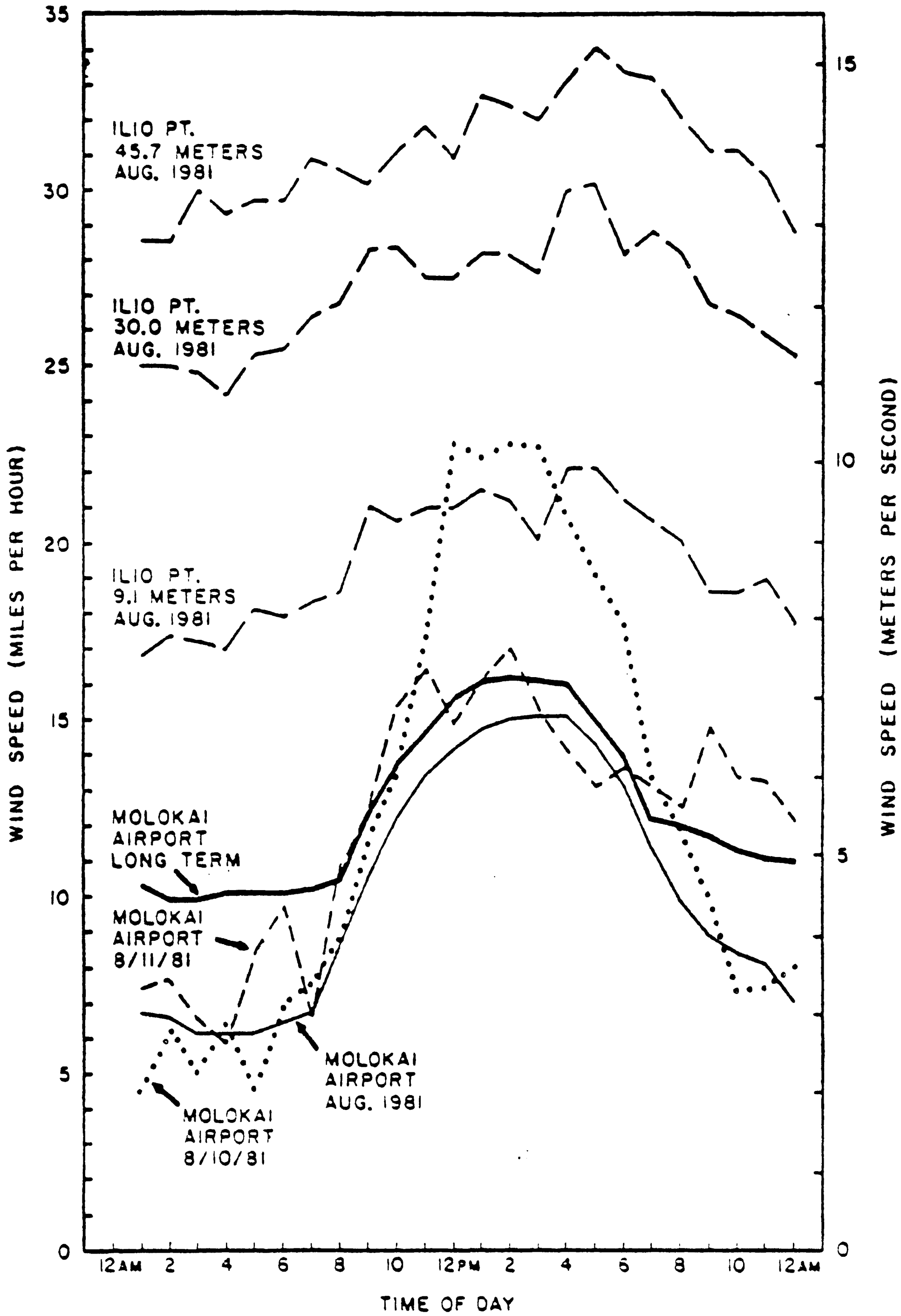


FIGURE 8.11 DIURNAL VARIATION OF WIND SPEED

The diurnal variation of wind speeds on Molokai indicates that winds are normally stronger in the afternoon than at night. Though long-term data provide the best "typical condition," this figure shows that for a given day or month and at different elevations there are very great differences. *From Hawaii Natural Energy Inst. Wind Energy Tech. Bull 82-1.*

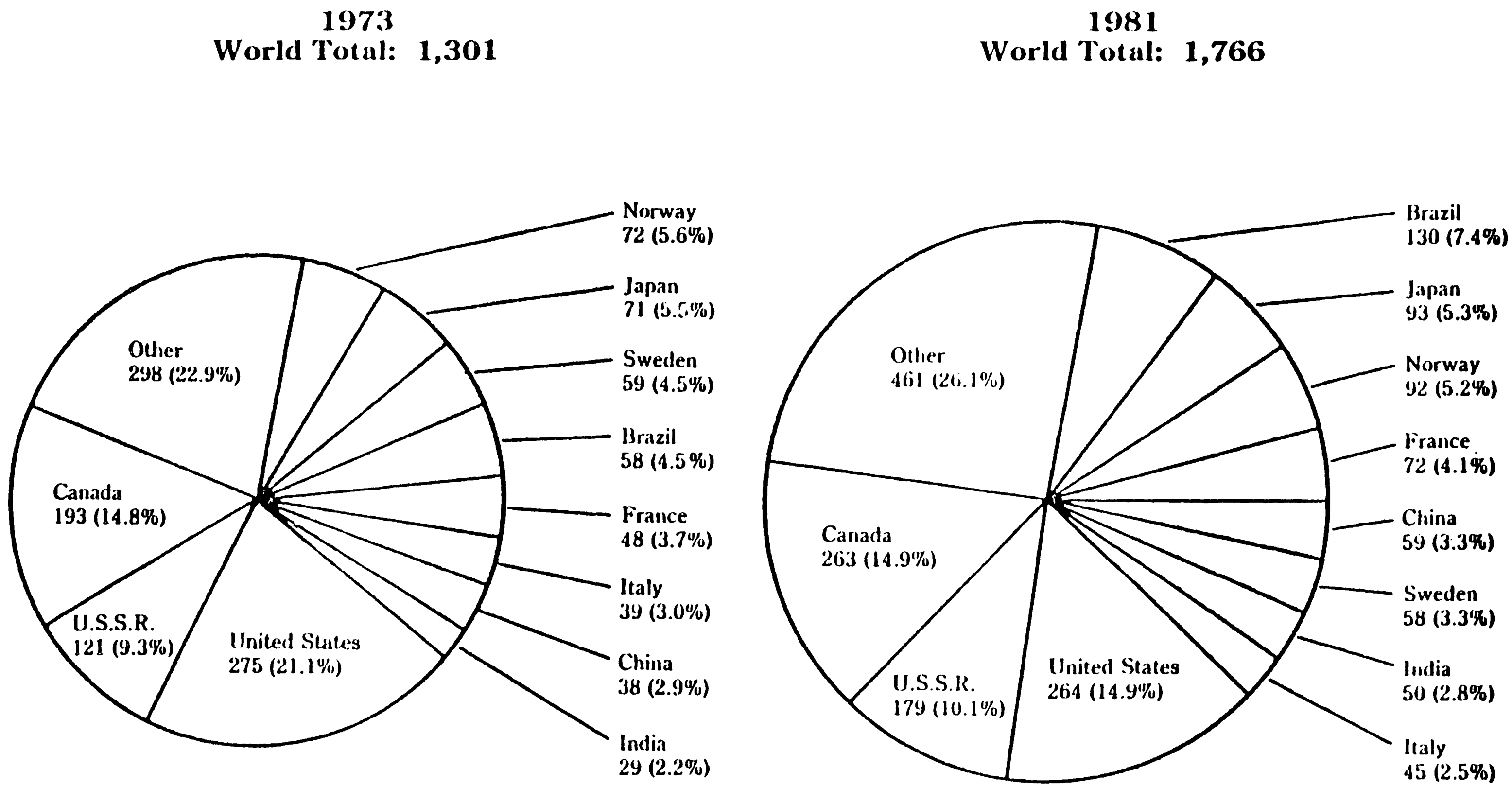


Figure 8.12. International Hydroelectric Power Production

10^9 kilowatt-hours. From 1982 Annual Energy Review, U.S. Dept. of Energy Report DOE/IEA-0384(82)

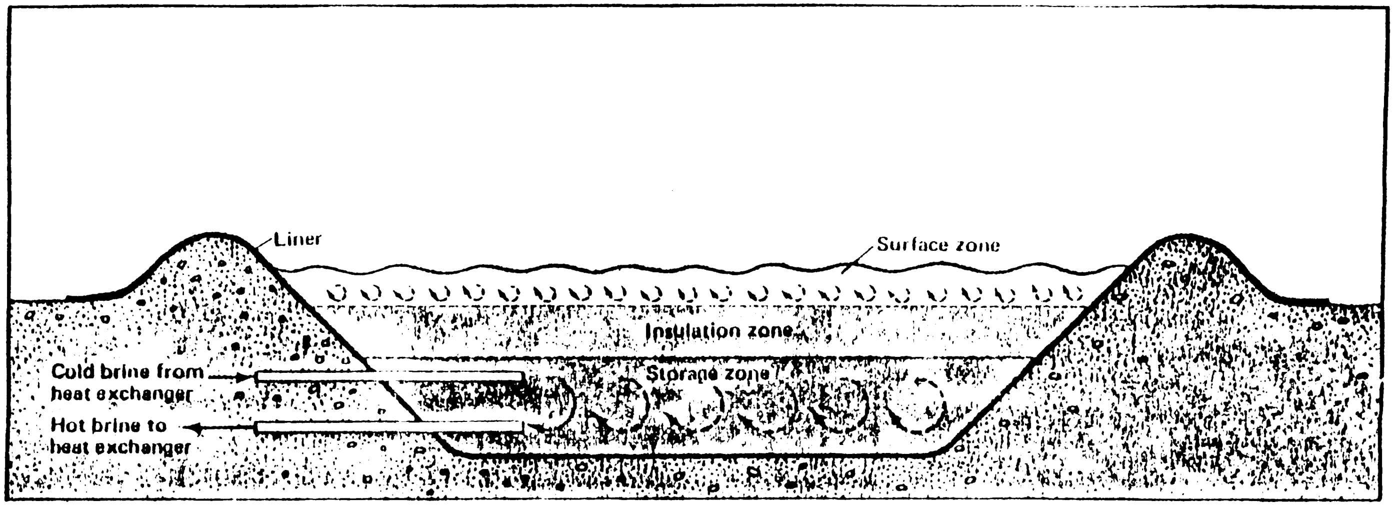


FIGURE 8.13 A SOLAR POND

Chapter 9

TOPICS ON ENERGY STORAGE AND ELECTRIC SYSTEM INTEGRATION

9.1 Introduction

Most of these topics connect, via electric power systems. Electric power is expected to increase its already large share of total energy, from both end-use and generation perspectives. Besides being clean at the point of use, its precise controllability and adaptability match it to the demands for our increasingly precise technological world. Steel made in electric arc furnaces has replaced steel made in open-hearth furnaces; metals surface-treated in gaseous plasmas replace those formerly treated in flames. Electric heat pumps replace oil- or gas- burning furnaces. Increasing urbanization of the world reinforces this trend; electric power is easier to distribute than many other energy forms in already-built cities, offering opportunity for cleaner living.

The world is becoming more electric; 35% of US primary energy went for electric power generation in 1983, up from 25% in 1970. In Canada, the year-1982 number was 39%. The Organization for Economic Cooperation and Development estimates that the fraction of primary energy so used will exceed 45% by year 2000. East Asia— Japan, Taiwan, Korea, the Peoples' Republic of China and other countries — are either well-electrified now or embarked on that route.

On the generation side, note how many new and recently-new energy options are mostly or entirely electric: photovoltaic, wind, nuclear, for example. The large amounts of coal burned now and projected to be burned in future go primarily to make electricity. Petroleum and natural gas supported a civilization designed around end-use of flames; the order is changing. These trends have appeared both implicitly and explicitly in the material of earlier chapters.

A vast literature exists at many levels of detail and technicality about electric power systems, and there is no intention to describe them here that way. More germane to this book is how some of the prospective energy options might be incorporated into present and future systems. To do more, or in that in detail, would double the length of the book, and besides that there is no need of it in this overview.

Nevertheless, a few general remarks are in order about electric utilities, especially in the United States up to the middle 1980's, especially regarding the preparation of new major options.

Chapter 7 contains some material on this; section 7.8 on electric utilities and architect-engineers, section 7.10 on new systems for smaller countries, section 7.11 on the electric utilities' interaction with the public, for example, which the reader may wish to revisit in this context.

It is interesting to compare the R&D histories of the telephone industry, especially American Telephone and Telegraph (AT&T) up to 1983, and the electric utility industry. Both are very large, capital intensive, highly regulated, technology-based, and must operate equipment for decades. For half a century AT&T allocated 2-3% of its gross revenue to R&D, either directly or via its subsidiaries (principally Western Electric Company). This fraction is typical of many industrial enterprises; many high-technology companies allocate much more. The result for AT&T was the continual development of an excellent system with many side-benefits, for example the transistor. This was done without government support. The national extent of AT&T and its technical and scientific base, for example Bell Telephone Laboratories, permitted AT&T to convince public utility commissions throughout the country that such

R&D allocations were both necessary and long-term cost-effective, hence belonged in the rate base. Lively and mutually-understood communication flowed through the Company, from R&D to the operating parts.

The US electric utility sector, in contrast, consists of hundreds of separate organizations, mostly private companies; except perhaps for a few of the largest, no one utility could capture enough of the benefits to make large R&D projects profitable. That work was done primarily by the major vendors (Westinghouse, General Electric, for example) who supported development out of sales. Major power plants were usually built with the aid of architect-engineering companies (Bechtel, for example), and a question lurks behind all this: are all the parties fully aware of mutual needs, and future complexity? The Federal Government appeared as another major option preparer, especially since the 1950s, especially in the nuclear sector, but also in solar power and other technologies. Sure enough, 2-3% of the gross electric bills of the country, several billion dollars per year, were and probably are going into R&D for electric power, but is it co-ordinated and optimally arranged?

The Electric Power Research Institute (EPRI), established and maintained with voluntary support from electric utility companies, originally to undertake long term holistic tasks of the sort envisaged in this discussion, has an annual budget of about $250 million. That is only about 1/4 of one percent of the US electric power bill. EPRI finds itself now mainly concerned with short-term, relatively narrowly-structured topics. What seems to be needed is a mechanism that will bring the whole electric utility industry as full and sophisticated partners in the preparation of their own future. Perhaps it is a new federal tax to be applied for such purposes (mention of which in the Congress in 1970 led to the utilities creating EPRI as a response), but it would be better if the government, which tends to control and sometimes guesses wrong, kept out of actual control. Perhaps it is a consortium of utilities and others operating a R&D limited partnership. In any event, a properly structured R&D program, rationally funded, deserves to be supported on the rate base. If that had been in place two decades ago, nuclear power and other electric options would probably have developed differently, with fewer misjudgements and surprises.

9.2 Storage: preliminary remarks

The long chain of events shown in Figure 1.10 demonstrates the separation between primary production and eventual use of energy, in both space and time. Electricity most nearly is produced as and when needed, but even here storage becomes increasingly important and economically attractive, as will be shown. Thus energy storage is a ubiquitous and important feature of energy systems. These sections are short not because the topic is simple or unimportant, but because energy storage has been incorporated into the material of many other chapters: residential systems in Chapter 4, hydropower and solar ponds in Chapter 8, for example.

The ideal energy storage system should be inexpensive, convenient and safe to use, quickly available on demand, compact, and non-polluting. Liquid hydrocarbon fuels satisfied most of the requirements in the past; their increasing cost and decreasing availability stimulates the search for different energy storage systems. Good substitutes are hard to find; to see this quickly and easily, consider that 10^6 BTU or 1000 megajoules of energy can be obtained from:

- 7 gallons of petroleum
- 200 metric tons traveling at 100 m/sec(224 miles/hr)
- 20 farads of capacitors charged to 10,000 volts (requiring a very large building to hold them)
- 250 charged lead-acid car batteries
- 1000 tons of water, falling through 100 meters vertical drop
- 70 kg of wood
- 5 tons of rock, 40°C above its ambient surroundings
- 2.5 tons of water, 100°C above its ambient surroundings
- 1000 jelly donuts

All these materials store energy. Some can deliver it effectively as mechanical work, some only as low-grade heat; some of the stored energy could be converted easily, some only with difficulty. But it is clear that: (1) energy storage has been and will be needed for many applications, ranging from home heating to vehicular transport and beyond, (2) energy storage systems to replace fossil fuels tend to be large, expensive, and/or inconvenient. However, there is much more to energy storage than merely serving as surrogates for fossil fuels.

A principal emphasis here is on storing the excess output of electric generators and redelivering it on demand. Electric Power systems are often characterized as "having no storage," reflecting the view that electric energy is produced in the amount required to be used at a given time. But this is not true in a deeper sense, and incorporating energy storage into the electric supply system can affect its cost, operation, choice of major components and configuration profoundly. Short-term storage affects the need for prompt reserve capacity; longer-term storage provides flexibility in meeting peak demand. Some interruptible consumer use can be looked upon as storage provided by the user (literally true for water heaters timed to operate only off-peak). Storage can sometimes permit using cheap fuel instead of expensive fuel; and can sometimes replace generating capacity.

The presence or absence of storage greatly affects the value of renewable, nondispatchable* and/or decentralized energy systems. For example, solar energy without storage is to a first approximation a capital-intensive method of saving on fuel costs at uncertain times; hence, storage is critical to making solar power economic on a large scale. However, it is important to note that storage per se does not guarantee that solar will be more economic than conventional supply alternatives. For example, if cheap storage of bulk electric energy became available, it could be used to store solar power for the night, or off-peak night-time nuclear power for the day and early evening. This indicates that storage can be a benefit to conventional as well as to non-dispatchable sources and that a judicious combination of sources could reduce the need for energy storage, hence total cost.

Biomass is usually storable, a global resource estimated to be a few terawatts at most; see Chapter 8. However, much of its use is liable to be restricted to places and times that do not match the needs for power on demand in industrialized societies; to a first approximation, we should look for storage elsewhere.

Several topics invite attention: batteries, hydropower (including pumped storage), compressed air, hydrogen (perhaps in later years), perhaps flywheels for limited applications, low temperature heat and cold

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* Sources such as wind and PV whose output at any time is much less predictable than conventional power plants, and hence cannot be dispatched by the electrical systems controller in the same manner.

(also discussed elsewhere).

Especially important in mobile systems, but also as an indicator of cost and inconvenience of some stationary ones, are the energy density, say kwh/kg, and the rate at which the energy can be extracted, say kw/kg.

A good fairly recent and readable review of energy storage systems is given by Kalzhammer (1979). Other more specific references will be associated with specific topics. But before turning to specific devices, it is useful to develop some simple economic ideas.

9.3 Energy Storage Cycles and Costs

An energy storage module will cost some amount C_1 per unit of energy stored, say per kilowatt-hour of electricity. This is quite different from the unit cost C_2 of storing energy in it. A simple battery system makes a good example to develop the relationship between these and other quantities.

Consider a car battery: 12 volt, 60 amp-hr, giving 1.2 kwhr, 4.3 MJ, at a cost of about $24 wholesale. That determines the cost C_1, here $20/kwh of storage capacity. Suppose now the system is to be cycled by a fraction f of its total capacity in each period of duration T, with a cycle efficiency η. Suppose also that it operates for N such cycles, then must be replaced, and that the cost of money is i per period (in the same units as T). The capitalization needed for this is

$$C_1\left\{1 + [(1 + i)^{NT} - 1]^{-1}\right\} \text{ \$/kwh storage} \quad , \qquad (1)$$

where the first term represents the initial investment, and the second represents the investment necessary to replace it every NT units of time.

The average power output is $\eta f/T$. In addition, auxilliary equipment must be supplied for charging and discharging, voltage and frequency conversion, and other purposes; that equipment can be thought of as costing a certain amount $\$K_1$/kw. With these simple approximations, we find the total capital cost to be

$$K_2 = \frac{C_1\ T(1+i)^{NT}}{\eta f[(1+i)^{NT}-1]} + K_1 \quad \$/\text{kw of output} \quad . \tag{2}$$

Consider two limits. For iNT small, which means that the device wears out much faster than money grows, $K_2 \approx (C_1/\eta f i N) + K_1$, showing the importance of many operating cycles. For $iNT \gg 1$, which means the device lasts a very long time, $K_2 \approx (TC_1/\eta f) + K_1$, showing the economic benefit of short cycles. In the battery example, let $\eta = 0.7$, $f = 0.2$, $i = (0.15/8760)$ per hour, $N = 1000$ cycles, $T = 24$ hrs. Then $iNT = 0.4$, an intermediate case, and $K_2 = \$(10{,}200 + K_1)$/kw.

Cost of the delivered energy, based on this capitalization, is just

$$C_2 = K_2\ i = \frac{C_1 iT(1+i)^{NT}}{\eta f[(1+i)^{NT}-1]} + K_1\ i \quad \$/\text{kwh} \quad . \tag{3}$$

Both C_1 and C_2 have the same units, but the former refers to storage capacity, the latter to delivered energy. If we neglect the input-output equipment K_1, this car battery delivers energy at a cost of \$0.175/kwh.

9.4 Batteries

The example of the previous section has already introduced this topic. The principal proposed applications of batteries are to electric vehicle propulsion, and electric power systems. Table 9,1 shows the status of development of advanced battery types in late 1979. The \$70-80/kwh cost for lead-acid batteries probably includes an allowance for their limited draw-down capability; note that for C_1 = \$20/kwh, f = 0.2 as the previous example, C_1/f = \$100/kwh.

Consider now electric vehicles. Even improved lead-acid batteries will not suffice; even now they strain the availability of lead, are not properly suited to the task (beside the fact that these batteries have low energy/kg and power/kg ratios, and the chemical cycles tend to degrade the electrodes physically). The limitations of all these batteries is apparent as we note that gasoline stores about 100 times the energy density of any of them.

Moderating this disadvantage somewhat are the greater efficiency of electric systems, and the inefficiency of conventional gasoline automobiles, especially as they almost always operate under light load. The electric systems shut off when stopped, and can in some designs incorporate regenerative braking, whereby the drive motor acts as a generator to return some of the vehicle energy to the battery. An overall efficiency of delivering stored energy to the wheels of 60 - 70% may be practical using modern solid state control systems. A pure gasoline engine can be designed for about 30% efficiency but the engine rarely does that well. The average is more like 10-15%. In general, the electric motors will be slightly lighter than the gasoline engine and its auxiliary equipment, but the difference is small compared to the weight of batteries. Thus the weight disadvantage of the battery system turns out to be a factor 15-20, consisting of the energy storage disadvantage (a factor of 100) moderated by (perhaps optimistic) increased efficiency (a factor of 5-7).

This still sizable number implies that electric vehicles will be heavy and have short range. A factor of two improvement over lead-acid batteries would, in the opinion of many, make commuter cars attractive, with a range of (say) 50 miles. The cost of electricity for operation is less than that of gasoline: 5¢/kwh electricity is $14/million BTU, or $1.75/gallon, but the higher efficiency of the electric system brings the equivalent cost well below $1.00/gallon.

The electric vehicle itself will still cost more, probably $1500-2000 per vehicle, representing principally the cost of the battery system. But ameliorating that disadvantage:

- Far fewer parts to break down or maintain: no starter, spark plugs, distributor, carburetor (or fuel injectors) fuel pump, pistons, valves, water pumps, radiator, muffler, oil filter, or pollution control devices.

- Lower overall emissions from the entire energy system. Pollution control is applied at the electric generating plant, where controls are much better than on a multitude of small engines, most of them badly maintained.

Many advantages of both systems (and some disadvantages) are found in the concept of hybrid vehicles. A small optimally-sized combustion engine provides just enough power for normal steady operation, plus a little extra to keep the battery charged. The battery is charged either from the power grid (i.e. at home in its garage) or from the engine while moving. The engine is designed to run in its most efficient and least-polluting mode, at or near a constant speed. For the average 1980's car, perhaps 30 horsepower (22 kw) would suffice. The load of batteries would be much smaller, perhaps capable of giving the vehicle a 10-20 mile range. Operating strategy would be:

- For short Trips, operate as much as possible on batteries, using energy stored from the power grid.

- For long trips, operate on the combustion engine, using the batteries for acceleration.

The Department of Energy supports research and development on systems of this kind, via the Electric Hybrid Vehicle Research, Development and Demonstration Act (PL 94-413) of 1976 and the Electric and Hybrid Vehicle Program Quarterly Report recorded the progress. Early 1980's estimates of such vehicles on U.S. roads in the year 2000 ranged from 2 to 20 million, depending on oil prices, developmental subsidies and other factors.

Depending on the manner of use, 10 million electric vehicles could save 0.4 million barrels of oil per day, if the energy is supplied by nuclear or coal-powered electric grids. Most of that oil might also be saved with hybrid vehicles, because much of the energy would still come from the electric utility system, and the small on-board engine would run efficiently.

Turning now to electric utility systems, we see a different set of trade-offs. Weight and technical complexity are not as important as before, but long life and reliability become more important.

A report prepared by the Electric Power Research Institute's UBOAT group (EPRI 1983) gives the following specification for substantial utility application (in a 20 MW, 100 MWhr capacity system):

C_1 = \$80/kwh

N = 7500 cycles

T = 24 hour cycle time

K = \$115/kw

f = 0.8

η = 0.65

Suppose i = 15%/y ($=1.71 \times 10^{-5}$/hr). Then Eq. (3) gives an incremental storage cost of 6.8¢/kwh, almost all of which comes from the cost of the batteries. If the batteries had only 2500 useful cycles, the cost would rise to about 10¢/kwh. Such a storage system also provides the equivalent of spinning reserve (but more expensively than pumped hydro if it is available).

Another report of EPRI (EPRI 1982) dealing with customer-side industrial application adopts a baseline battery cost of \$212/kwh dc, plus variations both up and down, and correspondingly higher costs for other items. That might be attractive to some users to eliminate high peak demand charges imposed by the electric utility, but probably not for major adoption by the utility companies themselves.

What is the present state of the battery art? Of the various types described in Table 9.1, sodium-sulfur uses relatively abundant materials, and progress in its development is good. Early 1980's difficulties with their development were cracking of the beta-alumina ceramic electrolyte tube and insulating seals, together with corrosion at the sulfur electrode, leading to shortened life. The General Electric Company reported (EPRI 1982b) that their C-45 cells incorporating modified beta-alumina and other improvements had largely overcome these difficulties, and would sell for \$45-\$60/kwh in quantity (1981 dollars). In the referenced report, G.E. stated that the new cells were undergoing extended life test.

A $50/kwh figure applied to our example above would lead to an incremental cost of electricity storage of about 4.6¢/kwh. This number compares favorably with the fuel cost alone of oil or gas for peak generation: at $6.00/GJ in 40% thermal efficiency plants this is 5.4c/kwh; on the other hand, the cost of coal at $2.00/GJ in the U.S. corresponds to only 1.75¢/kwh. However, if cheap baseload power is available, the storage can replace the plant as well as the fuel. For example, night-time nuclear power at a marginal fuel cycle cost of 1.5¢/kwh added to the 4.6¢/kwh of storage wins over any present peaking system.

Storage would be necessary for large installations of solar or wind power; the costs are higher. For example, electricity from a photovoltaic (PV) installation at $1.00/$W_p$ total system cost, at 15% interest rate, costs about 8¢/kwh. Wind at $1000/kwe nameplate capacity and 0.4 load factor (optimistic numbers) corresponds to 4.4¢/kwh. The sums of these plus our prospective battery storage (12.6¢ or 9.0¢ /kwh respectively, assuming diurnal cycles) compete with peaking power, but are a long way from replacing coal or nuclear baseload if the latter are permitted on the system.

How much storage might be required? A very simple calculation shows fairly accurately what could be accomplished. See Figure 9.1. A typical U.S. daily electric power demand looks approximately like a constant average, modulated 30% above and below by a sine curve with a peak at 3 pm, plus higher harmonics and week-end effects. These higher order and weekend effects can be ignored if a 20% $\pm$ error is allowed, good enough for this assessment.

The entire energy content lying above the mean in this case is 9.6% of the daily total, some 5×10^{13} joules or 1.49×10^{7} kwh, if the daily average is 6.1 GWe. The storage system would have to deliver 1.8 GWe peak, rising from and decreasing to zero over the 12-hour period.

Prospects for batteries providing a substantial part of such service appear bright. The generated alternating current must be rectified for dc storage, then reclaimed and reconstituted as ac, a task prohibitively expensive a generation ago, but now quite feasible with large solid state electric ac-dc and dc-ac converters, at high efficiency. A 30 megawatt-hour demonstration system was connected to the Wolverine Power Corporation grid in Northern Michigan in 1981, and a smaller system is connected to the New Jersey Public Service Electric and Gas Company (EPRI 1980).

The effects of a hypothetical but interesting solar PV system can be easily calculated. Suppose the PV system produces power corresponding to the upper half-size curve of power demand, but off-set in phase by three hours. The remaining misfit area must be supplied by storage (from the cheap off-peak baseload power). This total amount of energy corresponds to only 2.2% of the daily energy demand. In this 6.1 GWe scenario, some 3.2×10^6 kwh would need to be generated over a 7 1/2 hour period, at a maximum rate of about 1.2 GWe.

This simple example is not meant to show that PV systems could in fact take over that much of the load; such a system would require much spinning reserve and/or rapidly accessible storage in order to handle the vagaries of sunshine. What it does show is that the degree of penetration of storage and nondispatchable sources such as PV or wind affects other system components, and that where photovoltaic systems are most useful additions to utility grids, they tend to reduce the value of additions of electrical storage systems, and vice versa. Provided cheap night-time baseload power is available, the two are substitutes for each other. The situation would reverse if PV capacity increased to provide a high proportion of total grid generation. This conclusion has been remarked upon by Smith (1981) and complicates the development of both renewable and storage systems, the former probably more than the latter. As utility storage systems become available and economically attractive, so do cheap baseload systems become more attractive, and the market for all peaking and nondispatchable power systems declines.

9.5 Flywheels

Until very recently, energy storage by flywheels was limited to particular and usually small applications: on automotive crankshafts, to smooth the operation, for instance. Several features limited these applications:

1. The relatively low yield strength of most cast materials, such as steel.

2. Risk of severe damage if the unit fails structurally.

3. Windage and bearing friction energy losses.

4. Electrical and mechanical losses associated with the drive and energy extraction.

New technologies now ameliorate some of these difficulties: higher strength materials that fail by unraveling into relatively harmless fibers, magnetic bearings, operation in vacuum, and improved elecrric drive/extraction techniques.

It is easy and instructive to derive some simple criteria about flywheels. Figure 9.2 shows two configurations, both highly stylized; the radical difference in design will be used to show the importance of the tensile stress of the structural material.

Consider the rim design 1, where in first approximation the entire mass m can be considered to be at radius R; the moment of inertia $I = mR^2$, and the stored energy is

$$E = mR^2\omega^2/2 \tag{4}$$

at an angular rotation frequency ω. The total outward bursting force is $mR\omega^2$, which must be resisted by tensile forces in the rim. This tensile force is

$$T = mR\omega^2/2\pi = A\,\sigma \tag{5}$$

where the second equality means that the cross section of the rim is A and its working stress is σ pascals.

Eliminating $m\omega^2$ between the two equations, we find

$$E = (2\pi\ RA)\ \sigma/2 = \sigma\ (\text{volume of rim})/2. \tag{6}$$

Contrary to some naive beliefs, the maximum stored energy is independent of the mass (if the rotational frequency can be chosen to suit), and depends only on the strength of the material. In this rim design, the spokes and hub serve only to hold the flywheel in place, and transmit torque to and from the shaft; it is like a bicycle wheel.

Now consider the spoke design in Figure 8.2. In the approximation that the hub is small and there is no rim, it can just as easily be shown that

$$E = \sigma\ (\text{volume of spokes})/3, \tag{7}$$

limited by tensile stress at the hub. Thus again, the most important parameter is tensile strength, and we can conclude that in more realistic designs this will continue to be the case.

Cost is also important, and here some of the modern high-strength plastic fibers (e.g. Dupont's Kevlar) have both high strength per pound and moderate cost; if a spool of this material fails by overstressing, it tends to disintegrate as small threads and fuzz rather than as large destructive pieces.

Even with a working stress of 10^9 pa (147,000 psi), we can expect 5×10^8 joules storage per meter^3 of rim. However, the rotational speed will generally be very high. If ρ is the density of the material, we have for the rim configuration

$$\omega^2 = \sigma/R^2\rho \tag{8}$$

For $\rho = 10^3$ kg/m^3 corresponding to dense plastics and R = 0.5 m, we find $\omega = 2 \times 10^3$, or 19,000 rpm, an impressive rotational rate for something a meter in diameter.

The discussion so far has treated some of the problems and opportunities associated with the first two features mentioned at the start of this section. The high speeds show the importance of the others: windage and bearing friction losses. The windage is reduced by operating the rotor in a vacuum of about 10^{-2} torr, near the limit of what can be obtained with mechanical vacuum pumps.

Mechanical bearings have friction losses, especially in vacuum, where no thin film of air is present to act as a lubricant. The solution here is to suspend the rotor on magnetic bearings. Strong permanent magnets made with recently developed cobalt alloys find application here; five kilograms of magnet can support one or two tons of rotor; the hanging rotor tends to be unstable when so supported, but low-power electromagnetic servo loops can stabilize the system.

With everything now in vacuum, how is the system to be driven and power extracted? A brushless motor-generator can be mounted integrally with the flywheel in the vacuum; it has a rotating magnetic field that reacts against a stationary armature winding to produce torque. Useful flywheels would be high-technology items.

Millner (1979) gives an optimistic but informative and readable summary of the situation as of late 1979. For 25 kwh of residential storage, he estimates a 1980 cost of $500/kwh, and eventually $200 - $400/kwh; that is expensive compared to the cost of batteries, mentioned in Section 9.4 or the costs of $50-$100 for advanced long life batteries described in Table 9.1 This high cost could be justified if the cycle time T is short, say a few hours at most. The number of cycles in the useful life would be very high, greater than could be achieved with presently envisaged batteries.

Except for conversion losses of perhaps 25%, all the energy is available for electric or mechanical work. All these considerations suggest applications to short-haul public or commercial transport. A flywheel storage of 200 megajoules would have the total energy equivalent of 1.3 liters of gasoline, equivalent in effectiveness to several times that amount delivered to a lower-efficiency internal combustion engine. That amount of flywheel energy could be stored in one or two cubic meters and would be attractive for trolley-buses operating beyond the installed grid. The May 1981 issue of Industrial Research and Development, pp. 99 et seq. describes several recent advances, including flywheels for trolley buses;

they resemble fairly closely what has been derived here from simple considerations.

It seems fairly clear that flywheels will have very modest effect on global energy needs and patterns.

9.6 Hydropower and Compressed Air as Storage

The material of this section complements that of Chapter 8. Hydropower's availability and capability of rapid startup make it a very desirable addition to electric utility systems. Hydropower systems fall in two broad classes: one-way flow out of reservoirs through turbine-generators; and pumped storage, where specially designed waterwheels can act as pumps or turbines and the coupled generators can also run as motors. Thus at times of low electric demand, the systems run as motors and pumps, taking base-load power from the utility grid to pump water from a lower to a higher elevation. At times of peak demand, the system runs the other way, as a more-or-less conventional hydropower system. About 25 GW of this are planned to be installed by the mid-1980's.

Much of the cost of a large hydropower system is in foregone land use, the dam itself (or reservoir, for pumped storage) and other items whose cost does not depend very much on the rate of filling or emptying of the system (e.g. locks in a navigable river). Thus, hydropower systems, just like other energy storage schemes, work most cheaply if the filling and emptying cycle is short: non-flowing stored water increases capital cost, but not revenue. Pumped storage systems are then designed for daily (sometimes weekly) charge and discharge cycles. Natural rivers flow seasonally, so weeks, even months, of storage must be provided; thus the ratio (capital in the storage system)/(capital in the generating system) is higher for natural systems than for pumped storage ones, unless the pumped reservoir is exceptionally expensive, say as excavated caves.

These features of hydropower make it an attractive complement both to nondispatchable sources and to full-time baseload plants, although the schedule of demand will differ in the various cases. Whether it is natural hydropower or pumped storage is mainly a matter of geography, economics and environmental impact: if generators at a natural dam run only during periods of peak demand, their amortized cost is higher, a situation that applies to pumped hydro systems just as well. About the year 1940, Grand Coulee development in Washington State received its name and location because it was envisaged in part as a large seasonal pumped storage scheme.

Natural dams are liable to be much more important than pumped hydro, as a global average. The sites for pumped hydro, while regionally important, seem too few to dominate, and such installations generally cannot serve any other purpose, such as irrigation on demand, recreation or fish production.

Because of its availability on a multiplicity of time scales and because it can fulfill the role of spinning reserve, hydropower can be an excellent complement to non-dispatchable renewable sources. Consider for example wind/hydro systems; Sørenson (1981) outlines the possibilities well. He describes the results of a study made of the feasibility of combining Danish windpower and Norwegian hydropower. Data from three Danish wind years (good 1967, bad 1963 and typical 1961) with an average Norwegian hydro year were used to show that the maximum annual deviations in water level caused by the power exchange with the wind system were +11% and -5%. Those deviations are small compared with the natural variations caused by differences in annual precipitation.

Regarding this complementarity, we quote from Sørensen's excellent article directly.

> More ambitious wind-hydro systems have been proposed in California and in Scandinavia. The appealing feature of such schemes is that wind-energy converters embedded in a hydro system of sufficient size may effectively obtain full capacity credit at a very low expense. This hinges on a crucial feature of the regions under consideration for such installations: the average seasonal variation in wind energy is to a considerable extent positively correlated with variations in load and negatively correlated with variations in the water level of the hydro reservoirs. For this reason the impact on the water level in the reservoirs is on average very modest. If anything, the rise in water level tends to occur during the winter, when the wind power is highest and the water reservoirs are being emptied, whereas deficits in wind power leading to withdrawal of water from the reservoirs usually occur in summer, after the reservoirs have been filled by the melting of snow during the spring. Superimposed on these trends is a large amount of borrowing and repaying between the wind and hydro systems on a shorter time scale, ranging from a few hours to a few weeks.
>
> The addition of wind-energy converters to a hydro system with sufficient reservoir capacity may require reinforcement of transmission lines and increased hydro-turbine capacity, but does not require any enlargement of the two main components of the hydro installations: dams and reservoirs. In this sense the wind-energy converters may be given full capacity credit, although strictly speaking the increase in turbine capacity at the hydro installations carries a penalty in power rating. The point is that the power rating is not an adequate measure of capacity either for wind or for hydro installations. For wind turbines the proper measure of capacity may be the average power output at a given site, while for hydro installations it may be the average power of water flow over the year--neither of which is strongly correlated with the power rating of the generators.

Obtaining capacity credit for non-dispatchable systems increases their value very substantially, because it converts them from being mainly fuel savers to fuel-plus-plant savers. More on this later.

If pumped hydro with (usually expensive) underground reservoirs are contemplated, the terrain and the electric power system should also be studied to see if compressed air is feasible. The density of overburden rock is about 2.5 that of water, so a gas pressure equal to 40% of the overburden pressure at any particular depth corresponds to a static hydraulic head that high. A principle disadvantage is the loss of adiabatic heat in intercoolers during compression.

A well-publicized and apparently successful compressed air system has been operating at Huntorf, West Germany (see Figure 9.3). As with pumped hydro storage, the motor/generator switches roles on demand. Working as a motor, it pumps air at 7000 kpa (1000 psi) into 300,000 m^3 cavities leached in an underground salt dome. The product is 2.1×10^{12} joules. When the system runs as a generator, fuel burned in the expanding air heats it to operate gas turbines. This way, 290 megawatts can be generated for two hours, again a total of 2.1×10^{12} joules. Burning the fuel makes up the energy losses.

Circumstances favorable to compressed air storage seem less common than for hydropower.

9.7 Hydrogen

Hydrogen has been proposed as the transportable fuel of the future to replace petroleum and natural gas as their supplies dwindle. It could be made from water (and in a hydrogen economy would have to be); it forms no CO_2, therefore contributes nothing to the global greenhouse problem; it forms no polluting hydrocarbons; if burned in oxygen or reacted at low temperature in a fuel cell it produces no NO_x. Its heat of combustion is 140 MJ/kg, compared with 50 MJ/kg for gasoline and about 27 MJ/kg for good bituminous coal.

It also has these properties: combustion range, volume percent in air is 4-75% (compared to 5.3-15% for methane); combustion range volume percent in oxygen is 4-96% (5-61% for methane); detonation range in air is 18-59% (6.3-13.5% for methane); minimum ignition energy in air is 0.02 mJ (compared to 0.29 mJ for methane). Its boiling point is 20.3°K at one atmosphere pressure, and its liquid density is 0.0704 gm/cm^3. Some of these properties make it difficult and hazardous to use.

In 1980 in the U.S. about 0.7 quads of hydrogen were produced, nearly all of it for industrial use by reforming methane, a process irrelevant in the context of this section. The most promising non-fossil scheme is high temperature electrolysis of water; at 500°C, for example, the dissociation potential is reduced, and both heat and electric power from a large thermal power plant could be matched to the task. It has even been suggested that coal in plentiful supply would be used for fuel, to make transportable hydrogen, then methane and/or methanol to replace such fuels no longer available elsewhere; but coal gasification and/or liquefaction plants appear more likely, and all such schemes do nothing to ameliorate the CO_2-greenhouse problem.

Hydrogen will be expensive. Electric energy at $0.05/kwh used at 70% electrolytic conversion efficiency corresponds to $19.80/GJ or $109/barrel of petroleum.

Other schemes are or have been studied. A complicated thermal method involving a series of chemical reactions at temperatures only up to 500°C has been proposed, but the practicality is uncertain. More speculative but intriguing is the idea of photoelectron dissociation of water. Almost half the solar energy consists of photons with high enough energy to dissociate water, and the search proceeds for some arrangement of water and either soluble additives or immersed surfaces that provide conditions whereby the photons are absorbed into appropriate electronic states and not just as heat. Even if the search is successful, hydrogen will still be expensive.

Storing and transporting hydrogen also brings problems in addition to combustion and explosion hazards already mentioned. Consisting of small active atoms, it diffuses into many metals, and tends to concentrate at grain boundaries. There it weakens the metal and lowers its ductility, causing what is known as hydrogen embrittlement. Many ordinary steels exhibit this behavior, so pipes to transport or contain high pressure hydrogen must be specially made.

This same diffusive tendancy can be made useful. Many metals form hydrides at room temperature or above, some with as much as one hydrogen atom per metal atom, resulting in a hydrogen atom density higher than in liquid hydrogen. The penalties are: much increased weight; the exothermic hydride-forming reaction requires the storage system to be cooled while being charged, and heated while being discharged; contaminants such as carbon monoxide or sulfur dioxide can deactivate some metal hydrides.

Table 9.2 shows properties of some hydrides, compared to batteries and gasoline. Conversion efficiency and net energy density refer to present or contemplated practice, and include allowance for storage equipment.

Liquid hydrogen is probably too hazardous for general use in automobiles, but trials have been made. The Los Alamos Scientific Laboratory has done tests on a 1979 Buick Sedan, with a liquid hydrogen storage and fueling system developed in Germany (Stewart 1980). The engine needed little modification, gave good mileage, had too much heat leakage into the liquid hydrogen tank (correctible) and excessive NO_x emissions (not easy to correct).

Liquid hydrogen might be better as a fuel for large airplanes, where low weight is very valuable, but the volume disadvantage (compared with kerosine) may not be serious; additionally, the hydrogen could be handled only by trained employees.

In stationary applications, hydrogen gas could replace natural gas in many industrial applications, and probably could be distributed safely as far as sub-stations, but probably not to individual residences. Thus it has been proposed to generate electricity in local district fuel cells, with less transmission energy loss than is associated with electric power distribution. That idea appears unattractive at present, and perhaps also later. It conflicts with development of dispersed power generation, with power transmission in various directions through the power grid. A hydrogen distribution system could run in one directly only.

9.8 Heat and Cold

The energy density is low, but the storage medium often is not expensive, or is part of some structure and would have been there anyway. Thus storing heat most naturally applies to end-use: off-peak water heating, thermal storage walls or ceilings in houses, the dirt in a greenhouse, for example.

Many of these topics have been touched on elsewhere, for example in Chapter 4 on end-use, and electric system integration in the next sections. Successful application depends on minimizing heat loss, which translates to having good insulation, and keeping air infiltration losses to the minimum level consistent with health. Regarding this latter point, it is not often recognized that air pollution indoors, where most people spend most of their time, usually exceeds outdoor air pollution. The pollution arises from activities in the home (e.g., smoke, vapors), from materials used there (e.g., formaldehyde), radon diffusing fromthe ground below, even from the energy storage structures themselves (e.g., mold in rock-bins). Inexpensive air-to-air heat exchangers in exterior walls ameliorate many of these difficulties.

Storing high-quality heat (e.g. hot water and steam in steel pressure vessels) has been tried, for example at the Berlin-Charlottenberg generating plant in the 1920's; but the idea is presently economically unattractive and promises to continue so.

One can store cold as well as heat. Cutting ice from winter ponds and storing it in underground ice-houses for summer use was common 50-100 years ago. In a modern variation, (ACES, 1980; Abbatiello et al 1981; Baxter 1981) a heat pump freezes water into ice in a large insulated basement bin during the winter, using the extracted heat to warm the house. Then the ice cools the house in the summer. The scheme was too expensive (in the early 1980's), but may be more attractive by 1990 as heat pumps become more reliable and (relatively) inexpensive, if fuel oil costs increase to $2.00 per gallon.

9.9 Electric Power System Integration: Initial Remarks

Here we consider how both fossil and nonfossil energy sources can best be combined in an electric utility system. This interest in electric systems in our work arises because (a) many of the nonfossil supply options are electric; (b) the electric energy fraction of total energy use grows steadily worldwide. We are particularly interested in what happens with high penetration of "nondispatchable" energy sources, such as solar photovoltaic and wind; they pose novel problems as well as offering new opportunities. The sections on wind, photovoltaic, and storage systems in chapter 8 and earlier sections here touched on them briefly.

We cannot here review in detail the vast literature on how electric power systems are arranged so as to call on various units at different locations and times to match present and anticipated demand, nor do we need to. Our interest is mainly on the effect of new options, on both supply and demand. We will conclude that substantial amounts of wind or photovoltaic power--perhaps 20 or 30 percent of the system capacity--can be incorporated into the utility system, provided some other features that are desirable in their own right are also incorporated. Chief among these are energy storage (e.g., batteries and/or pumped hydro) and load management (e.g. short-term microshedding of interruptible loads). These system developments--storage and management--benefit baseload options such as nuclear power just as well and conceivably even more, because they make off-peak baseload capacity available to meet off-base demands. Thus the very measures that permit extensive penetration of what has customarily been called non-dispatchable power units into the grid also appear to encourage the introduction of the very opposite type of power plants. This is because both non-dispatchable and base load units are very rigid in terms of electric power system operation. The base load units are inflexible because it is very uneconomic to run them at any rate other than full power (and because of that some have not been designed to shift easily from one power level to a different one). The non-dispatchables generate power at a rate totally outside the control of the system's dispatcher. Storage and load management are extremely flexible options and their availability in a power system enhances the level at which rigid options can be introduced, without hindering the system's operational capabilities.

These apparently opposite trends can be reconciled by realizing that <u>both</u> are non-dispatchable, only in different ways: the large baseload units cannot now load-follow to any appreciable extent; storage, load management, peaking units, intermediate-load units etc., in this sense all serve the same purpose--to match the generation and the anticipated load. To be sure, the output mismatches occur for different reasons, with different patterns of fluctuations, and in different parts of the system--the wind dropped, or everyone turned on their television sets--but the need to match provision and use is the same in all cases.

One can then ask which direction, or combination of directions is best. That depends on a host of other important considerations: Cost and expected performance of each particular type of unit; perceived environmental impact: whether small units can be economically added in order to match long-term load growth as closely as possible; size of the grid system; social preference for or against any particular type of unit. Some of those advantages and disadvantages have been discussed elsewhere; many of the others are system-specific, hence, not within our present scope.

Despite our intent not to revisit system analysis in general, we offer a brief review of selected topics, in order to establish a basis for the later discussion.

9.10 Demand and Supply Fluctuations, Characteristic Times, and Responses

A useful perspective on systems integration follows from understanding how demand and supply vary both in time and at various levels of demand (i.e., local, subdivision, town, region). Figure 9.4 deals with a hypothetical electric utility system of a few GW total size; in particular it illustrates how the demand (solid lines) might appear, with a nondispatchable source added (dotted lines). For convenience in discussion, let it be wind and, for the moment, assume (unrealistically) that all the windmachines are in one location.

Consider the top diagram of Figure 9.4, where the solid lines show events over one hour. At the 1-kw single residence level, lights get turned on and off, the refrigerator runs, then stops, etc., and we see large fluctuations. At the 100-kw subdivision level, many of those fluctuations are smoothed out, but others may appear, like the peak at 45 minutes when people turned their lights on during a solar eclipse. At the 10-MW level, the demand is further smoothed, but the eclipse (or some other) phenomenon appears here, too. Finally at the 1-GW regional level, the demand is almost smooth, affected somewhat by a few regionally correlated events.

Now consider the behavior of windmachines during this hour (the dotted lines). The figure shows them providing a relatively large fraction (≈30%) of the average demand. For convenience in the discussion, this fraction is administratively allocated among all the users (so that the average wind/demand remains approximately constant throughout the system). The wind blows variably, and not at all sometimes. Most important, this variability is not appreciably diminished as we proceed toward higher levels of integration, from the 1-kw to the 1-GW level; recall that all the windmachines were at the same place. Thus a "noise" appears on the whole system that did not exist before, and the system must cope with this, if the benefits of the wind generation are to be captured.

Next, consider the one day time scale. In the 1-kw house, people go to bed, go out, cook supper, etc. At the subdivision level, these cancel only partly, and the diurnal power demand starts to show through. In this example, we see also a 24-hour power load, because this subdivision included a small industry that operates around the clock, e.g., an electric heater life-test laboratory. At the town level, the average daily pattern dominates, and even more so at the 1-GW regional level. Again, the wind blows, more during that afternoon, but with some calm periods; and, again, this behavior runs through the entire system.

The weekly variation shows daily regularity even at the 1-kw level, but it is noisy, as someone relaxes on Friday but stays up most of the night, cooks a banquet on Saturday, etc. At the 100-kw level and above, the familiar weekly pattern emerges (see also Figure 9.1).

But again, the wind fluctuations penetrate the entire system, and we see no daily pattern, except for a tendency to blow in the afternoons and, by chance, not on Friday.

The one-year picture cannot be so easily illustrated: 52 one-week experiences look on this scale like average levels with noise, although the weekly pattern of demand is there in fact. At the 1-GW level, we see the annual variation of demand (it is a summer-peaking system), and the range of weekly and daily fluctuations. Again, the wind fluctuations penetrate the system from lowest to highest level of aggregation, although they cannot be shown here. But we see that the wind tends to blow well from March to mid-December, and not much in the winter; that happens in Hawaii.

How the combination of the electric utility system and its customers can respond to these and other loads and fluctuations is clear if we spectrum-analyze these data. Figure 9.5 shows how they would appear at the four aggregation levels, but now the entire frequency spectrum is shown (very nonlinearly) from steady operation over the life of the society, to one-second variations.

It is easiest to start at the 1-GW (most aggregated) level. The system never shuts down (the infinite-time component), has a one-year component corresponding to the summer peaking, but also small spectral content up to several times that frequency, because the summer-winter variation is not perfectly sinusoidal. The weekly spectrum is notable, corresponding to reduced demand on Saturday and Sunday; it has distinct harmonics because the fluctuation looks like 5 days on, 2 days off. The diurnal signal is very strong, and so are its first few harmonics, corresponding to daily peaks and valleys. But at higher frequency, there is very little from the demand side. The whole supply side is not shown, but if one large unit were to stop, we would have a high-frequency transient, not easily shown in this figure; the spinning reserve, dynamic control, etc., are built into the system to take care of such events, of which more anon.

At lower levels of aggregation, the principal changes are a broadening of the peaks and spectral content between them; the spectrum becomes more noisy. At the 1-kw level, it has much noise, extending into periods smaller than one hour, a relatively high-frequency region that is almost without contents at the 1-GW level.

Our wind spectrum has two main frequency bands: one year, with some harmonics and variation, corresponding to the annual changes; and diurnal with variation. Also we have higher frequency noise, corresponding to the wind's well-known fickleness. All this wind spectrum penetrates the entire system.

A main goal of system integration, and our goal here, is to reduce unwanted peaks as far as possible and either to cope with or eliminate this spectral noise in the system. Many options available on different time scales are placed on Figure 9.5 on approximately their appropriate ranges. Several may be available to cover any one time period.

How any specific utility system should best respond to fluctuations over different times can only be determined by specific detailed calculations. That would involve performing joint statistical and analytic computations of the real electric demand and wind data over time, data shown allegorically in Figure 9.4. But even without such calculations, we can identify many of the principal trends and possibilities from Figure 9.5.

As an example, consider these hypothetical wind data. The presence and operation of the wind machines allows the total system to deliver any given output more reliably than before because the wind may be blowing when some other generator is forced to shut down. Thus for a given level of reliability, a kilowatt of wind nameplate capacity can displace some part of the conventional system. More precisely, not so many new conventional units need to be added to a growing system, or provided as replacements for obsolete units. However, the substitution is usually much less than a one-for-one tradeoff because the wind may not be blowing when needed. Thus a so-called "capacity credit" exists whose real value requires determining how the system load curve, as calculated without non-dispatchable sources, is modified by their presence, under the assumption that the effect of these sources is to modify the output of the rest of the generating system. That is, by treating both the output of various conventional generators in response to demand—shown by the load duration curve in Fig. 9.6 —and their outages as independent random variables, one can calculate the probability that demand exceeds installed capacity minus plant outages as a function of demand.

This brings us to the threshold of several topics, particularly loss-of-load probability (LOLP) and spinning reserve, that have many important complications, the resolution of which depends very much on what degrees of performance and reliability are desired.

In the usual simplified analyses recapitulated here, the data of Figure 9.6 are recast in the form of Figure 9.7, as Curve A of that figure. A standard measure of system reliability is now set by technical, economic and sociopolitical considerations; that is the LOLP, to which the system is supposed to conform. Curve B illustrates the point that by adding non-dispatchable units (in these paragraphs we mean wind and photovoltaic units, that have much impaired predictable availability) to the grid, one can achieve the same LOLP with fewer conventional generators. The actual capacity credit depends sensitively on the amount and type of conventional generation which is displaced; illustrative data are presented in the next section.*

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* But as explained earlier in this paragraph, the capacity credit refers to long run imputed cost saving, because some future additions will not be required.

From the perspective of determining whether there is a feasible maximum penetration of non-dispatchable sources, the important point is that the capturable capacity credit decreases as the level of penetration of the non-dispatchable sources increases for two reasons: (1) With increasing penetration, the output of the non-dispatchables starts replacing that of the less costly conventional generators (e.g., baseload nuclear); this could also be envisaged as the solar economics getting worse, rather than a loss of capacity credit. (2) The larger resulting fluctuations in generating capacity require the addition of more reliable back-up power to achieve the same LOLP as previously specified for the system. That is, the system must now be able to accommodate the loss of the largest plant, the maximum probable increase in load, and simultaneously, the maximum probable decrease in non-dispatchable output. More precisely, adding non-dispatchable sources to a grid increases the requirements for both load-following and spinning reserve capacity. These impacts have become the subject of an increasing literature, some of which is discussed in the next section. However, we can already gain insight into this problem and possible remedies by reference to Figure 9.4. Thus, spinning reserve is responsive to events on the time scale of roughly 0 - 100 seconds, and in Figure 9.5 this corresponds to the high frequency part of the spectrum. If the non-dispatchable sources are co-located, their intermittent output in this part of the spectrum penetrates the system, and it is intuitively clear that spinning reserve must be added on virtually a one-for-one basis with non-dispatchable capacity to maintain a given level of system reliability.

Having written this, we now insert some caveats. First, the LOLP is a planning concept, not an operating parameter; real systems are much more complicated. Second, the emphasis here on the importance of spinning reserve, the implied importance of holding frequency very constant, of exact cycle counts every few minutes, etc. is a conventional U.S. electric system view. Such precise standards do not exist in most other places, and good arguments have been made that they should not, perhaps not even in the U.S. Such expensive precision is not necessary for almost all end-uses for which electric utility systems are built; the few exceptions can be handled in other ways. If the standards are moderately relaxed, the spinning reserve requirements decrease.

Several other ways (besides relaxing unnecessary precision) exist to reduce both spinning reserve and the load-following penalty. One is to disperse the non-dispatchable sources since this tends to even out the effects of microclimates and short-term fluctuations. In the language of Figure 9.5, the steady outputs add directly, but to the extent that outputs of the non-dispatchable sources are uncorrelated in Figure 9.4, the time fluctuations add like noise power, and the effective signal/noise ratio increases. Other means to this end include the addition of short-term storage to the grid and various "homeostatic control" load-management options; e.g., microshedding and power energy rescheduling. We discuss some of the latter techniques in Section 9.11; for a fuller treatment of homeostatic control and its impact on the integration of solar electric technologies see (Tabors 1981). As to storage options, consider; e.g., batteries. At \$200/KWh for the complete installation (see Section 9.4), 300 seconds of battery storage would cost \$200/12 = \$17 per installed kilowatt of wind, a cheap and attractive fix on this time scale.* This would not be an economic option for long outages, but for them we could utilize slower load shedding, hydropower, including pumped storage, peaking turbines, as well as other homeostatic control measures such as spot pricing.

We note that ability to accurately predict wind speed and solar insolations can improve system operation in the sense that the fluctuations in non-dispatchable source output can be handled better. For example, several hours advance warning of a large drop in wind output provides the time required to bring additional steam reserve units up to load, thus reducing the need for additional spinning reserve. This effect is even more relevant in the case of small-scale hydro, where the time lag introduced by the precipitation-runoff process allows more time to predict generation from precipitation data obtained, for example, via satellites using a precipitation-runoff generation model of the hydrologic basins.

9.11 Recent Analyses of Non-Dispatchable Source Integration Issues

Here we briefly review ideas contained in studies at Systems Control, Inc. (SCI 1980), MIT (Tabors et al 1981) and Oak Ridge National Laboratory (Reddoch et al, 1982). The point of view in these studies is similar. However, the analysis of Tabors et al does not include the effect of the

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*We do not propose that batteries could or should charge and discharge on 5-minute time scales, but rather that the arrangements made for longer (e.g., diurnal) storage can at small marginal cost also satisfy these short term needs.

additional spinning reserve and load-following requirement of non-dispatchable source integration which, as we shall see, can be a severe penalty at high penetration levels without innovations in load management.

(a) Capacity and Fuel Credit

Table 9.3 shows the results of adding two levels of photovoltaic generation to a small synthesized utility system as calculated by Tabors et al. (The system capacity for Boston, Miami, and Omaha was about 6500 MW, while Phoenix was 7550 MW). Note the differences: Phoenix is by far the best system match due to high insolation, summer peaking, large mid-day air conditioning load. For small (3.1%) penetration, the capacity credit is 40% of the solar nameplate peak rating, dropping to 34% at 15.9% penetration. On the other hand, Omaha is winter-peaking, a poor match for photovoltaic power.

Note in Table 11.3 that the fuel credit exceeds the capacity credit by about a factor 3. This ratio is in accord with the results of the simple calculation of wind systems (chap. 8) that non-dispatchable units are more fuel-saving than capacity saving, at least with present fuel prices and utility generation mix.

The SCI results are similar in general, but different in detail. For example, for a wind system at Clayton, New Mexico, they calculate the following: 1% nameplate penetration of wind machines can displace 0.46% of the 5000 MW prior system capacity; 10% penetration displaces 4.5%; 30% displaces only 5%.

These results can be expressed in other ways, for example, in terms of the breakeven capital cost of a non-dispatchable system as a function of system penetration. Figure 9.8 shows SCI's calculations for solar PV in Albuquerque NM. These breakeven costs at high penetrations lie near the midrange of our estimates for eventual costs of solar PV (e.g. ≈ $850/kw at 20% penetration, 0.2 effective capacity and 15%/year capital charge rate corresponds to an energy cost of about $18/GJ.)

(b) Taking Account of Load-Following and Spinning Reserve Requirements

The SCI calculations indicate that the addition of non-dispatchable generation to a grid causes an increase in both load-following and spinning reserve requirements that are fairly linear with respect to penetration and very similar for both wind and PV generation. (See Figure 11.9) This is in line with the more qualitative discussions in section 9.10

The impact of this on the economics of non-dispatchable generation is severe at penetrations greater than 1%. For example, at 10% penetration of wind systems, the breakeven capital cost drops from $993/KW to zero when load-following and spinning reserve are considered. These impacts can be partially ameliorated by spatial diversity; e.g., if the wind systems are dispersed at 25 locations within a 500 kilometer range in the SCI scenario, the spinning reserve requirement is reduced from 18% to 14.5%--the requirement without wind systems is 8%--and the allowable capital cost is again positive at $560/KW.

These reports, the SCI in particular, also make several other relevant observations.

. The operating and maintenance costs tend to be exhorbitantly high for small installations, for example, about 20 mills/kwh, in the several kilowatt range. This is due to the lack of on-site maintenance and the cost of providing it on call from some distance away. Systems 10MWe and above are better.

. The majority of outages are not caused by failures in generation, but in transmission and distribution. This leads SCI to suggest locating non-dispatchable units near the load. If improving service reliability is the goal, it is generally cheaper per kilowatt to improve the distribution and transmission.

It should be noted however that these and other studies suffer from several general deficiencies:

. There is no real evaluation of the benefits possible from spatial diversification (analyses based on single systems).

. There is no evaluation of the potential benefits from a diversified mix of non-dispatchable technologies (photovoltaics, solar thermal, different types of wind machines, etc.).

. There is little consideration of the benefits from storage, not only in terms of added capability to support more stochastic generation, but also on the re-optimized dispatch of the rest of the system and in the case of hydro storage, from enhanced regulation of the hydroelectric system.

To phrase the matter slightly differently, the studies usually freeze the generation mix and style of operation in a pattern more suited to the present techno-economic features, then add the non-dispatchable generators without re-optimizing the system as a whole. The general cause for these deficiencies is the fact that including optimization loops for all these issues into the capacity expansion and/or economic dispatch models used in the studies is a very complex task. The treatment of storage in these models, for instance, has been a hot issue long before non-dispatchable generation came into the picture (Castillo Bonet 1983).

Not unrelated to this discussion is the Public Utility Regulatory Policies Act of 1978 (PURPA) and the various incentives for renewable energy, that favor small decentralized systems. It can be reasonably argued that the purpose of it all is to stimulate development of economical energy from renewable sources. But it should also be realized that these incentives can also act to stimulate installation of systems whose main purpose is to take advantage of these incentives. Tabors et al point out how under some interpretations of PURPA, a larcenous supposed small producer could make money by doing essentially nothing: if the small producer is paid the utilities "full avoided cost," this could mean a marginal cost that is considerably higher than the average: but if the utility has only a single rate for selling, based on the average cost, the small producer could in principle get both money and free electricity from the utility company. However, a comprehensive analysis of practice in the New England region shows that the electric utility companies and small producers manage their mutual affairs quite well, to their mutual (and the public) benefit (Davidson 1982).

9.12 A More Holistic View of the Problem

It appears to us that a somewhat different approach to system integration is needed and indeed is developing.* Consider Figure 9.5 once more. Operations

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* Confirmed in discussions with colleagues at the Massachusetts Institute of Technology, summer-fall 1983.

per unit of energy are usually most expensive in the near right corner of the isometric graph, and cheapest in the vicinity of the far left corner--that is, large base-load plants. One can move in the favorable direction via larger units (keeping in mind the diseconomy of scale that can arise if the units become so few that economic advantages of serial production disappear), or via smoothing the system.

Combined utility-customer load management can do much to smooth the short-term fluctuations shown schematically in Figure 9.5, hence reduce the penalty associated with non-dispatchable components. Here are some relevant data, concerning electric energy use in the U.S. residential and commercial (R & C) sectors. In 1977 and 1980 R & C accounted for 57.5% of total generated electricity, while in 1982 it accounted for 60.1% (DOE 1982); the fraction has remained almost constant since the early 1970's. Table 9.4 from the Oak Ridge National Laboratory (ORNL 1979) gives a breakdown of energy consumption in the R & C sectors in 1977 (note that half the total is electricity, on a primary energy basis). Of the total electric use, water heaters consume 9%, that is, 5.4% of total generated electric energy, and opportunities to operate them off-peak have been recognized for years. Electricity used for all heating and cooling (including hot water and refrigeration) is 60% of the R & C total, and 36% of the entire generated energy. This category includes devices with thermal inertia which can be left to coast for varying times, almost always for minutes, sometimes for an hour or more, without affecting the user adversely. Thus load control can remove much of the high frequency system noise in Figure 9.5 without harming the user. Even if only half this component of the load is in blocks large enough to be worth the trouble of controlling, 18% penetration of non-dispatchable units might be incorporated into a load-dispatched system without having to install additional rapid-response spinning reserve.

Modern communication and control systems make this type of load management possible now, at moderate cost that has been decreasing with time. Schweppe and co-authors, leaders in this field, have described the possibilities (Schweppe 1978; Schweppe, Tabors, Kirtley 1982). A more general review is given by (Morgan and Talukdar 1979). Experiments are underway to test these ideas in practice. For example, the Oak Ridge National Laboratory and the Athens Tennessee Utility Board are now carrying out an experiment on utility control of loads, in that utility district of about 25,000 residents and 77 MWe peak demand (McConnell et al 1982).

Another smoothing alternative is storage on the generation side, as described earlier. This could be by batteries or hydro. The latter has both the advantages of fast start and long term; Section 8.7 gives an example: synchronized in 90 seconds; if already spinning, it can go from zero to full load in 45 seconds. Responses of whole power plants to changing loads is reviewed by (Reppen and Ribeiro 1979). Modern oil-fired power plants are also being designed to follow load more quickly than before (Bieber 1979). By such strategies, even larger non-dispatchable penetration can be envisaged.

To conclude these sections, we recapitulate what we wrote near their beginning. If it is possible to modify the system to accept non-dispatchable power via addition of control and storage either at the generator or user end, then it should be possible also to apply the same techniques to use baseload power during peaking periods. This latter option appears to us likely to be much cheaper in most locations, because on an energy basis the off-peak power is very much cheaper than non-dispatchable sources developed or even envisaged up to now. In other words, many of the present analyses of how to incorporate non-dispatchable units into otherwise conventional grids may be far from an economic optimum.

To put the matter somewhat over-simply for the sake of emphasis, we can fairly easily envisage a modest penetration (10%?) of non-dispatchables incorporated into the grid, with the associated penalty taken up by relatively inexpensive strategies such as load shedding of particularly simple items. Beyond that, the costs of incorporation rise, and above some higher level (30%?)baseload plus storage will be preferable, at least from this systems point of view.

Which alternative is best depends on a holistic view which accounts for diverse factors: cost per unit of electric energy, size of the system (i.e., is it large enough for economical base-load units), on regional opportunity to use non-dispatchable sources to best advantage (i.e., solar PV in Albuquerque or wind in Hawaii), and on social and/or environmental preferences of one system over another. But in any event, storage and load control appear as essential ingredients in all good choices. Given that, subsequent analyses and comparisons become much easier to make.

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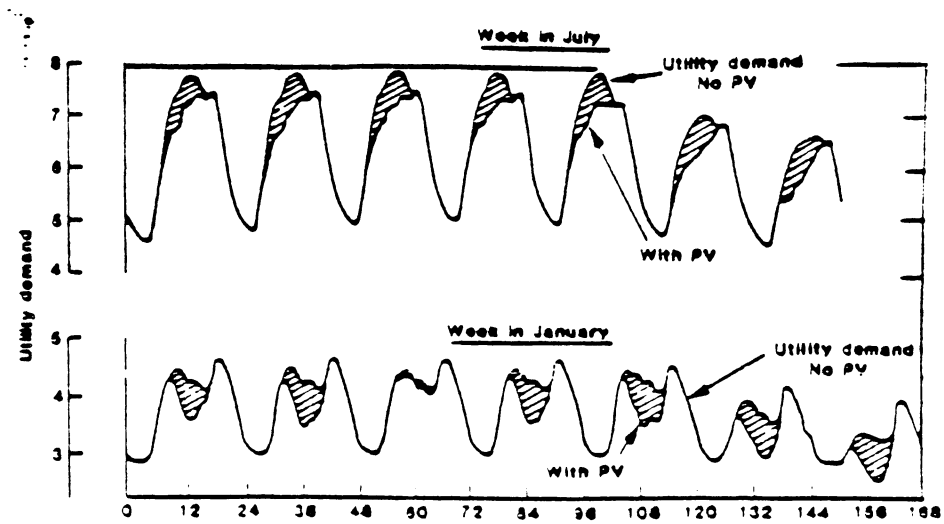
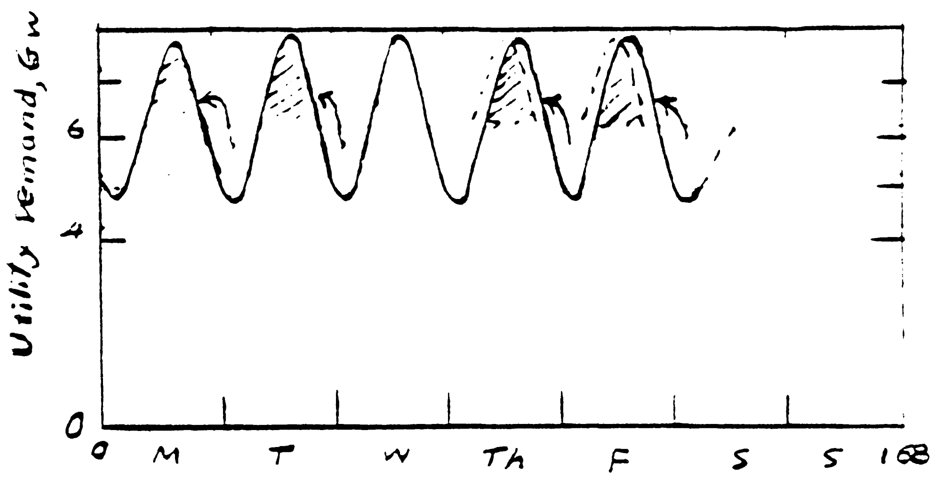


(a) Simulation by Aerospace Corp.



(b) Simplified model of the July weekdays

Figure 9,1 Simulation of a Utility Load profile, with and without photovoltaics or storage in the Southeastern United States

(a) Adaptation by Jeffrey L. Smith [Science, Vol 212, 1472(1981)] of data from Report ATR-80(7694-1)-1, Energy and Resources Division, Aerospace Corp., El Segundo, California.

(b) A simplified model of the July data during weekdays: 6.13 [illegible] average plus 30% sinewave modulation peaked at 1500 hrs. The above-average shaded parts on Monday and Tuesday comprise 9.6% of the total, and could be met from electricity generated and stored in the slack periods. The hypothetical solar contributions on Thursday and Friday, centered about 1200 hrs, leave only 2.2% of the total demand unmet, to be supplied from off-peak storage

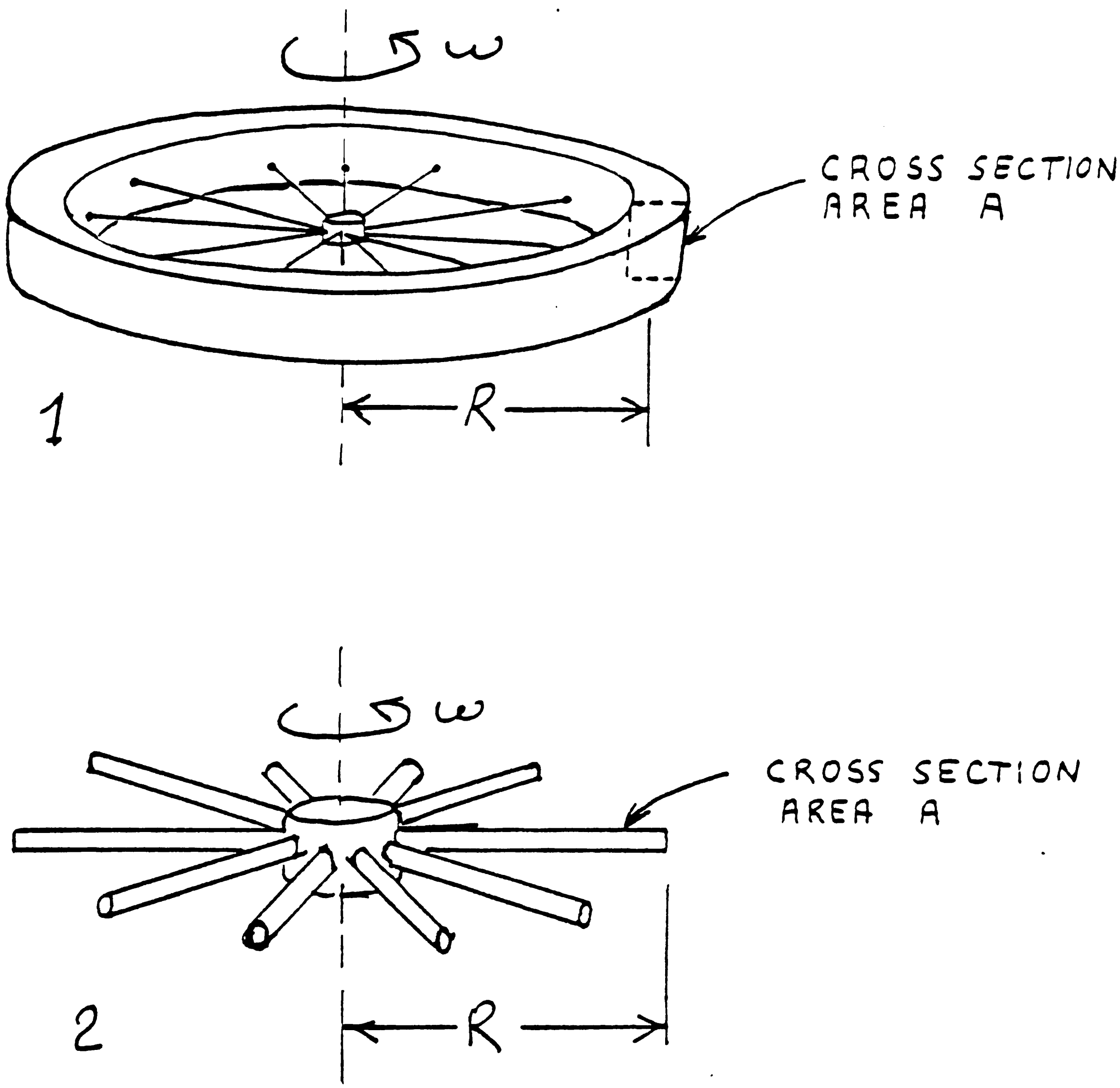


Figure 9.2 Two highly idealized configurations of a flywheel. Wheel 1 consists of a rim only, and 2 of spokes only, in the ideal limitation. A practical flywheel combines both parts.

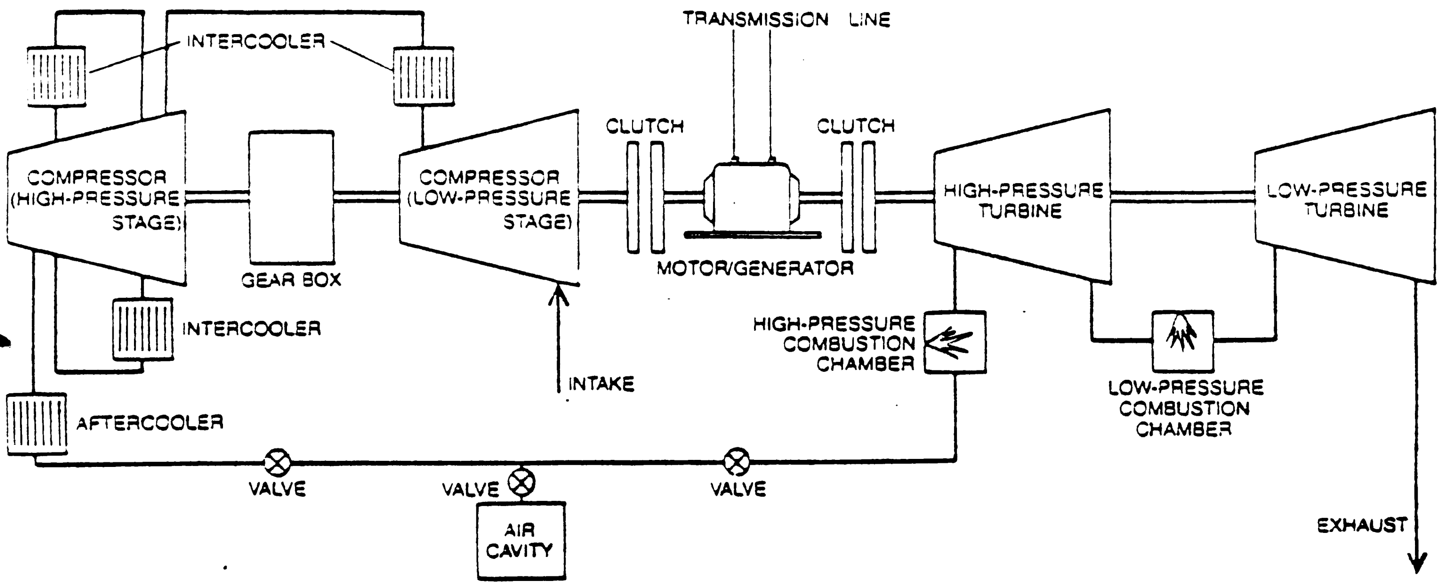


Figure 9.3 Schematic design of the compressed air energy storage system at Huntorf, near Bremen, West Germany. From F. R. Kalzhammer Sci. Amer. Dec. 1979 p. 56 et seq.

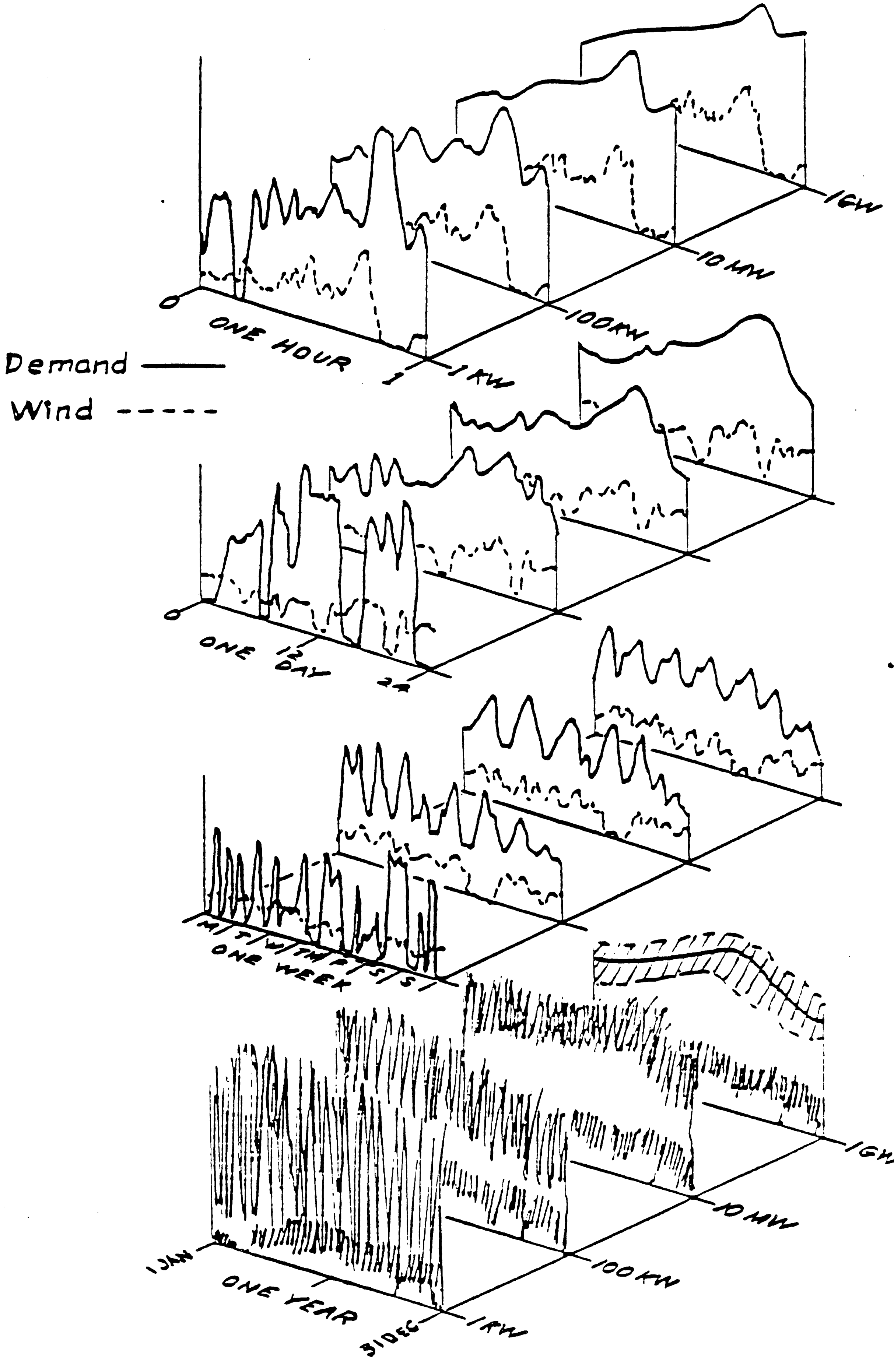


Figure 9.4 Experience of a hypothetical electric utility system, at four levels of aggregation (single residence, subdivision, town, region), on different time scales. The solid lines are electric power demand; dotted lines are output of a wind generator. See text for discussion.

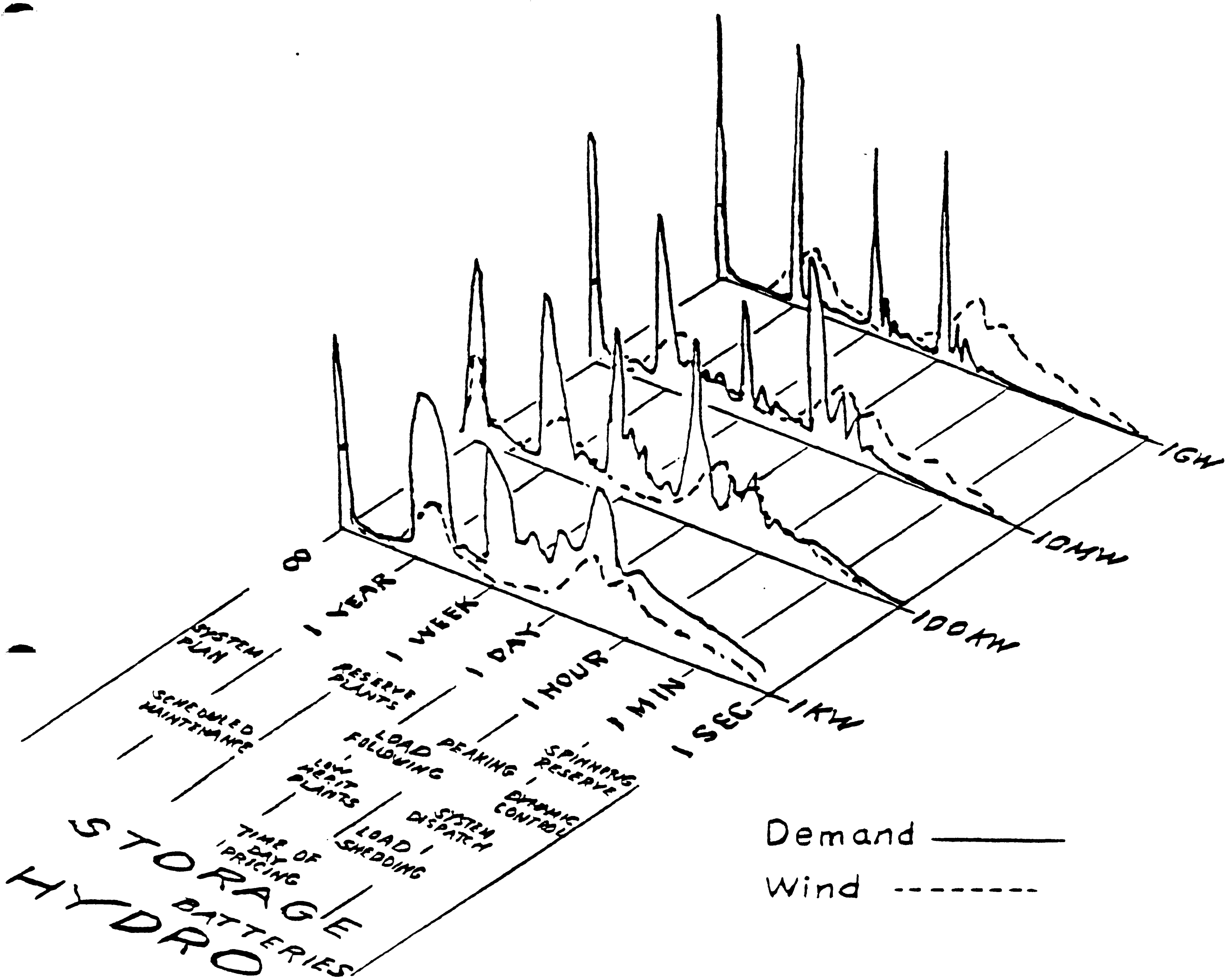


Figure 9.5 Spectrum analysis of the "data" of Figure 1, showing characteristic times and options for system response.

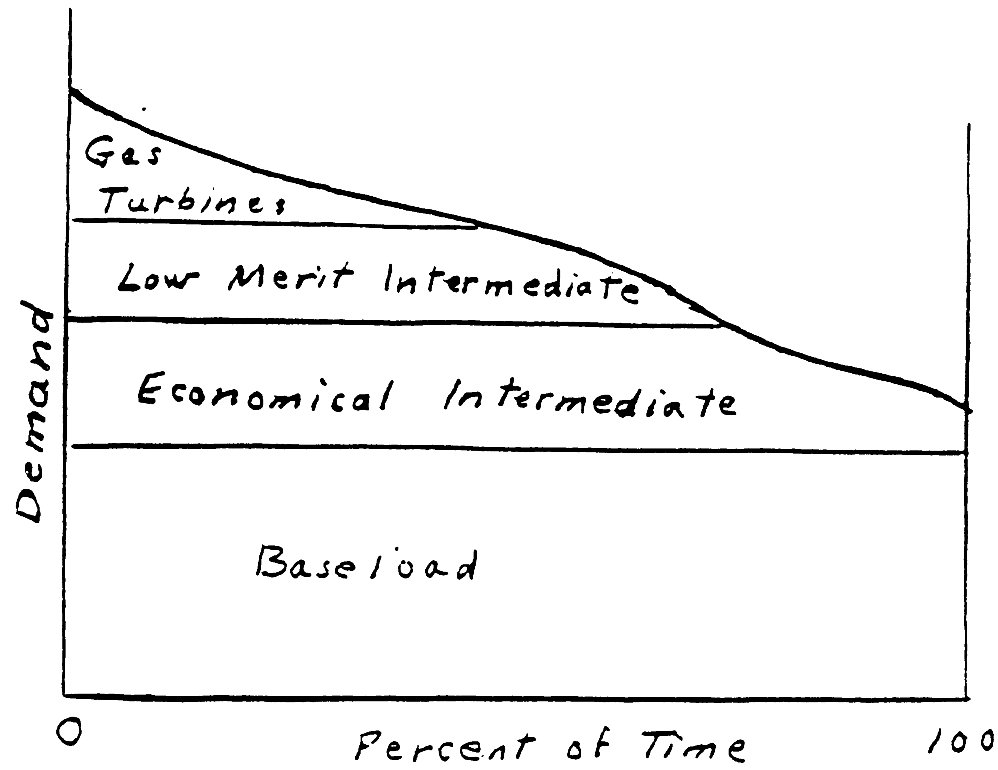


Figure 9.6. Load duration curve

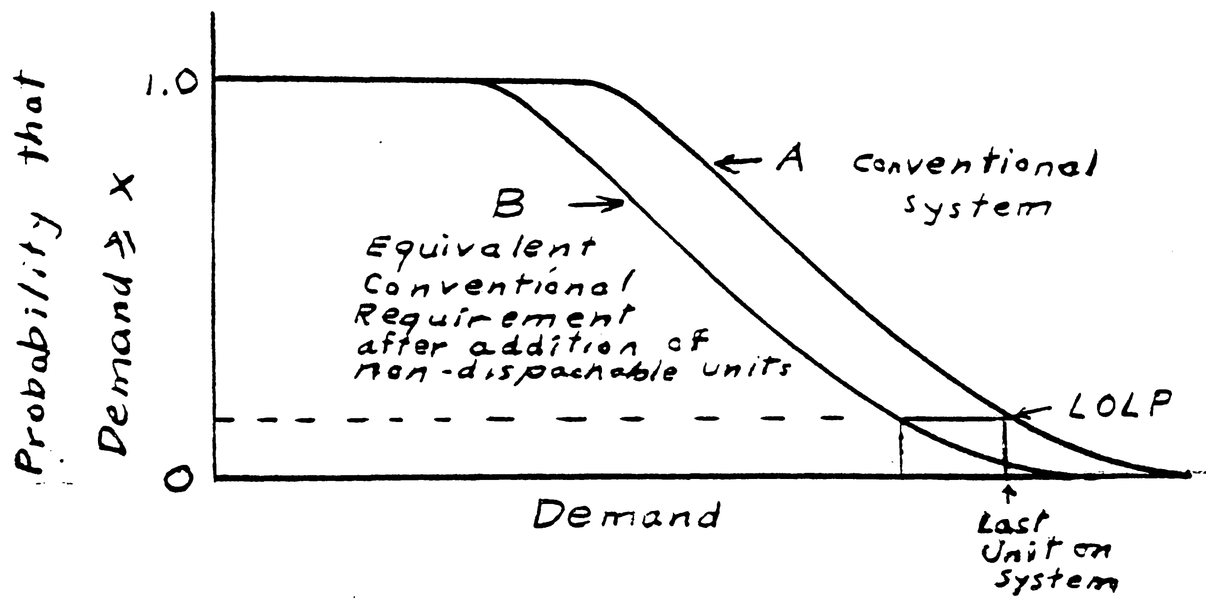
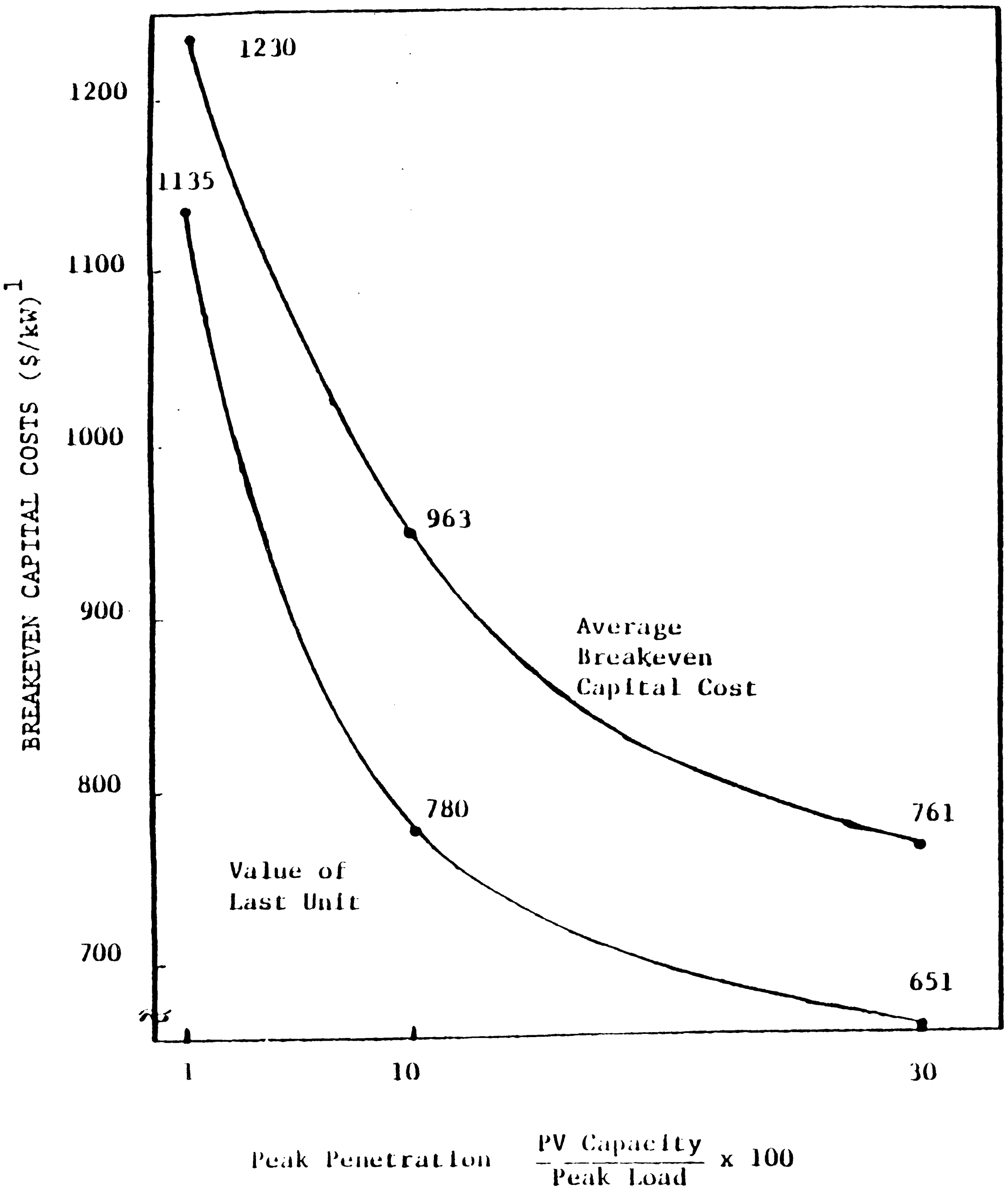


Figure 9.7 Equivalent load duration curve

LOLP ≡ Loss of load probability

Fig 9.8 BREAKEVEN CAPITAL COSTS FOR FLAT-PLAT PV SYSTEMS AT VARIOUS PENETRATION LEVELS



Assumptions:

Photovoltaic System Description:

Cell Type	Silicon
Cell Area	50 m^2
Cell Efficiency at 28°C .	11.5%
Inverter Efficiency . . .	87%
Tilt Angle	20° South Facing

Site: . . . . Albuquerque, NM

Latitude	35°N
Data Source	National Climate Center
Data Type	SOLMET TMY
Data Frequency	Hourly

Utility System Model: . . . EPRI Summer-Peaking Scenario 'E'

Peak Load . . . . 5000 MW

Load Temperature Adjustment Based on SOLMET TMY Albuquerque Data

Economic Assumptions:

Annual Fixed Charge Rate 15%

[1] $/kW assume standard operating conditions of 28°C, 1 kW/m^2 incident radiation, inverter efficiency of 87%, and cell efficiency at 28°C of 11.5%.

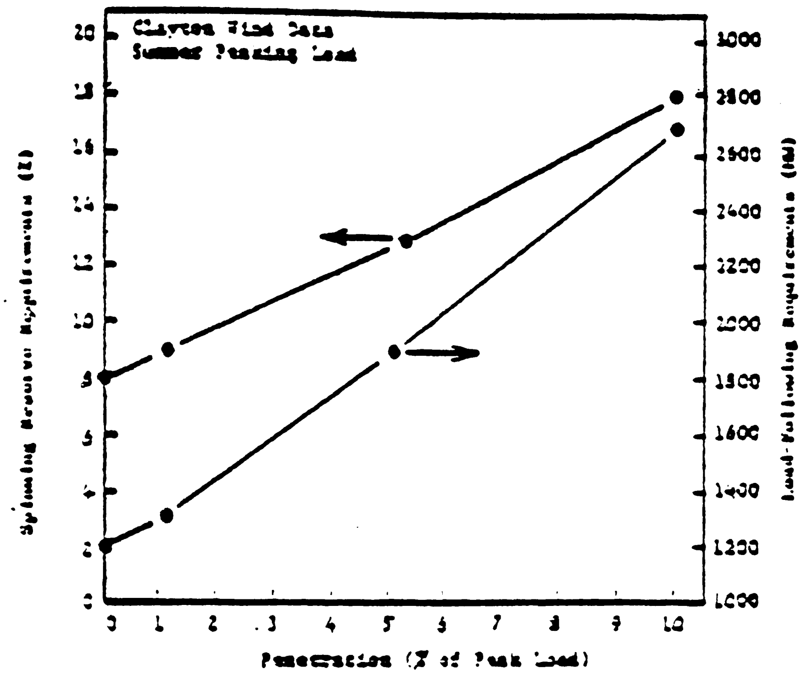


Figure 9.9 Load Following and Spinning Reserve Requirements versus Penetration of MOD-OA Wind Generation Capacity (From SCI 1981).

Battery Type	Operating Temperature (Degrees Celsius)	Energy Density (Watt-Hours Per Kilogram)	Power Density (Watts Per Kilogram)	Estimated Cycle Life	Estimated Cost (Dollars Per Kilowatt-Hour)	Estimated Availability (Year) (Prototypes or Early Commercial Models)
Lead Acid						
Utility Design	ambient	–	–	2,000	80	1984
Vehicle Design (Improved)	ambient	40	70	>1,000	70	1982
Nickel-Iron	ambient	55	100	>2,000(?)	100	1983
Nickel-Zinc	ambient	75	120	800(?)	100	1982
Zinc-Chlorine						
Utility Design	30-50	–	–	2,000(?)	50	1984
Vehicle Design	30-50	90	90	>1,000(?)	75	1985
Sodium-Sulfur						
Utility Design	300-350	–	–	>2,000	50	1986
Vehicle Design	300-350	90	100	>1,000	75	1985
Lithium-Iron Sulfide	400-450	100	>100	1,000(?)	80	1985
Gasoline	–	13,000	–	–	–	–

Table 9.1 Properties of various advanced types of batteries under development in 1979. After F. R. Kalzhammer, Sci. Amer. Dec. 1979, p. 56 et seq.

Table 9.2

Some Properties of Metal Hydrides, and Other Things

Storage Medium	Hydrogen Storage Capacity By weight (percent)	Hydrogen Storage Capacity By volume grams/milliliter	Energy Density Watt-hours/kg	Approximate Conversion Efficiency	Net Energy Density Watt-hours/kg	Operation Temp °C
Magnesium Hydride MgH_2	7	.101	2332	30	700	300
Iron-Titanium Hydride $FeTiH_{1.95}$	1.75	.096	510	30	153	ambient
Magnesium-Nickel Hydride Mg_2NiH_4	3.16	.081	1110	30	333	
Lead-Acid Battery			50	70	35	ambient
Nickel-Iron Battery			100	70	70	ambient
Gasoline			13000	23(?)	3000	
Liquid Hydrogen	100	.0704	39000	?	?	?

TABLE 9.3

Region	Nameplate Capacity		Effective Capacity		Capital Credit	Operating Credit	Breakeven Cost*
	1	2	3	4 = [3]/[1]	5	6	7 = [5] + [6]
	(MW)	percent of utility system	(MW)	percent of nameplate	(1980$/Watt)		
Miami	200	3.1	59	29.5	.316	1.080	1.396
Miami	1200	18.3	185	23.8	.280	1.032	1.312
Boston	200	3.1	71	35.5	.286	.806	1.092
Boston	1200	18.3	304	25.3	.238	.790	1.028
Omaha	200	3.1	19	9.5	.139	.465	.604
Omaha	1200	18.5	74	6.2	.108	.461	.569
Phoenix	200	3.1	80	40.0	.287	1.257	1.524
Phoenix	1200	15.9	407	33.9	.263	.803	1.066

*The breakeven cost is the amount the utility would be willing to pay, per watt, such that the utility is no better or worse off after installation of the system.

Table 9.4. U.S. energy consumption by sector, fuel type, and end use, 1977 (10^{15} Btu)

	Electricity[a]	Gas	Oil	Other	Total
		Residential			
Space heaters	1.25	3.64	2.26	0.54	7.69
Water heaters	1.17	0.87	0.14	0.08	2.26
Refrigerators	1.49				1.49
Freezers	0.64				0.64
Ranges/ovens	0.52	0.31			0.83
Air conditioners	1.10				1.10
Lights	0.96				0.96
Other	0.68	0.48			1.15
Total	7.81	5.30	2.40	0.62	16.12
		Commercial			
Space heaters	0.37	1.94	1.90	0.35	4.56
Air conditioners	2.03	0.16			2.19
Water heaters	0.04	0.09	0.10		0.23
Lights	2.23				2.33
Other	0.85	0.20			1.05
Total	5.62	2.39	2.00	0.35	10.36

[a] Electricity is reported as primary energy (11,500 Btu/kWhr).

Sources: The ORNL Residential Energy Use Model and the ORNL Commercial Energy Demand Model, as quoted in Ref. (ORNL 1979)

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