ECONOMIC AND ENVIRONMENTAL IMPLICATIONS OF A U.S. NUCLEAR MORATORIUM, 1985-2010

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Preface

The study was conducted by the Institute for Energy Analysis (IEA) of Oak Ridge Associated Universities (ORAU) under subcontract to the National Research Council and under the sponsorship of the Energy Research and Development Administration (ERDA).

The study is based on results presented in other separate research papers. For the reader's convenience, the titles of those papers are listed at the end of the volume.

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Contents

List of Tables

List of Figures

Summary 1

This study assesses some economic and environmental implications of a nuclear moratorium in the United States. The moratorium is assumed to prohibit new construction starts of reactors after 1980, but to allow continued operation of reactors on line by 1985. Though the main focus is the period between 1980 and 2010, some consideration is given to the implications of a permanent loss of the nuclear option.

Projected Energy and Economic Growth

The effects of a nuclear moratorium depend very strongly on the future demand for energy, particularly for electricity. These demands, in turn, are largely determined by future gross national product (GNP) and population of the United States. Recognizing the uncertainties in such estimates, we have developed two alternative demand scenarios for all our projections. The results of this analysis are summarized in Table 1.

Even out "high" estimate for total energy 126 quads (1 equals 10^{15} Btu) in the year 2000, is much lower than most previously published estimates. If our estimates are valid, they could imply considerable rethinking of those elements of energy policy and energy R&D policy that are premised on higher overall

TABLE 1. GNP, Energy, and Electricity Demand
(total and per capita)

	Total					
	GNP (10^9 1975 $)		Energy and electricity (quads)		Population (10^6)	
Year	*Low*	*High*	*Low*	*High*	*Low*	*High*
1975	1,499	1,499	71.1 (20.1)	71.1 (20.1)	213	213
1985	2,135	2,135	82.1 (30.8)	88.0 (34.1)	228	231
2000	3,184	3,326	101.4 (47.3)	125.9 (64.0)	245	254
2010	4,076	4,470	118.3 (55.5)	158.8 (82.4)	250	264

	Per capita					
	GNP (1975 $)		Energy demand (10^6 Btu)		Electricity (10^6 Btu and percent)	
Year	*Low*	*High*	*Low*	*High*	*Low*	*High*
1975	7,038	7,038	334	334	94 (0.28)	94 (0.28)
1985	9,364	9,242	360	381	134 (0.38)	147 (0.39)
2000	12,996	13,094	414	496	193 (0.47)	252 (0.51)
2010	16,304	16,932	473	602	222 (0.47)	312 (0.52)

projections. On the other hand, our estimates for electricity demand in 2000—between 47 and 64 q—though somewhat lower than other published estimates, represent a much smaller deviation from the present course of growth of electricity, suggesting that electric supply modalities will continue to grow significantly. Nevertheless, because our electricity projections are somewhat lower than historic growth rates and estimates of previous studies, the effects of this nuclear moratorium are less than might have been expected.

Our projections of future energy demand are in no sense "normative"—that is, we do not suggest what the energy demand, and by implication the life style, *ought* to be. Instead, our projections result from fairly straightforward extrapolations of historic trends that determine energy demand. In this sense, we would describe our projections as "surprise free." Indeed, although the aggregate energy demands and GNP increase rather modestly, the energy demands per capita and GNP per capita increase at rates comparable to or higher than historic rates.

Total energy demand is the sum of demand in five sectors: household, commercial, personal automobiles, industry, and transport of goods and services. The size of the first three factors is related directly to the population and that of the last two factors to the GNP. Population is estimated to grow to no more than 264 million by 2010—a key difference between our projections and most of those made previously and on which much energy policy is now based. GNP is estimated to rise by an average of 2.5-3.0 percent per year, largely because labor productivity is not expected to grow at long-term rates higher than historic rates of the past 35 years. In each end-use energy sector we have assumed improvements in energy efficiency: these are admittedly somewhat arbitrary but are generally based on partially implemented, mandated improvements (automobiles) or on historic trends (decreasing energy to GNP ratio).

The shift to electricity—from some 28 percent of our total energy supply in 1975 to about 50 percent by 2000—stems largely from our belief that oil and gas prices, in response to scarcity of domestic sources, will rise more sharply than coal and nuclear prices, and that new, improved electric devices, such as heat pumps, will make a large penetration of the market by this time. Our supply scenarios do include contributions from solar, geothermal, and hydroelectric sources; the contributions are assumed to be the same in the nuclear and nonnuclear scenarios.

Our model of the future does not introduce prices explicitly. However, we have estimated long-term prices of oil, gas, and coal, largely on the basis of other studies and our own judgment. These estimates are given in Table 2. Price and income elasticities have been developed corresponding to the alternative demand scenarios. These elasticities fall well within the range of values found in other studies.

In order to test the internal consistency of our projections, we have constructed a modified constant elasticity of substitution economic model that relates GNP to labor, capital, technological change, and energy. The model suggests that our projections of GNP are achievable with the price schedule that we have assumed and that lower energy demands can be reached without serious economic effects if energy price increases are gradual and anticipated.

Economic Implications

We have examined five possible economic implications of a moratorium: future cost of electricity, regional dislocations, nuclear industry impacts, effect on coal industry, and international impacts. In estimating these economic implications, we have examined two alternative supply options: a primary one in which coal is chosen to make up the deficit in electricity demand caused by rejection of nuclear energy and a case, more briefly treated, in which imported oil is used to provide most of the difference.

The mix of fuels required for the generated electricity in the three alternative supply cases is summarized for each demand scenario in Table 3. (We do not include in the table electric energy from hydroelectric, solar, or geothermal sources.)

1. Future cost of electricity

Central to the analysis is an estimate of the future costs of electricity generated in coal-fired and in nuclear power plants. Two primary results stand out:

(1) For regions of the United States (except the Rocky Mountain and Great Plains states), under a wide range of assumptions, nuclear power appears to be cheaper than fossil-fueled power. The difference between the cost of nuclear and

TABLE 2. Estimated Prices of Different Energy Modalities
(relative to 1975 in constant dollars)

	1975	1985	2000	2010
Coal	1.0	1.22	1.65	2.00
Oil	1.0	1.54	2.40	3.23
Gas	1.0	6.42	10.00	13.40
Electricity	1.0	1.22	1.65	2.00

Note: The 1975 average prices were as follows: coal, $17.50 per ton, delivered to utilities; oil, $10.40 per barrel, composite cost to refiners; natural gas, $0.43 per thousand cubic feet at the wellhead; electricity, 27 mills per kilowatt-hour (kWhr) to consumer.

TABLE 3. Summary of Electricity Fuel Inputs (Alternative Options) (10^{15} Btu)

	1975	1985	2000	2[illegible]
Low demand (101 q in 2000)				
High nuclear				
Coal	8.8	10.1	7.1	2.1
Oil and gas	6.5	5.9	4.8	1.2
Nuclear	1.7	10.6	27.2	39.6
High coal				
Coal	8.8	10.1	23.7	33.0
Oil and gas	6.5	5.9	4.8	1.2
Nuclear	1.7	10.6	10.6	8.6
High imports				
Coal	8.8	10.1	11.1	17.2
Oil and gas	6.5	5.9	17.4	17.0
Nuclear	1.7	10.6	10.6	8.6
High demand (126 q in 2000)				
High nuclear				
Coal	8.8	10.4	20.0	14.5
Oil and gas	6.5	8.9	4.8	1.2
Nuclear	1.7	10.6	31.0	53.4
High coal				
Coal	8.8	10.4	40.0	59.3
Oil and gas	6.5	8.9	4.8	1.2
Nuclear	1.7	10.6	10.6	8.6
High imports				
Coal	8.8	10.4	20.0	38.9
Oil and gas	6.5	8.9	25.2	21.6
Nuclear	1.7	10.6	10.6	8.6

coal-based electricity varies strongly from region to region. Where low-sulfur coal can be surface-mined, electricity from coal would be no more expensive than nuclear, and might be less expensive.

TABLE 4. Effect of Fuel Escalation Rates on Differences Between Cost of Nuclear- and Coal-Generated Electricity

Assumptions on net fuel cost increase (per year)	Percent electricity cost advantage (disadvantage) of nuclear over coal	
	Nuclear over coal without scrubbers	*Nuclear over coal with scrubbers*
Coal 0%, nuclear 0%	9	18
Coal 0%, nuclear 2%	–1	8
Coal 0%, nuclear 4%	–12	–4
Coal 2%, nuclear 2%	17	24
Coal 2%, nuclear 4%	4	10
Coal 2%, nuclear 6%	–11	–5
Coal 4%, nuclear 4%	26	31

Note: Percent difference = [(coal cost – nuclear cost)/nuclear cost] x 100. Base case assumes 5 percent inflation and 11 percent operating discount rate (6 percent net discount rate).

(2) The long-term difference in generating cost between coal and nuclear depends on the effective cost of money and on the relative rate of escalation of coal and uranium prices compared with general inflation. The ratios of differences in levelized and nuclear coal costs to levelized nuclear costs under various assumptions are summarized in Table 4. In general, the cost of generating nuclear electricity is relatively less sensitive to inflation than is the cost of generating electricity from coal.

A summary of the additional cumulative costs (in 1975 dollars) of electricity due to a moratorium over the period 1975-2010 is presented in Table 5 for alternative capital charge and fuel escalation rates. If entries in Table 5 are compared with the cumulative GNP (1975 dollars) for the same period, in no case does the cost exceed 1.0 percent of the cumulative GNP. (The cumulative cost and GNP are current year values measured in 1975 dollars.)

The estimated cumulative increase in electric power costs would total about $420 billion by 2010 in the high-demand case and $314 billion in the low-demand case, assuming 2 percent fuel escalation, 12 percent capital charge rate, and a mixed coal supply.

2. Regional impacts

We estimate in our base case (5 percent inflation, 2 percent fuel escalation, 6 percent net discount rate) that coal will be cheaper than nuclear power in the Northern Rocky Mountains and Northern Great Plains. This result is sensitive to

TABLE 5. Additional Cumulative Cost of Electricity Due to a Moratorium (1985-2010) for Alternative Fuel Escalation and Fixed Capital Charge Rates
(billions of 1975 dollars)

Case	Levelized effective fixed capital charge rate	Fuel escalation rate: *2% coal 2% U*	*2% coal 3% U*	*3% coal 2% U*	*3% coal 3% U*	*3% coal 4% U*
		Mixed low-sulfur and high-sulfur coal*				
Low demand	7%	362	256	602	497	358
	9%	342	237	583	478	339
	12%	314	208	554	449	310
	15%	285	179	525	420	281
High demand	7%	484	341	810	667	479
	9%	458	316	784	641	453
	12%	420	277	746	603	415
	15%	382	239	708	565	376
		High-sulfur coal				
Low demand	7%	346	241	577	470	331
	9%	334	228	562	457	318
	12%	314	209	543	438	299
	15%	295	190	524	418	279
High demand	7%	463	320	773	630	442
	9%	446	303	756	613	425
	12%	421	278	730	587	399
	15%	395	252	705	562	373

*Assumes incremental requirements for coal in case of a moratorium will require two-thirds of plants without scrubbers and one-third with scrubbers.

various economic and environmental assumptions, but in no other regions do we find coal to be cheaper than nuclear energy under a wide range of assumptions. We therefore judge that the loss of the nuclear option would raise the price of electricity most significantly in New England, which has no access to cheap fossil fuel. However, our studies of regional effects are rather schematic and more additional work is needed to assess fully the regional impacts.

3. Nuclear industry

A moratorium would eliminate about 50,000 jobs in the nuclear and related industries and would embarrass reactor manufacturers. However, because all the reactor manufacturers and architect-engineering firms also build equipment for other energy systems, the displacement caused by the moratorium would be temporary. Smaller industries that supply goods and services only to the nuclear enterprise would be hit much harder.

4. Coal industry

The most important impact of a nuclear moratorium would be its effect on the amount of coal required. Table 6 summarizes the amount of coal needed under the various assumptions.

The annual production of the extra 1.3 billion tons of coal by the year 2000 (in the moratorium case for the high scenario) would require about 113,000 more miners and provide employment for a large number of other people in the transportation of coal.

Assuming that renewable supplies (solar, hydroelectric, and geothermal) do not increase extensively, coal, under our highest scenario, would be required to provide 94 q of energy in 2010, of which 59 q would go for electricity. This demand would require mining 4.8×10^9 tons of coal per year by 2010 in the case of the moratorium, 2.5×10^9 tons in the absence of the moratorium. Although other studies suggest that these are achievable goals, we consider this to be one of the most uncertain implications of energy growth after the year 2000 for the case of high energy demand and the moratorium. Should the low demand occur, the required amount of coal would be cut almost in half (2.9×10^9 tons with the moratorium, 1.2×10^9 tons without), and would be more easily achievable. The problems associated with mining and transporting these amounts of coal have not been examined independently in this study.

5. International

Two major international effects of the moratorium have been considered:

(1) The foreign exchange costs of importing oil rather than using domestic coal to make up the energy deficit.

TABLE 6. Coal Required for 1975-2010*
(10^9 tons per year)

	1975	1985	2000	2010
Low demand (101 q in 2000)				
High nuclear	0.61	0.71	0.78	1.15
High coal	0.61	0.71	1.50	2.94
High demand (126 q in 2000)				
High nuclear	0.61	0.73	1.37	2.51
High coal	0.61	0.73	2.63	4.81

*See also Table 31.

(2) The probable impacts on the nuclear industry because of international developments flowing from a domestic moratorium.

We estimate that the nuclear shortfall in 2000 would be 16.6 q (low scenario) and 20.4 q (high scenario). If this shortfall were made up by importing oil at $25 per barrel (the estimated cost for the year 2000), the total utility industry oil import bill in 2000 would be around $83 billion and the total oil import bill around $97 billion. This import bill accounts for the same proportion of estimated total imports (~25 percent) as it did in 1975.

U.S. reactor manufacturers are multinational corporations which already operate nuclear-oriented production facilities abroad. With all of the reactor orders and a large share of the component business coming from abroad (in case of a U.S. moratorium), pressures to move production facilities outside the United States would be very strong. Such a move would further shift our net balance of payments to our disadvantage.

Environmental Implications

We have examined four levels of environmental tradeoffs as a result of shifting the additional fuel requirements from nuclear to coal after 1985. These examined alternative tradeoffs include proliferation of nuclear weapons and greatly increased carbon dioxide (CO_2) from fossil fuels on a global scale; reactor accident probabilities and expected coal mining accidents at a local level; impacts from reactor radiation emissions and coal-fired plant emissions on public health; and impacts of uranium mining and coal mining on land use.

1. Global effects

(1) Proliferation: Countries wishing to rely primarily on the nuclear option can do so whether or not the United States abandons nuclear power. Thus, a domestic moratorium on nuclear energy would have little effect on proliferation unless the rest of the world abandoned nuclear power.

(2) CO_2: Should 20 percent of the world's fossil fuel be burned, the CO_2 concentration might double; this could lead to unacceptable changes in the world's climate. A U.S. moratorium per se would have little effect on this possibility; however, loss of the nuclear option through much of the world, which is a conceivable consequence of a U.S. moratorium, might make it more difficult to respond quickly to a perceived danger from higher CO_2 levels in the atmosphere.

2. Accidents

(1) Reactors: Assuming that the accident probabilities given in the Rasmussen report are applicable throughout the period, we estimate the number of expected reactor meltdowns that release a significant amount of radioactivity occurring by the year 2010 to be about 0.6 without the moratorium and 0.2 with the moratorium; of these meltdowns, about one-third could be expected to actually breach aboveground containment. These results are essentially independent of which energy demand scenario is chosen, but depend on the assumption that the Rasmussen accident probabilities will *not* be improved as the technology matures.

(2) Coal mining: The injuries and fatalities from coal mining accidents per year in 2010 are estimated to be about halved without the moratorium compared to what they would be with the moratorium.

3. Low-level atmospheric pollution

(1) Radioactivity: With the moratorium, the estimated annual whole-body

TABLE 7. Estimated U.S. Air Pollution Emissions for A.D. 2000*
(millions of tons per year)

Pollutant	Present	Nuclear supply case: High energy	Nuclear supply case: Low energy	Coal supply case: High energy	Coal supply case: Low energy
Sulfur dioxide	20	12	9	15	12
Nitrogen oxides	23	27	22	34	28
Particulates	5	12	11	13	12
Hydrocarbons	14	6	5	7	5
Carbon monoxide	108	24	21	25	22

*From Brookhaven Energy Systems Model calculation for IEA scenarios. For full table and assumptions, see Table 38.

radiation dose per person from energy technologies in 2010 comes to about 0.12 millirems (mrems) per person; without the moratorium, these numbers are 0.7 and 0.5 in the high and low scenarios, respectively. These figures are to be compared with the average annual exposure of 120 mrems per person from natural background.

(2) Emissions from coal plants: U.S. air pollution from sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (CH_x), and particulates will be higher with the moratorium than without it. The increase appears to be significant for SO_2 and NO_x. If the control assumptions used here (based on the Brookhaven Energy Systems Model) remain valid, emissions of SO_2, CH_x, and CO will be relatively lower in 2000 than at present for all scenarios. The range of potential assumptions about emission control is probably as important as a moratorium in projecting emissions. These estimates are summarized in Table 7.

4. Land impacts

With a moratorium, the land disturbed for uranium mining is only about one-third as much as in the nuclear supply case by the year 2000. The land required for coal mining is approximately doubled by that year as a result of the shift from nuclear to coal. The land requirements for a unit of energy from coal mining are much larger than from uranium mining, and will depend on the mix of deep mining and surface mining and the source of coal (Western, Midwestern, or Appalachian). Table 8 illustrates the land requirements by the year 2000 under the different assumptions.

Alternative Long-Range Energy Futures

The final section of this study speculates on the shape of a distant nonfossil future, when the primary energy system is based on nuclear energy or on solar energy. This section of the study is included because of our belief that these two contrasting perceptions of the very long-range future underlie much of the debate on nuclear energy.

1. Solar option

Our speculations suggest that solar energy, though very useful as a supplement to other energy systems, becomes especially awkward and expensive if it is the prime source of energy. Because of intermittency, most solar energy systems require storage; this can become extremely expensive if the solar system stands alone and is not backed up by a large, completely firm energy system. Even without storage, solar electricity appears expensive unless the cost of components

TABLE 8. **Land Requirements for Annual Fuel Production in the Year 2000**
(acres)

	Demand case	
	Low	*High*
Uranium mining (20% deep, 80% surface)		
High nuclear	5,700	6,540
High coal (moratorium)	2,320	2,320
Coal mining cases (30% deep, 70% strip)		
(1) High nuclear	88,000	155,000
High coal	177,000	273,000
(2) High nuclear	104,000	192,000
High coal	206,000	317,000
(3) High nuclear	231,000	426,000
High coal	457,000	703,000

Case (1)—60% Western, 30% Midwestern, 10% Appalachian.
Case (2)—50% Western, 25% Midwestern, 25% Appalachian.
Case (3)—14% Western, 35% Midwestern, 51% Appalachian (1970 distribution).

can be reduced sharply. Of the solar systems that are not intermittent, we have considered only biomass. Our analysis, though very preliminary, suggests that if biomass were to be used as our primary energy system it would greatly tax our resources of land, water, and fertilizer. We have not examined ocean thermal energy conversion (OTEC), which is also a nonintermittent solar energy source.

2. Nuclear option

Our long-range nuclear system depends on breeders that supply most of society's electricity. We assume that geologic waste disposal is in principle acceptable; having made this assumption, we can find no physical constraint—land use, availability of uranium, heat dissipation—that makes such a system untenable. However, we believe the less quantifiable hazards of nuclear energy—diversion, sabotage, possibility of reactor accident—become impediments to the use of nuclear breeders on the contemplated scale over the very long future. We therefore propose "fixes" that might enable man to live comfortably with fission. The primary fix proposed is to confine all reactors, processing plants, and waste disposal in the United States to some 100 sites occupying 50 sq miles each. In addition, we suggest that in the asymptotic nuclear energy system, generation of nuclear energy ought to be separated organizationally from its distribution and marketing, and that the entire enterprise ought to be in the hands of a highly trained, specialized cadre.

In the final analysis, we conclude that an all-solar society is almost surely a low-energy society, but one that does not require the vigilance and care demanded by a nuclear society. The all-nuclear society can be a much higher-energy society, but may require the social and technological fixes implicit in the reorganization of the enterprise that we visualize here.

Conclusions

Recognizing the uncertainties of any projections, we nevertheless offer the following main conclusions of our study:

(1) There are strong reasons to believe that total energy demand will increase at a considerably lower rate than most other published studies indicate. Electricity demand probably will grow faster than total demand, but at a lower rate than projected in most other estimates.

(2) Under a wide range of assumptions with respect to the rates of inflation and fuel costs, nuclear power appears to be cheaper than fossil fuel-generated power in most regions of the United States. The estimated direct average cost per year of a nuclear moratorium lies in the vicinity of 1 percent of yearly GNP.

(3) The regional economic impacts of a long-run moratorium would vary greatly, from severe in New England to virtually zero in the Northern Plains states.

(4) A nuclear moratorium coupled with limited oil imports might require some 1-3 billion tons more coal to be mined per year in the period 2000 to 2010 than would be the case if there were no nuclear moratorium.

(5) Total emissions of SO_2, NO_X, particulates, hydrocarbons, and CO would be about 20 percent lower if nuclear power were not curtailed; however, if scrubbers are used on utility boilers, and if projected improvements on automotive emissions are achieved, total emissions in 2000 for all pollutants except particulates would be lower than present levels with or without a moratorium.

(6) In the long run, atmospheric levels of CO_2 might lead to unacceptable changes in climate. Though a U.S. nuclear moratorium would not affect these levels significantly, loss of the nuclear option throughout the world could exacerbate the CO_2 problem in the next century.

(7) In the very long run, the society may have only solar energy and nuclear power as its major energy options. Solar energy, especially as a stand-alone electric system, presently appears to be much more expensive than nuclear energy.

(8) This study disclosed several areas where additional research is needed: (a) specific regional impacts from alternative energy strategies; (b) the feasibility of mining multibillion tonnages of coal; (c) potential long-range environmental impacts, particularly that of CO_2; and (d) long-range asymptotic energy supply and demand beyond 2010.

Introduction

2

For two decades American policy makers, energy planners, public utility officials, and consumers have assumed—explicitly or implicitly—that nuclear power could be counted on to make an increasingly important contribution to meeting the energy requirements of the United States. This assumption is reflected in current energy planning and long-term estimates. Thus it is now expected that installed nuclear electric generating capacity will grow from 38,000 megawatts (MW) in 1975 to 175,000 MW by 1985. Plans for the longer run are obviously less firm, but the capacity is expected to expand to between 450,000 and 512,000 MW by the year 2000. This long-term estimate represents about a 50 percent reduction in a high estimate put forward just two years ago.[1,2]

Although assumptions about the future of nuclear energy may have been—and, indeed, may still be—optimistic in terms of the pace of construction, costs, and public acceptance, the fact that nuclear energy would play a growing role in America's energy future has been taken for granted in both government and private sector planning. Recently, the role of nuclear energy as a source of energy for America has become a matter of considerable controversy.[3] The considerations involved are at the heart of important and far-reaching national issues: the future shape of the American economy; the economic well-being of various geographic regions; the future of several major industries; the tradeoffs among types of environmental costs and between environmental and economic costs; the future shape of energy-related public and private institutions; the economic, social, and environmental tradeoffs between centralized and decentralized energy systems; and the shape and scale of research and development programs, national security, international relations, international trade, future life styles, and federal-state relations.

Major stakes hang on how the issue is ultimately resolved. The outcome not only is consequential in terms of this generation, but also will affect the lives and life styles of generations to come. The wrong decisions could be costly and difficult to reverse. Clearly, Americans are now facing one of the most profound choices in their history.

Various groups opposing the expansion of the nuclear industry have advanced proposals ranging from complete abandonment of the technology to contingent moratoria and planned restrictions on the rate of expansion of nuclear power plants.[4] The broad issues raised by these groups include the possible risks from reactor accidents, the diversion of plutonium for weapons, nuclear proliferation, the safe storage of radioactive wastes from the nuclear fuel cycle, the toxicity of plutonium, the economics of nuclear power, the need for rapid economic and energy growth, the potential for energy supply from alternative sources, and the potential role of conservation.

Other, less concrete issues have become entwined in the often emotional and highly charged debate between pro- and antinuclear advocates. For many, nuclear power has become a symbol of big government, big industry, lethal weapons, unfettered science and technology, rapid economic growth, and higher (and unnecessary) energy consumption. For others, nuclear power is viewed as a means of assuring that future life styles are a matter of choice and are not limited by the unavailability of energy.

This study addresses some economic and environmental implications of a nuclear moratorium for the United States—the moratorium is a temporary but prolonged period during which the contribution of nuclear energy to the total energy supply is frozen at the level in production or under construction in 1980. The social and institutional implications of a moratorium are not examined here. This is not because they are regarded as unimportant, but rather because they lie outside the bounds of this study, and are much less amenable to analysis than are the economic and environmental implications.

The moratorium which forms the basis for this analysis is one that is announced to begin in 1980. For practical purposes its effect would not be felt until 1985, since new nuclear plants under license as of January 1, 1980, would continue to be built. The time scale for in-depth study is through the year 2010, although some obviously important questions must be addressed beyond that date. For convenience of analysis, the time frame has been divided into four periods.

The period 1975-1985 is the *base period* or the near term. It is the period in which the moratorium decision is made and implemented, and in which various proposed conservation and supply technologies are assessed and put into effect at the state and regional levels by local institutions.

The period 1985-2000 is a *transition period* during which the domestic supplies of oil and gas peak and then begin to decline, even with price deregulation and with the additional production from Alaskan and offshore reserves. Preparation must be made during this period for a rapid transition to other energy supply systems based on oil shale, solar energy, breeder reactors, fusion, synthetic fuels from coal, or a combination of these technologies. This period will see the real potential of energy conservation brought to bear on the U.S. system as a consequence of rising energy prices.

The decade 2000-2010 is the period of *rapid deployment of the new supply* *technologies* and/or stringent conservation measures. In this period world oil and gas production is expected to peak and begin to decline. If the decline of U.S. oil and gas production does not bring sufficient pressure to push the U.S. toward greater energy independence in the 1985-2000 period, it will surely come when world production of oil and gas peaks and begins to decline.

The *long term* much beyond 2010 is the period in which the U.S. population and labor force are assumed to approach some asymptotic level through a combination of fertility rates and controlled immigration, and the fossil fuels are largely gone. Asymptotic scenarios for this period must be considered in any decisions foregoing energy supply options during the earlier transition periods.

The strategy used in this study is to present a plausible range of future economic growth and energy demand scenarios extending out to 2010. This range has been developed in an IEA project for ERDA.[5] Using these demand scenarios, the study then provides the likely components of the future energy supply system based on current plans and on estimates of future relative costs of the various energy supplies. The alternative supply options used include those with and without the continued expansion of the nuclear power industry beyond 1985. Next, an assessment is made of the economic impacts associated with shifting from an expanded nuclear power base after 1985 to a power base with the nuclear electric capacity frozen at the 1985 level and with the additional electricity provided by either coal or imported oil.[6,7] The capital costs required to put in place the alternative U.S. energy supply systems are compared on a national level, and two specific regional cases are analyzed.[8] Finally, the economic impacts of the moratorium on the coal industry, the nuclear industry,[9] and international trade are examined.

Since there are serious environmental questions related to the various energy supply options, the relative environmental impacts are compared using currently available data on land use and air pollutants.[10] A comparison is presented both with and without the expanded nuclear system on the basis of total environmental residuals. Important issues are raised about local and regional environmental impacts and a potential world climatic problem with CO_2 from fossil fuels. The discussion of the latter is based on an analysis of the CO_2 problem prepared by IEA for ERDA.[11]

Plausible asymptotic energy scenarios beyond 2010 and the broad issues likely to be connected with such futures are briefly addressed, since the risks involved in foreclosing future energy options need to be evaluated.[12]

3 Projected Energy and Economic Growth

The growth in U.S. energy demands for the next 35 years (1975-2010) is assumed to be determined by the rate of growth of the economy, changes in demographic and life-style factors, and changes in the efficiency of energy-use technologies in the various sectors of the economy. These three broad determinants are interdependent and each in turn depends on even more basic factors of input. Several recent studies, notably the one sponsored by the Edison Electric Institute,[13] present arguments for relatively high energy and economic growth. However, several basic factors affecting the U.S. economic future have recently become evident which could signal a downturn in the course of economic growth and energy consumption over the next 35 years compared with the past 35 years. If the lower trends in fertility rate[14] and labor productivity should continue to operate over the long term (as now appears probable), the actual growth in energy demand would be well below that projected in the great majority of scenarios put forward during the past few years. Lower projections considered to be more realistic than the higher ones proposed in other studies have been estimated in a separate IEA study.[15] A summary of these projections is presented here and used in this study.

Population and Economic Growth

Economic growth can be considered as the product of two factors: the growth in the labor force and the growth in average productivity or output per worker. The growth of the labor force in turn depends on population growth and on changes in the rate of participation in the labor force, especially as influenced by changing employment patterns for women, minority groups, those under 20, and those over 55. The growth in productivity depends on the stock of capital goods, the current rate of new capital formation, the application of new technology, the availability of essential supporting services (transportation, communication, and financial facilities), the availability of raw materials and energy needed for industry, the quality of managerial skills, and government policies.

1. Labor force

The growth projections for the labor force are based on two different assumptions about future U.S. population growth. The lower population projection assumes that the fertility rate (average number of children per woman of childbearing age) will continue to drop from the current rate of 1.8 to 1.7 by the year 2000 (U.S. Bureau of the Census Series III).[16] The higher population projection assumes that the fertility rate will reverse and increase to 1.9 by the year 2000. The historic annual total fertility rates and our lower and higher projections are shown in Figure 1. Our projections for population and labor force and our assumed participation rates are presented in Table 9.

There is essentially no numerical difference in our labor force projections until after 1995. For each of our scenarios the participation rate is assumed to increase from the current 0.61 to 0.63 by the year 2000. This reflects a balance between continued increased participation in the labor force by women and minority groups and a continuation of the trend toward earlier retirement by those over 60.

2. Average productivity

Growth in labor productivity depends on several factors which we have listed previously. The historic trend since 1940 shows an overall 35-year average annual increase of 1.6 percent.[17] In the period 1950-1965 there was 2.2 percent growth; in the period 1965-1975 there was 0.9 percent growth. Historic trends since 1940 and alternative projections to 2010 for GNP, labor productivity, and labor force are shown in Figure 2. We have assumed for the *lower* case that future annual growth rates for labor productivity will be 1.7 percent until 1985, 2.0 percent from 1985 to 2000, and 2.05 percent from 2000 to 2010. For the *higher* growth case, we have assumed that the productivity growth rates will be 1.7 percent, 2.2 percent, and 2.4 percent, respectively. We believe that both the lower and higher projections are on the high side, considering the difficulties that have been experienced and can be expected in raising investment capital, and considering recent trends in work-related attitudes.[18]

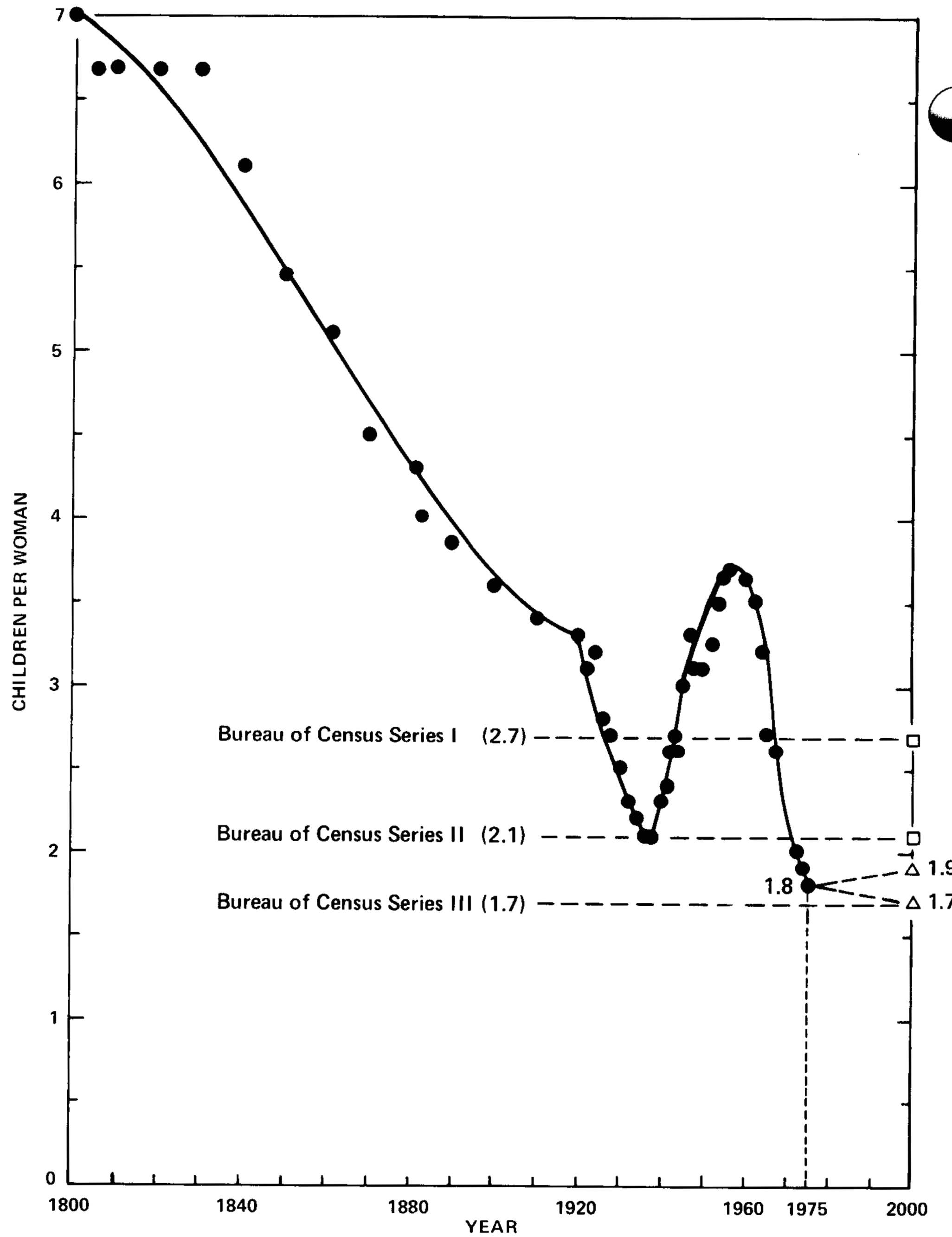
3. Gross national product (GNP)

Growth in GNP equals growth in labor force plus growth in labor productivity. Economic growth rates for our lower and higher cases are presented in Table 10. Using these growth rates, projected values of GNP are developed as shown in Table 11.[19]

4. Energy use and GNP

For the past 50 years the ratio of GNP to energy demand has generally increased in spite of declining energy prices during the same period.[20,21] In the

Figure 1 U.S. total fertility rates.



early years of this period, the increasing ratio (a type of efficiency) was largely due to technological innovations. More recently it can be accounted for by shifts in the structure of the economy toward such larger service-oriented sectors as education, travel, and health care.

Energy Demands

In the study undertaken for ERDA,[22] we estimated future U.S. energy demand by dividing energy use into five broad sectors—households, commercial space, personal automobiles, transport of goods and services, and industrial processes as shown in Table 12. Estimates of the future energy demand growth in

TABLE 9. Population and Labor Force Projections

	Low projection				High projection			
	Population (10^6)		*Partici-pation rate*	*(10^6) Labor force*	*Population (10^6)*		*Partici-pation rate*	*(10^6) Labor force*
Year	Total	16 and over			Total	16 and over		
1975	213	156	0.61	95	213	156	0.61	95
1985	228	177	0.625	110	231	177	0.625	110
2000	245	195	0.63	123	254	197	0.63	124
2010	250	204	0.63	128	264	210	0.63	132

each sector were determined by combining demographic-economic assumptions with assumptions about improved technical changes in specific energy-consuming devices. Final energy demands were obtained by moving from population projections to estimates of "intermediate factors"—households, commercial space,

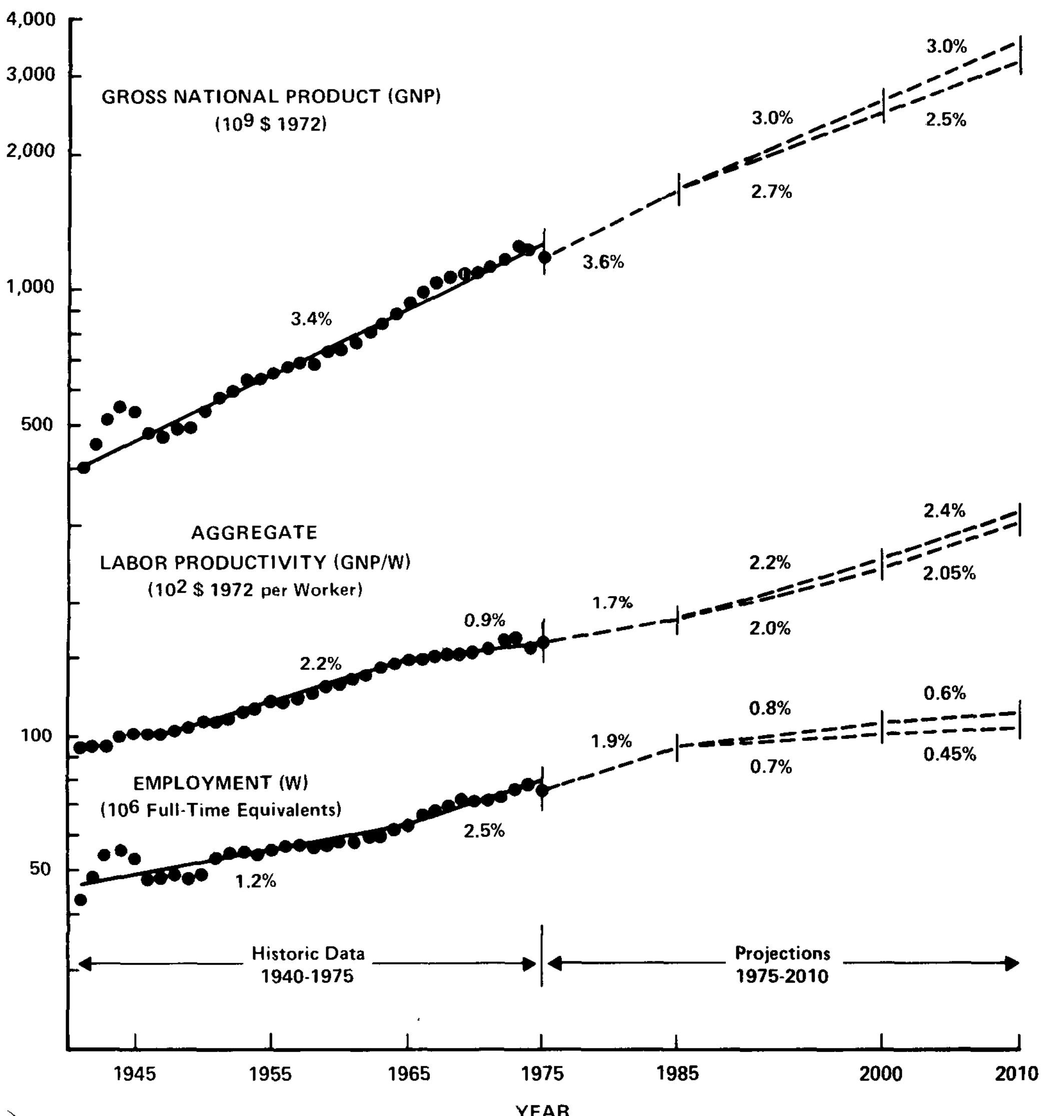


Figure 2 Growth trends in the U.S. GNP, labor productivity, and employment (1940-2010).

automobiles, services transport, and industrial output—and then to final energy-use categories. The specific energy demands determined by analyzing each end-use category were summed and divided by the corresponding projections for GNP to obtain values for energy productivity (the reciprocal of an E to GNP ratio).

1. Intermediate factors

Actual projections for the first three intermediate factors—the number of households, the square feet of commercial space, and the number of automobiles—were developed from population projections broken down by age groups. These are presented in Table 13. For each case a lower and a higher scenario were developed.

The intermediate factors are used in combination with technical efficiency factors to determine specific energy demands for each category. Households, commercial space, and automobiles are directly related to population; industrial output and transportation are directly related to the GNP. Figure 3 illustrates these relationships.

2. Energy demand by sector and end use

Growth factors for energy demand in the *household sector* were determined from population projections by assuming those over 21 years of age are eligible to form households. By combining the number of households with assumptions about future average size of housing units (or energy use per household) and future efficiency factors for household energy technologies, we have projected household energy demands for each energy use. These steps are illustrated in Figure 4.

We determined the growth of energy demands in the *commercial sector* from the projected number of households and from assumptions about the amount of commercial space required to serve each household (a commercial space-household ratio). (This is a surrogate for the services sector which reflects direct and indirect services to households.) By combining the projected commercial space with assumptions about improved energy-use technologies in this sector, we developed our estimates for commercial-sector energy demands.

We have estimated growth factors of energy demands for the *personal automobile* from the population projections of the 16-and-over age group and

TABLE 10. Annual Growth Rates
(percent)

Period	Participating labor force	Average productivity	GNP
	Low-growth case		
1975-1985	1.9*	1.7	3.6
1985-2000	0.7	2.0	2.7
2000-2010	0.45	2.05	2.5
	High-growth case		
1975-1985	1.9*	1.7	3.6
1985-2000	0.8	2.2	3.0
2000-2010	0.6	2.4	3.0

*Assumes a reduction in unemployment to a 4-5 percent level during this decade.

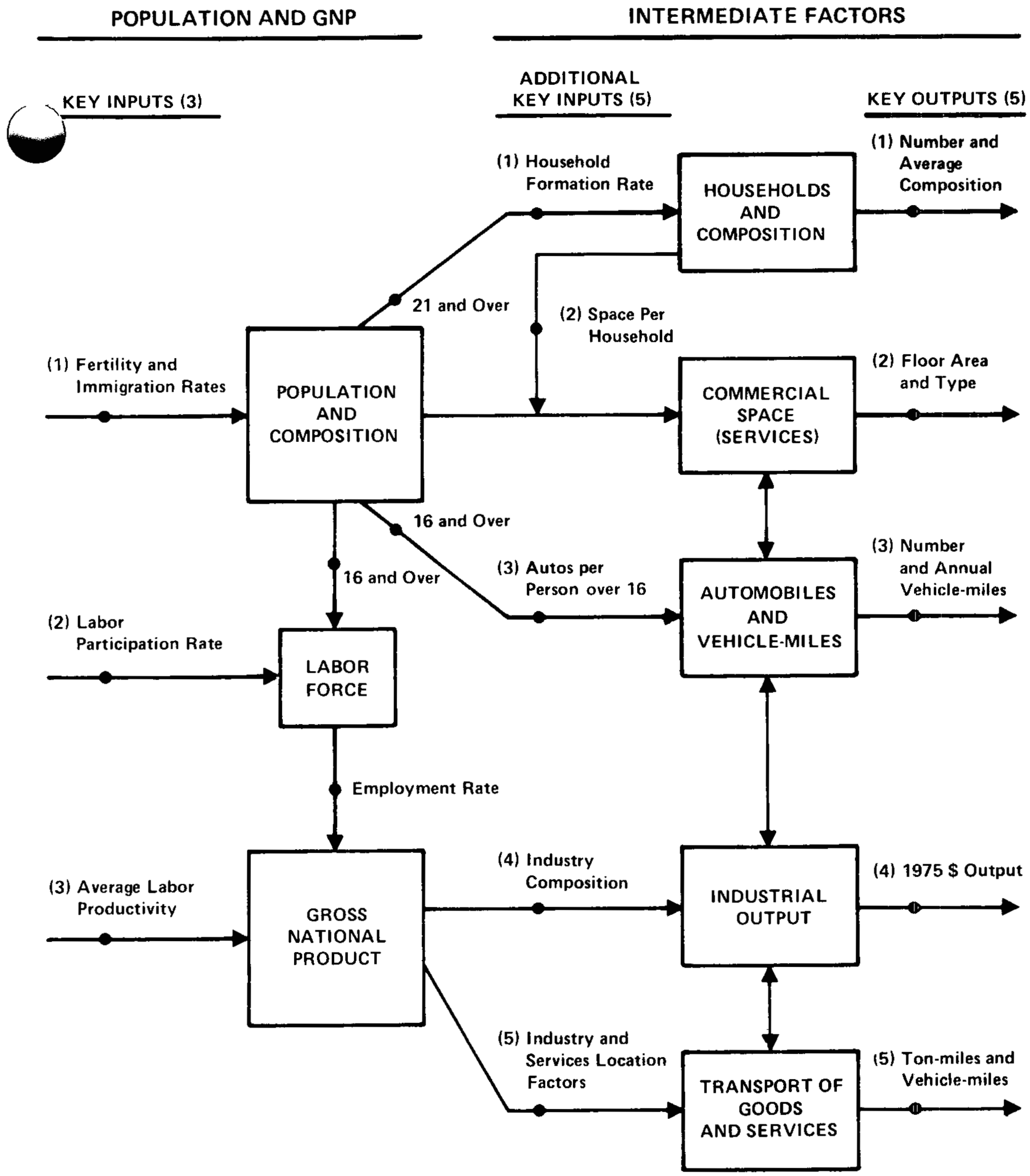


Figure 3 The relations between population and GNP, and intermediate factors.

from assumptions about the number of autos per person over 16 years of age. This yielded projections for the annual inventory of personal automobiles. Annual mileage per vehicle and improved mileage efficiencies were then combined with this inventory to obtain projected energy demands.

The growth rates of energy consumption in the *industrial sector* and in the *transport of goods and services* are more directly related to growth in GNP than to population growth. Consequently, we first projected the growth of GNP from population projections, labor force participation rate, employment rate, and labor productivity. We assumed that the average growth rate in the industrial sector and in the transportation of goods and services would be the same as the growth in GNP. The growth rates assumed for the individual end-use categories were different. These assumed rates were then combined with judgments about changes in the efficiencies of energy use to obtain the projected energy demands for each use category.

We established the quantitative relationships between energy demands, the intermediate factors, and the economic and demographic factors by examining in some detail the energy required to operate the specific service and process equipment in each sector of the economy. On the basis of these energy demand relationships, estimates of future demands were made through the year 20[illegible] taking into account various factors governing economic growth and ene[illegible] demand. This involved making certain specific assumptions about househo[illegible] formation, requirements for commercial space, use of the personal automobile, and industrial output (as described earlier), and about changes in the effective efficiencies for various end-use processes as described below. These are presented in Table 14.

3. New technologies and improved efficiencies

Changes in the effective energy efficiencies for each end-use device were determined from assessments of currently available and near-term improved energy-use technologies not now uniformly or widely used. We identified several conservation technologies as being potentially favorable for commercialization. Those which would have the largest impact on energy savings if promoted through price inducement, tax differentials, or government intervention are

(1) Smaller, lighter-weight automobiles and service trucks with more efficient engines and transmissions using less steel and aluminum per vehicle.

(2) New building designs to take advantage of static solar heating and improved insulation standards. Improved electric heat pumps, some of which are designed to freeze ice in the winter for heating and to thaw ice in the summer for cooling.

(3) New industrial boiler designs for process steam and heat from fluidized-bed coal combustion. Improved heat recovery processes in the energy-intensive manufacturing industries.

(4) Electric load-level switching for the large appliances and hot water heaters in households as well as load leveling for the large consumer of electricity.

Over and above these, we expect improved efficiencies in other energy-use devices as well as in the electric generating and transmission efficiencies through use of superheaters, topping and bottoming cycles, and transmission and switching equipment. We also expect that cogeneration of electricity and process heat for industrial use will become more widespread. However, since the gains from improved electric generating efficiencies may be balanced by losses resulting from required increased pollution control, we have not factored in credits for such improvements.

We arrived at the projected effective energy efficiency for each end-use device by first assessing the potential improvements and time schedules put forward in several conservation studies.[23] Among those we considered were studies by the National Petroleum Council,[24] the Dow Chemical Company,[25] the Council on Environmental Quality,[26] the American Institute of Physics,[27] the Energy Policy Project,[28] the Energy Research and Development Administration,[29] and the Federal Energy Administration.[30] We have incorporated less drastic efficiency improvement factors than most of these reports would suggest. Our estimates of efficiencies are based on the assumption that energy prices will escalate at an average net annual rate 2.0 percent higher than prices in the general economy.

4. Specific energy demands

By combining growth factors with improved efficiency factors, we have obtained the energy demands by sector for the lower and the higher growth cases as shown in Table 15. These scenarios project much lower energy demands than do most other projections. Thus, we estimate that the demand will be 101 q by

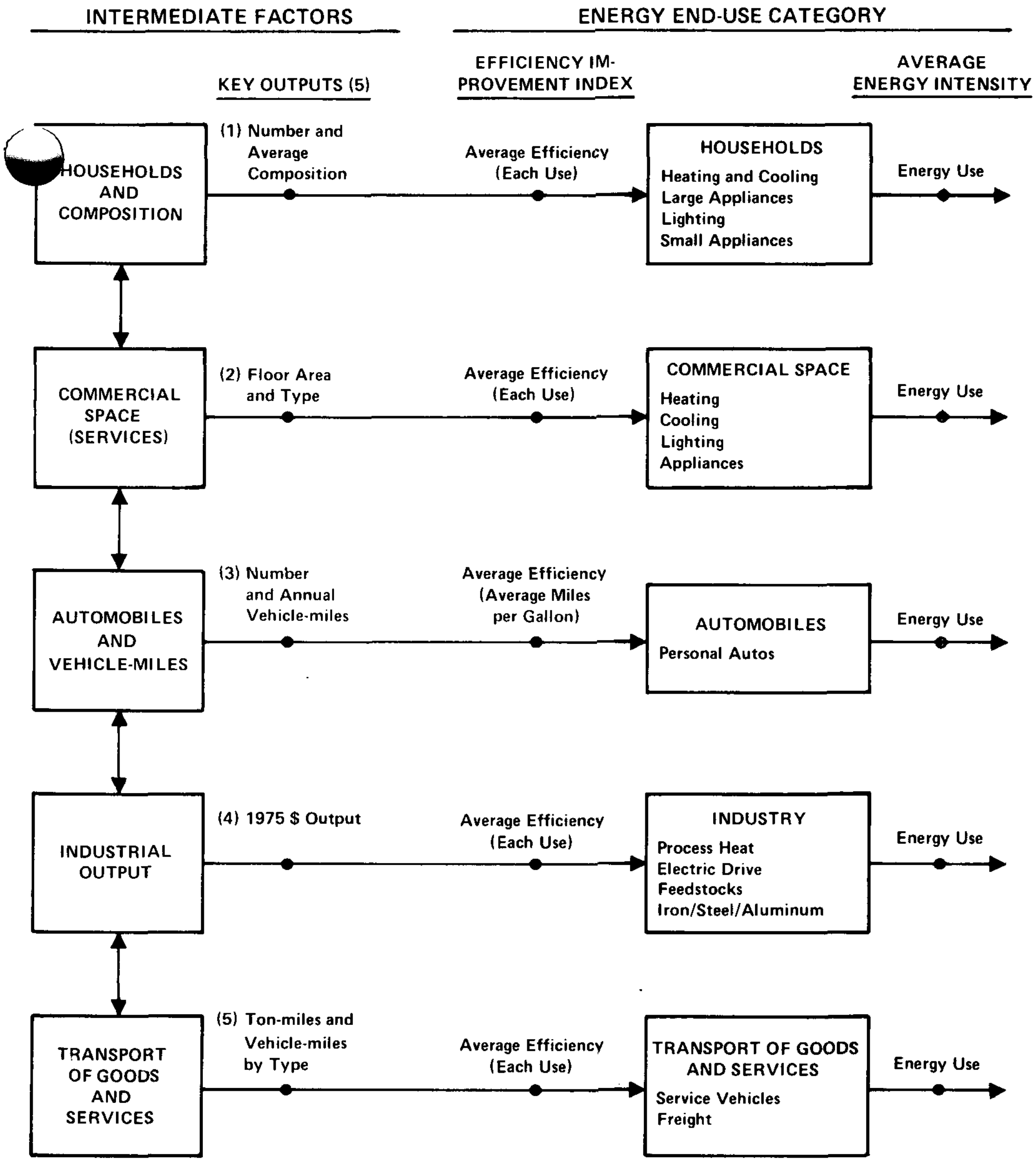


Figure 4 Relations between intermediate factors and energy demands.

the year 2000 in the lower case, and 126 q by 2000 in the higher case. It should be noted, however, that our estimates for electricity demand are only slightly lower than estimates in other studies[31,32] (47 q of fuel for electricity by the year 2000 in the lower case, and 64 q in the higher case); savings occur mostly in oil and gas, which are in short supply. The specific fuel demands shown in Tables 16 and 17 result from technical strategies used for conservation and from a deliberate shift from oil and gas to coal and electricity. The introduction of available newer technology timed to coincide with the normal replacement of energy-using devices will shift the mixture of future fuel demands. Individual energy demands were derived from our growth assumptions and estimates of technical efficiencies, and the total energy demands were obtained from the summing of the individual energy demands.

Historic data and projections for total energy demand, total GNP, GNP to energy ratio, per capita energy use, and per capita GNP are presented in Figures 5 and 6. Note that in the higher scenario the growth rate in per capita energy use for the next 35 years approximates the average growth rate for the past 35 years,

TABLE 11. Gross National Product (GNP) and Labor Force

Year	Population (10^6) 16 and over	Labor: *Jobs per 16 and over*	Labor: *Labor fo[illegible] (10^6)*
		Low case	
1975	156	0.61	95
1985	177	0.625	110
2000	195	0.63	123
2010	204	0.63	128
		High case	
1975	156	0.61	95
1985	177	0.625	110
2000	197	0.63	124
2010	210	0.63	132

Year	Employment: *Full-time equivalent (10^6)*	Labor productivity*: *(10^3 $ per worker)*	GNP*: *(10^9 $)*
		Low case	
1975	77.0	19.5	1,499
1985	92.9	23.0	2,135
2000	103.3	30.8	3,184
2010	108.1	37.7	4,076
		High case	
1975	77.0	19.5	1,499
1985	92.9	23.0	2,135
2000	104.6	31.8	3,326
2010	111.4	40.1	4,470

*Output per worker and GNP are in 1975 dollars.

and that the projected growth in per capita GNP exceeds the average historic growth rates.

Energy Supply Scenarios

For each of the two demand scenarios presented in the previous section, three alternative energy supply options for electricity have been developed.[33] The alternatives differ mainly in their underlying pricing and policy constraints. Only one supply option for the direct use of coal, oil and gas, and heat is presented for each demand case.

1. Supply assumptions

In the first supply option for electricity (base supply), we have assumed that nuclear reactors will expand beyond currently planned 1985 capacity commitments (175,000 MW) to between 450,000 and 512,000 MW by the year 2000.[34]

In the second supply option (coal supply), we set the number of reactors at the scheduled 1985 level to reflect our hypothetical moratorium on new construction beyond 1980. In this option, the projected additions to nuclear capacity are shifted to coal-steam systems. The third supply option for electricity (imported oil supply) assumes the same moratorium, but the projected nuclear capacity additions between 1985 and 2000 are replaced by oil-fired generating plants using imported oil; after 2000, additional new units are coal fired. (The shift of new units to coal after 2000 reflects our estimate that world oil production will peak in the year 2005.)

Requirements for liquids and gases in our scenarios will be met primarily by domestic oil and gas including new additions from Alaskan and offshore reserves. These will be supplemented by (1) oil from the richer shale deposits when oil prices rise to about $16-18 per barrel (measured in 1975 prices) around 1985[35]; (2) synthetic oil from coal when prices rise to about $25 per barrel around the year 2000[36]; and (3) continuation of imported oil to provide the required difference to meet demands. Future U.S. energy supplies of liquids and gases are expected to be a changing mixture comprised of these four fuel sources. The particular mixture at a specific given time will depend on world oil prices, opportunities for fuel substitutions, and government policy. The supply strategies

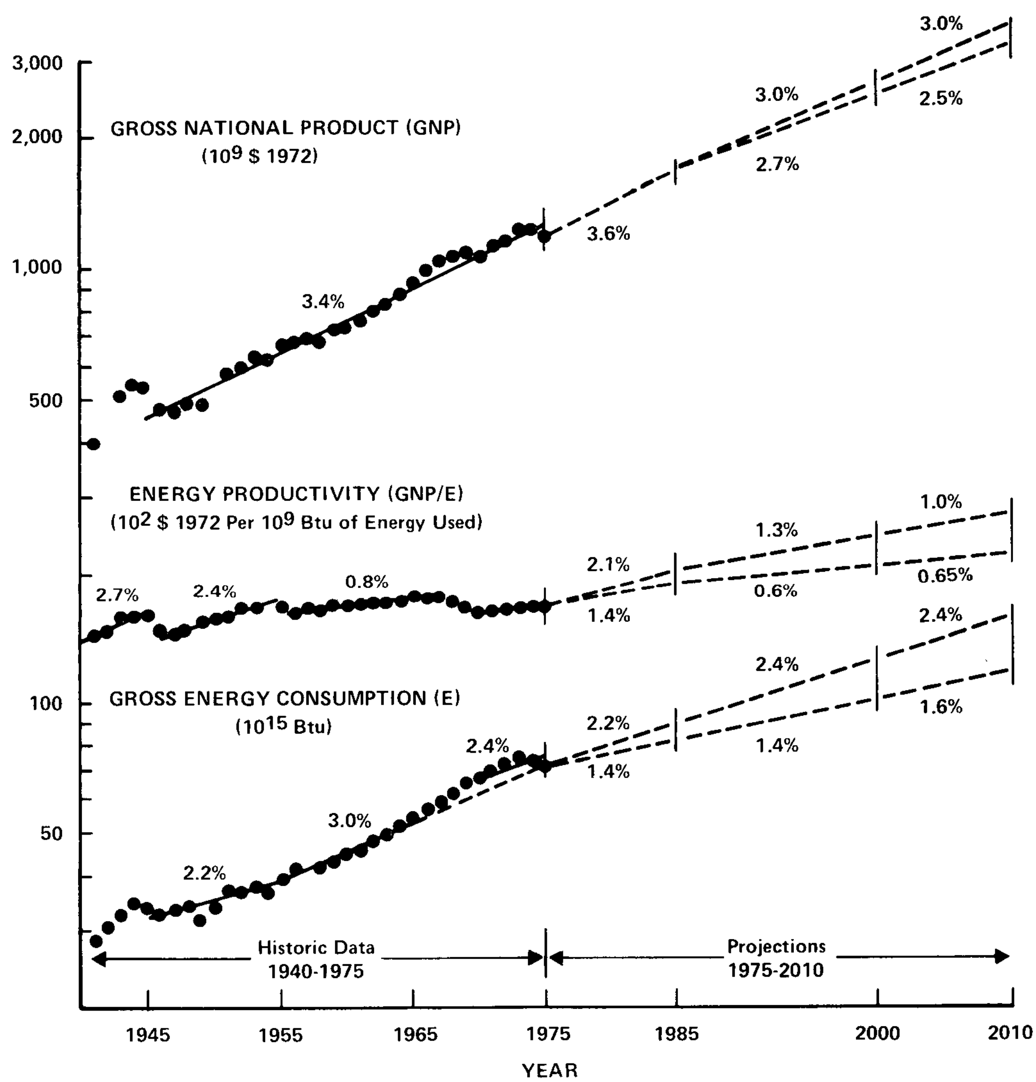


Figure 5 U.S. GNP, energy productivity, and energy use.

TABLE 12. Summary of 1975 U.S. Energy Demands by Source
(fuel inputs to sectors in 10^{15} Btu)

Use category	Coal	Oil	Gas	Elect.	Other elect.	Total
Households	–	3.8	4.9	7.1	–	15.8
Space heating/cooling		3.1	3.7	1.5		8.3
Lighting/small appliances				3.8		3.8
Water/large appliances		0.7	1.2	1.8		3.7
Commercial space	0.3	2.0	2.5	4.5	–	9.3
Space heating/cooling	0.3	1.9	2.1	0.9		5.2
Lighting/small appliances				3.3		3.3
Water/large appliances		0.1	0.4	0.3		0.8
Automobiles	–	8.3	–	–	–	8.3
Transport of goods and services	–	9.6	0.6	0.1	–	10.3
Service vehicles		2.8				2.8
Truck/rail/bus/tractor		3.5		0.1		3.6
Air transport		2.4				2.4
Ship/barge/pipeline		0.9	0.6			1.5
Industrial processes	4.3	5.7	9.0	8.4	–	27.4
Process steam/heat–high/low	1.7	1.9	8.3			11.9
Iron/steel	2.4			0.4		2.8
Aluminum				0.8		0.8
Electric drive/lighting				7.2		7.2
Feedstocks	0.2	3.8	0.7			4.7
Electricity inputs	8.8	3.3	3.2	20.1	4.8	–
Totals (10^{15} Btu)	13.4	32.7	20.2	–	4.8	71.1
Percent of total	18.7	46.0	28.4	(28.3)	6.9	100.0

sketched here would meet the demand requirements assessed in the previous section at prices which we will discuss later.

2. Electricity

In the event of a nuclear moratorium, we believe that demands for electricity will be met by the use of all available low-cost local energy resources from hydroelectric, solar, and geothermal sources; the use of currently planned nuclear capacity to 1985, followed by one of our post-1985 options; and the use of coal-steam systems for the balance of the base load and intermediate load electric generation. The peak load would continue to be provided by oil- and gas-fired systems to augment hydroelectricity, but these oil and gas systems would be retired as future peak load requirements decrease through improved load-level management by consumers and addition of pumped storage systems by the utilities.

Proposed systems for generating electricity include solar electricity and fusion systems. These systems are now under development, and their economics have not been sufficiently demonstrated to include a contribution before the year 2000. In the supply options assumed here, solar electricity contributes 1 q by 2000 and 3 q by 2010.[37] The fusion systems are not expected to be available until sometime well after 2010.[38] The results of this study do not depend on any distinction between the light water reactor (LWR) and liquid metal fast breeder reactor

(LMFBR) until after 2010, but the long-term viability of the nuclear option does depend on the ultimate development of breeders.

3. Domestic oil and gas

In all our supply options the projected production schedule for domestic oil and gas was based on a production-depletion resource curve which uses the U.S. Geological Survey's recently published estimates for the most probable recoverable U.S. oil and gas.[39] This schedule (shown in Figure 7) assumes a policy of price deregulation on both fuels so that production from Alaskan and offshore reserves will flow before 1985. Even with price deregulation and the additional production expected from Alaskan and offshore sites, domestic oil and gas production is expected to peak about 1985. At about this time, oil from the high-grade Western shales (25-100 gal/ton) can be produced at $16-18 per barrel (in terms of 1975 prices). This production is expected to rise to about 8.5-9.5 q by the year 2000, and to 11-14 q by 2010. We do not believe that oil produced from shale is likely to be limited by lack of water in the western United States until after 2000, when production reaches the projected 10-14 q level.[40] The oil production scenario uses synthetic oil from coal beginning about the year 2000.

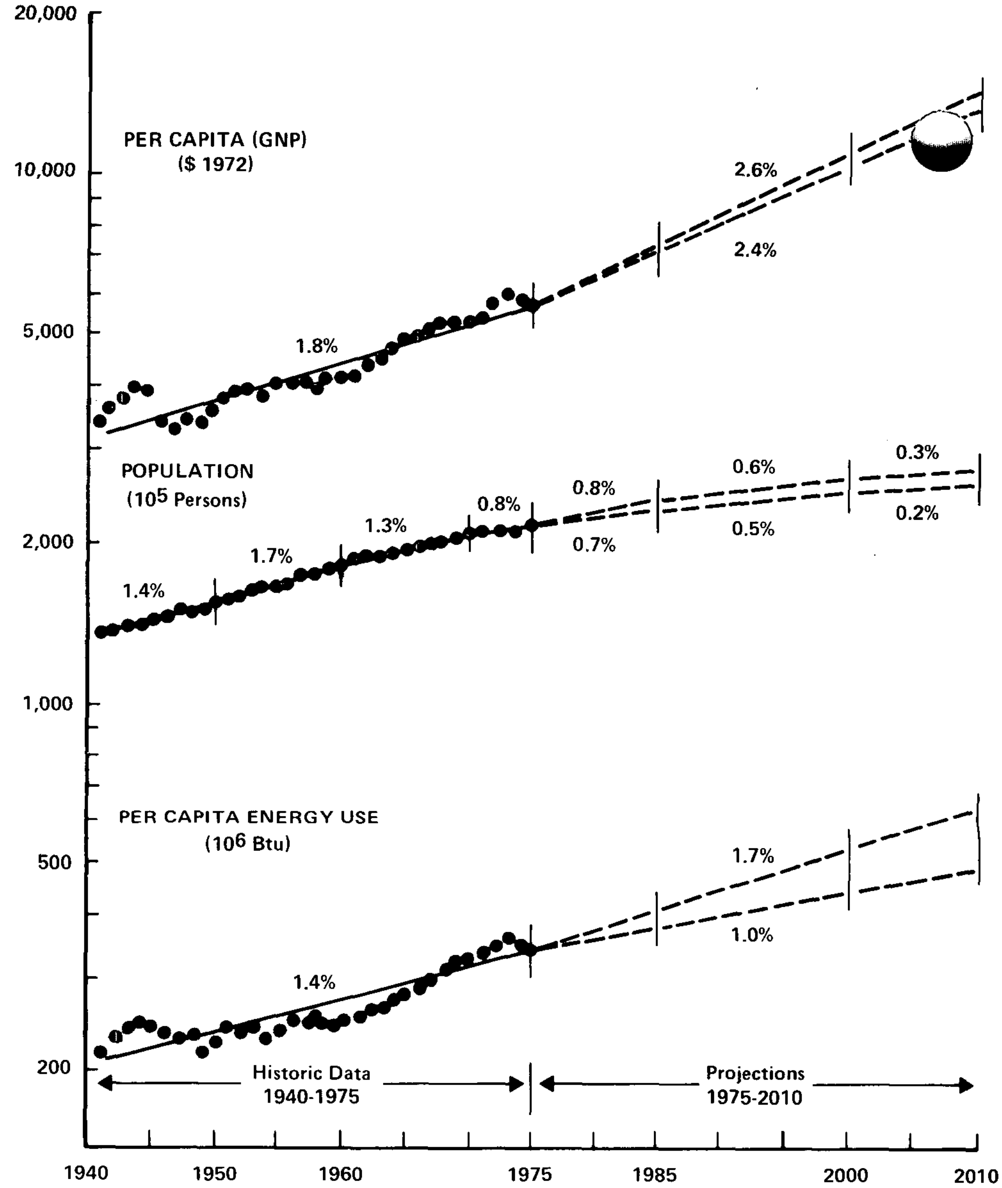
TABLE 13. Projections of Households, Commercial Space, and Autos

	Population (10^6)		Households	
Year	*21 and over*	*16 and over*	*No. per adult**	*No. (10^6)*
		Low case		
1975	135	156	0.53	72
1985	158	177	0.55	87
2000	177	195	0.57	101
2010	186	204	0.56	104
		High case		
1975	135	156	0.53	72
1985	158	177	0.55	87
2000	178	197	0.57	101
2010	191	210	0.56	107

*In this instance, an adult is considered to be over 21 years of age.

	Commercial space		Autos	
Year	*Ft² per household*	*Amount (10^9 ft²)*	*No. per 16 and over*	*No. (10^6)*
		Low case		
1975	350	25.2	0.67	105
1985	350	30.5	0.65	115
2000	350	35.4	0.65	127
2010	350	36.4	0.64	130
		High case		
1975	350	25.2	0.67	105
1985	387	33.7	0.71	126
2000	449	45.3	0.77	152
2010	496	53.1	0.79	166

Figure 6 Trends in growth of U.S. population, per capita GNP, and per capita energy use.



By the year 2010 about 10-20 q of synthetic fuel is produced from coal sources, which is likely to be, over the long term, a basic source for industrial petrochemical feedstocks.[41]

4. Supply strategies for liquids, gases, and electricity

Table 18 describes each supply strategy considered in this analysis for liquids and gases and for electricity. Each strategy is listed from least costly to most costly. We assume that imported oil will not amount to more than about 50 percent of total oil consumption.

5. Direct heat and coal

In addition to the sources we have listed, useful heat is available directly from geothermal and solar sources, from the cogeneration of process heat with electricity, and from the direct use of coal for process steam and heat.[42] These heat sources will have limited and specific uses for heating buildings and industrial processing.

The growth in the total projected demand (in 10^{15} Btu) for coal, as shown in Table 19 for the nuclear supply case, is 2.2 percent annually to 1985, 4.3 percent per year from 1985 to 2000, and 6.0 percent after 2000. The growth rates for coal in the high scenario with a moratorium are presented in Table 31. The high growth rates after 1985 range between 5 and 9 percent per year and are well within the constraining limits placed on coal expansion by several recent studies[43]; nevertheless, the extraction of 4.8 billion tons of coal in one year (as projected in 2010 for high demand and the moratorium) appears formidable.

6. Summary

Summaries of base case energy sources to meet the demands are found in Tables 20 and 21. Three alternative supply options for electricity (labeled "Base Supply," "Coal for Nuclear Supply," and "Imported Oil for Nuclear Supply") are presented in Tables 21 and 22 for each demand case. Table 23 gives sources of liquids and gases.

Energy Prices

Estimates of future energy prices over the next three and one-half decades obviously involve great uncertainties. We expect, however, that average energy prices will increase more rapidly during this time than general prices in the

TABLE 14. Major Energy-Saving Technical Strategies

1. Household and commercial heating, cooling, hot water, lighting, and appliances

A. Construct new buildings with better design and insulation standards and with improved heat pumps such as solar-assisted Annual Cycle Energy System (ACES). Cut average heat losses by 1.3 and fuel requirements by 1.5 on all new construction. Retrofit existing buildings to cut fuel requirements by an average of 1.69 on retrofits. Shift oil- and gas-fired systems to be retired to electric heat pump systems.

B. Improve water heater insulation and eliminate severe pipe losses. Improve large appliance efficiencies. Fuel requirements per unit decrease by 1.05 in 1985, 1.08 by 2000, and 1.10 by 2010 for hot water, cooking, refrigeration, and clothes drying.

C. Improve H/C electric lighting and small electric appliance efficiencies by 1.05 by 1985, 1.08 by 2000, and 1.10 by 2010.

2. Transportation

A. Manufacture lighter-weight automobiles and service trucks with more efficient engines and transmissions using less steel and aluminum per vehicle. Increase the average miles per gallon for autos from current 14 to 20 by 1985, to 27 by 2000, and to 30 by 2010; and for service trucks from current 11 to 14 by 1985, to 18 by 2000, and to 20 by 2010.

B. Improve the efficiencies in other transport modes through improved engine efficiencies, vehicle design, and vehicle load and route strategies. Improve overall efficiencies by 10 percent by 1985, 15 percent by 2000, and 17 percent by 2010.

3. Industrial process steam and heat, and electric drive

A. Improve industrial boiler design and heat recovery processes, cutting fuel consumption per unit 1.15 by 1985, 1.25 by 2000, and 1.30 by 2010. Shift industrial boilers for low-temperature heat and steam from oil and gas to the direct use of coal and nuclear or to electricity.

B. Improve iron/steel processes and aluminum processes to decrease average energy use per ton 1.05 by 1985, 1.10 by 2000, and 1.12 by 2010.

C. Improve industrial electric lighting efficiencies by 1.10 by 1985, 1.17 by 2000, and 1.20 by 2010.

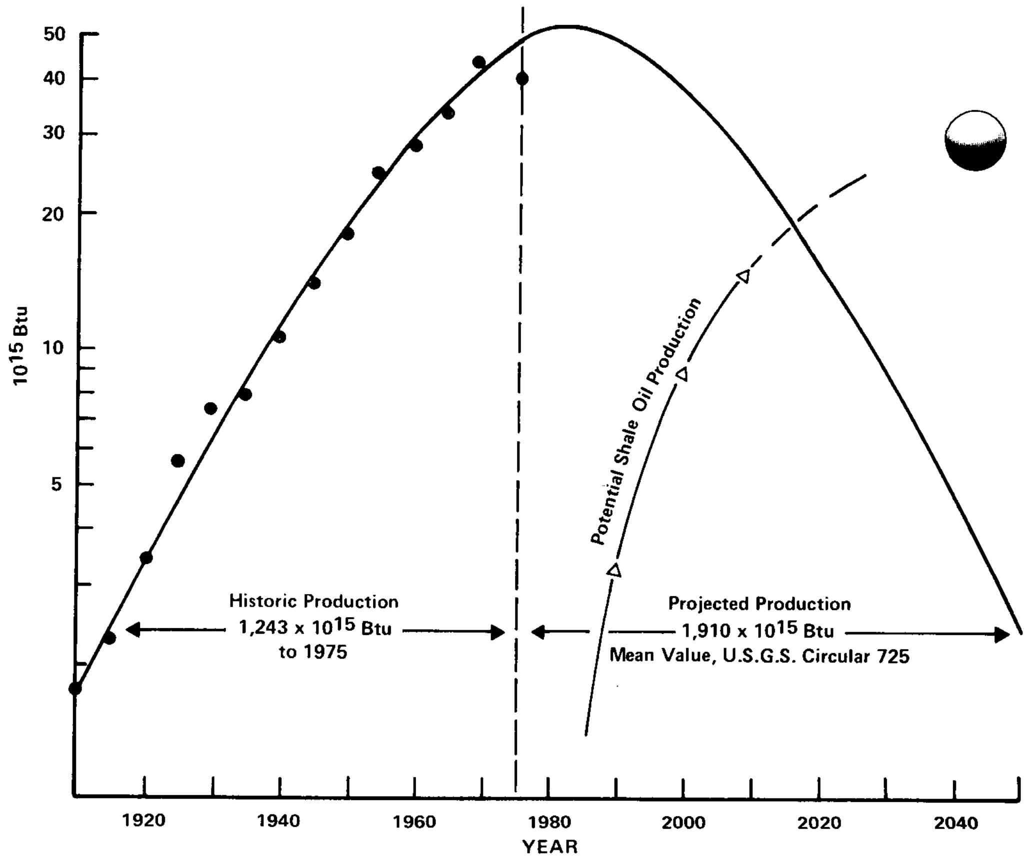


Figure 7 Estimated U.S. production of oil and gas, and shale oil potential.

economy because (1) world energy demands will keep growing in response to population and GNP growth and (2) more costly energy resources will be tapped and transported at higher costs to satisfy these demands. In the short term,

TABLE 15. Summary of Energy Demand Scenarios by Sector
(energy inputs in 10^{15} Btu)

	1975	1985	2000	2010
Lower scenario—total (with improved efficiencies)	71.1	82.1	101.4	118.3
Transportation	18.6	19.2	22.2	25.3
Residential	15.8	17.2	18.0	17.7
Commercial	9.3	10.2	10.9	10.8
Industrial	27.4	35.5	50.3	61.3
Coal to oil conversion losses				3.2
Higher scenario—total (with improved efficiencies)	71.1	88.0	125.9	158.8
Transportation	18.6	21.4	28.1	33.9
Residential	15.8	19.3	24.3	26.8
Commercial	9.3	11.8	15.4	17.9
Industrial	27.4	35.5	58.1	73.1
Coal to oil conversion losses				7.1

TABLE 16. Summary of Total and Sector Energy Inputs by Source, 1975-2010
(quads or 10^{15} Btu—lower case, 101.4 q by 2000)

	Total	Direct fuels: Coal	Oil	Gas	Elect.	Heat
1975						
Transportation	18.6		17.9	0.6	0.1	
Residential/commercial	25.1	0.3	5.8	7.4	11.6	
Industrial	27.4	4.3	5.7	9.0	8.4	
Total	71.1	4.6	29.4	17.0	20.1	
1985						
Transportation	19.2		18.4	0.6	0.2	
Residential/commercial	27.4	0.1	2.7	7.4	17.2	
Industrial	35.5	6.1	4.7	10.7	13.4	0.6
Total	82.1	6.2	25.8	18.7	30.8	0.6
2000						
Transportation	22.2		21.2	0.6	0.4	
Residential/commercial	28.9		0.7	2.8	25.4	
Industrial	50.3	10.6	6.0	10.2	21.5	2.0
Total	101.4	10.6	27.9	13.6	47.3	2.0
2010						
Transportation	25.3		24.2	0.6	0.5	
Residential/commercial	28.5			1.3	27.2	
Industrial	61.3	15.2	7.0	7.3	27.8	4.0
Total	115.1	15.2	31.2	9.2	55.5	4.0
Coal to oil conversion losses	3.2					
Total	118.3					

unsettling events of limited duration could bring sharp, but temporary, price increases.

1. Coal

Since coal-fired plants are more likely to substitute for nuclear power than are oil-fired ones, we have given careful consideration to future trends in coal prices in the event of a moratorium. Coal reserves in the United States are very large and coal does not appear to present a production problem, at least over the next 25 years. However, the lead time needed to develop large underground mines is about 4-5 years. Surface mines, the predominant mine type in the western United States, can be developed more quickly, but the process is still time consuming.[44]

Hence coal supply is not elastic in the short run. In the long run, since production is not concentrated in a few firms and the entry of new firms is not impeded by either institutional constraints or higher capital costs, coal prices are expected to approximate the costs of production, defined to include an economy-wide average rate of profit.

Projections of coal prices to 1985 have been estimated by the Federal Energy Administration for individual geographic regions. For representative regions, these p[illegible]cted price increases between 1975 and 1985 are calculated to be about 22

TABLE 17. Summary of Total and Sector Energy Inputs by 1975-2010 (quads or 10^{15} Btu—higher case, 125.9 q by 2000)

	Total	Direct fuels: Coal	Oil	Gas	Elect.	Heat
1975						
Transportation	18.6		17.9	0.6	0.1	
Residential/commercial	25.1	0.3	5.8	7.4	11.6	
Industrial	27.4	4.3	5.7	9.0	8.4	
Total	71.1	4.6	29.4	17.0	20.1	
1985						
Transportation	21.4		20.6	0.6	0.2	
Residential/commercial	31.1	0.1	2.7	7.4	20.9	
Industrial	35.5	6.1	4.2	11.6	13.0	0.6
Total	88.0	6.2	27.5	19.6	34.1	0.6
2000						
Transportation	28.1		27.1	0.6	0.4	
Residential/commercial	39.7		0.7	2.8	36.2	
Industrial	58.1	11.2	7.3	10.2	27.4	2.0
Total	125.9	11.2	35.1	13.6	64.0	2.0
2010						
Transportation	33.9		32.8	0.6	0.5	
Residential/commercial	44.7			1.3	43.4	
Industrial	73.1	14.2	9.1	7.3	38.5	4.0
Total	151.7	14.2	41.9	9.2	82.4	4.0
Coal to oil conversion losses	7.1					
Total	158.8					

percent, measured in constant 1975 dollars. We have used the same annual percentage increase (2 percent) for the period beyond 1985.[45]

Given the slow growth in additional coal-fired generating facilities, would the real costs of coal expansion push coal prices up faster than a net 2 percent per year? The greatest expansion of the coal industry, experts believe, will come

TABLE 18. Ranking of Energy Supply Strategies

Liquids and gases	Electricity
1. Domestic oil and natural gas	1. Local sources of hydroelectric, geothermal, and wind energy
2. Liquids from shale*	2. Light water reactors (tossup)
3. Synthetics from coal*	3. Coal-fired plants (tossup)
4. Imported oil (includes vulnerability costs)	4. Advanced systems of solar, breeder, and fusion

*These sources will not be developed until they cost less than import

TABLE 19. Summary of Total Coal and Other Direct Heat (1975-2010)
(quads or 10^{15} Btu—base case)

Year	Low case			High case		
	Total	*Indust.*	*Elect.*	*Total*	*Indust.*	*Elect.*
1975	13.4	4.6	8.8	13.4	4.6	8.8
1985	16.3	6.2	10.1	16.6	6.2	10.4
2000	17.7	10.6	7.1	31.2	11.2	20.0
2010	26.3	24.3	2.0	49.0	34.5	14.5

about in the western United States. An Argonne National Laboratory study of expansion capability in the 1974-1982 period concludes that price increases will be moderate if annual growth does not exceed 25 percent per year. The same study expects actual growth to 1980 to be about 25 percent per year, reaching 120 million tons in that year from mines in Montana and Wyoming. The growth will be accompanied by an annual net price escalation of 3.3 percent.[46] This rate of expansion is far above that required to satisfy the coal needs of our scenarios; hence we would expect a lower rate of price increase.

2. Oil and natural gas

Domestic oil prices, on the other hand, are expected to increase substantially between now and 1985, and to equal world oil prices in or prior to 1985.[47] Although domestic price controls may be extended beyond May 1979, a net increase in world oil prices of 2.1 percent annually would bring them to $16 per barrel by 1985. (This is the estimated 1985 average price we have used in this analysis.) Thereafter, oil prices are expected to increase more rapidly as domestic production peaks (about 1985), even with the additional production from Alaskan and offshore sources.[48] (The Alaskan oil price structure will not be announced by the President until February 1977.) Extraction of oil in the longer term is expected to include increasingly difficult (and therefore higher-cost) environments, such as the Beaufort Sea.

TABLE 20. Summary of Total Energy Input Demands (1975-2010)
(by carrier in quads or 10^{15} Btu—all cases)

Year	Total	Coal	Nuclear	Oil and gas	Hydro and geothermal	Wind and solar
			Low case			
1975	71.1	13.4	1.7	52.8	3.2	—
1985	82.1	16.3	10.6	50.4	4.2	0.6
2000	101.4	17.7	27.2	46.3	8.2	2.0
2010	118.3	26.3	39.6	35.7	11.7	5.0
			High case			
1975	71.1	13.4	1.7	52.8	3.2	—
1985	88.0	16.6	10.6	56.0	4.2	0.6
2000	125.9	31.2	31.0	53.5	8.2	2.0
2010	158.8	49.0	53.4	39.1	11.7	5.0

As a bargaining tactic, the OPEC organization has insisted that future price adjustments should at least offset Western inflation.[49] During 1974-1975, inflation in other industrialized nations ran much higher than in the United States. These domestic price increases were reflected in goods imported to the Middle East from the West. Over this time period (and for the foreseeable future) the most visible price increases are those for military products imported into the Middle East (for which it is not possible to construct meaningful price indices). This makes "inflation" price increases for oil a matter of negotiation rather than exact determination. Under these circumstances, OPEC price demands could average 10 percent per year, or substantially more than the rate of U.S. inflation now expected. (If hourly wage increases in the United States can be kept below 9 percent, the anticipated growth in output per hour would hold domestic inflation to 6 percent or less annually.) Under the twin key factors expected to govern future oil prices after 1985—a fall in U.S. oil output and strong OPEC bargaining—domestic oil prices will be determined by world oil prices.[50] In our scenario we project a 3 percent annual increase above the rate of inflation.

We expect that shale oil will be in commercial use at the equivalent of $16-18 per barrel of oil (1975 prices). This would bring shale into the market during the 1985-1990 period; shale would account for about 9 q by the year 2000 and about 14 q by 2010, and then be limited by lack of water. Synthetics from coal are higher priced—about $25 per barrel—and are not incorporated in our supply scenarios until after 2000.[51]

Natural gas prices are assumed to increase by 1985 to $2.76 per 10^6 Btu, the equivalent Btu price for $16 per barrel of oil. The rapid price adjustment for natural gas, in the face of limited deregulation, began in 1975, when wellhead prices increased 43 percent.[52] Beyond 1985, natural gas prices are assumed to follow oil prices on a Btu basis.

3. Electricity

The future cost of electricity in the United States will depend on the mixture of electric generating plants in service, the economic factors governing discount and inflation rates and fuel costs, the demand for electricity as a substitute for processes now using oil and gas, and the specific regional characteristics related to energy demands and fuel supplies. The future demand for electricity is projected to grow to the year 2000 at an average annual rate of 3.5 percent for the lower-demand case and 4.8 percent for the higher case.

TABLE 21. Summary of Electricity Inputs (1975-2010)
(by source in quads or 10^{15} Btu)

Year	Total	Hydro and geothermal	Wind and solar	Oil and gas	Nuclear	Coal
			Base supply—low case			
1975	20.1	3.1	–	6.5	1.7	8.8
1985	30.8	4.2	–	5.9	10.6	10.1
2000	47.3	7.2	1.0	4.8	27.2	7.1
2010	55.5	9.7	3.0	1.2	39.6	2.0
			Base supply—high case			
1975	20.1	3.1	–	6.5	1.7	8.8
1985	34.1	4.2	–	8.9	10.6	10.4
2000	64.0	7.2	1.0	4.8	31.0	20.0
2010	82.4	9.7	3.6	1.2	53.4	14.5

TABLE 22. Summary of Electricity Inputs for Nuclear Moratorium Cases (1975-2010)
(by source in quads or 10^{15} Btu)

Year	Total	Hydro and geothermal	Wind and solar	Oil and gas	Nuclear	Coal
		Coal for nuclear supply—low case				
1975	20.1	3.1	–	6.5	1.7	8.8
1985	30.8	4.2	–	5.9	10.6	10.1
2000	47.3	7.2	1.0	4.8	10.6	23.7
2010	55.5	9.7	3.0	1.2	8.6	33.0
		Coal for nuclear supply—high case				
1975	20.1	3.1	–	6.5	1.7	8.8
1985	34.1	4.2	–	8.9	10.6	10.4
2000	64.0	7.2	1.0	4.8	10.6	40.0
2010	82.4	9.7	3.0	1.2	8.6	59.3
		Imported oil for nuclear supply—low case				
1975	20.1	3.1	–	6.5	1.7	8.8
1985	30.8	4.2	–	5.9	10.6	10.1
2000	47.3	7.2	1.0	17.4	10.6	11.1
2010	55.5	9.7	3.0	17.0	8.6	17.2
		Imported oil for nuclear supply—high case				
1975	20.1	3.1	–	6.5	1.7	8.8
1985	34.1	4.2	–	8.9	10.6	10.4
2000	64.0	7.2	1.0	25.2	10.6	20.0
2010	82.4	9.7	3.0	21.6	8.6	38.9

Our estimated prices of different energy modalities are summarized in Table 24.

4. Checks for consistency

A. Price and income elasticities

Our estimates of energy demand have not depended explicitly on projected

TABLE 23. Summary of Liquid and Gas Inputs (1975-2010)
(by source in quads or 10^{15} Btu—all cases)

Year	Total	Coal	Shale and biomass	Domestic crude	Imported crude	Domestic natural gas
			Low case			
1975	52.8	–	–	19.9	12.8	20.1
1985	50.4	–	0.3	20.8	6.7	22.6
2000	46.3	–	8.5	19.4	–	18.4
2010	44.8	9.1	11.0	14.3	–	10.4
			High case			
1975	52.8	–	–	19.9	12.8	20.1
1985	56.0	–	0.3	20.8	12.3	22.6
2000	53.5	–	9.5	19.4	6.2	18.4
2010	59.4	20.3	14.4	14.3	–	10.4

TABLE 24. Estimated Prices of Different Energy Modalities
(relative to 1975 in constant dollars)

	1975	1985	2000	201[illegible]
Coal	1.0	1.22	1.65	2.00
Oil	1.0	1.54	2.40	3.23
Gas	1.0	6.42	10.00	13.40
Electricity	1.0	1.22	1.65	2.00

Note: The 1975 average prices were as follows: coal, $17.50 per ton, delivered to utilities; oil, $10.40 per barrel, composite cost to refiners; natural gas, $0.43 per thousand cubic feet at the wellhead; electricity, 27 mills per kilowatt-hour (kWhr) to consumer.

prices or incomes, and it is important to check whether the price and income elasticities implied in our scenarios make sense. We have therefore estimated elasticities for each end-use sector by comparing the demands, prices, and incomes in our actual scenarios with the same quantities in a reference projection of demand which is our high scenario but with no efficiency improvements and essentially no price increases. The basic idea behind this procedure is that the higher prices lead to the improvements in efficiency and substitution assumed in our actual scenarios. We ask whether the prices and incomes we have assumed are likely to lead to the energy demands we have projected or even lower ones; and whether these elasticities are consistent with historically derived elasticities.

To determine price elasticities for our low and high scenarios (in comparison to the reference case), we have had to assume price cross-elasticities from various other studies. For the residential and commercial sectors, cross-elasticities developed by Chern at ORNL are used.[53] For the transportation sector, future demand is assumed to remain on oil and the cross-elasticities are taken to be zero (no fuel substitution). For the industrial sector, price elasticities for total energy have been estimated, since no cross-elasticities are available from other studies. Income elasticities from a FEA study are used to compare the low scenario with the reference case.[54] Table 25 gives a summary of results.[55] It is gratifying to note that these elasticities fall within the range of estimates from other studies.[56]

B. Macroeconomic modeling

As a further test of the internal consistency of our projections, we have constructed a modified constant elasticity of substitution economic model that relates GNP to labor, capital, technological change, and energy.[57] The model suggests that our projections of GNP are achievable with the price schedule that we have assumed; and that lower energy demands can be reached without serious economic effects if energy price increases are gradual and anticipated.

TABLE 25. Estimated Price Elasticities by Sector

	Low scenario				High scenario			
Sector	*Coal*	*Oil*	*Gas*	*Elect.*	*Coal*	*Oil*	*Gas*	*Elect.*
Residential	0	–0.97	–1.21	–1.08	0	–1.03	–1.43	–0.60
Commercial	0	–0.97	–1.21	–1.19	0	–1.03	–1.43	–0.61
Transportation	0	–0.57	0.08	0.08	0	–0.26	0	0
Industrial								
Total		–0.41				–0.29		

Economic Implications 4

Economic implications of a U.S. nuclear moratorium are examined here in terms of: (1) average national impacts on investment requirements and costs of electricity, (2) certain regional impacts, and (3) impacts on the coal and nuclear industries and on international trade.

Investment Requirements and Cost of Electricity

There are many difficulties inherent in estimating future costs of alternative energy supply options. Not the least of these is that the future is essentially unpredictable. Energy costs will be determined by future tax, inflation, fuel escalation, and discount rates, none of which can be known. To compound the problem, no uniform method for estimating alternative energy costs on an equitable basis now exists. For example, inclusion or exclusion of such factors as taxation in calculating costs will cause a bias in favor of one of the energy alternatives. Perhaps most important, technological developments and regulatory policies impose great uncertainties on all our estimates.

The capital investments required for projected energy facilities in the 1975-2000 period are compared here for alternative supply scenarios (with and without the moratorium) using the Bechtel Energy Supply Planning Model.[58]

This model assumes specific cost coefficients in constant dollars and other details for various types of energy extraction, processing, conversion, and transport facilities. The total investment requirements are calculated for each of the projected demand cases and alternative supply scenarios described in the previous section.

Under a wide range of assumptions about future inflation, fuel escalation, and discount rates, nuclear electricity appears to be cheaper than electricity from coal, according to a recent IEA study on the relative costs of coal and nuclear supply systems.[59] A summary of this study is found in Volume III. The cost advantage (or disadvantage) of a nuclear system over coal has been calculated for various net fuel escalation rates at a fixed inflation and capital discount rate.

Additional cumulative costs of generating electricity in case of a nuclear moratorium are calculated for the 1985-2010 period using a simplified, undiscounted approach described in a separate paper in Volume II. A range of assumptions regarding capital and fuel costs has been used to calculate cumulative impacts on electricity costs.[60]

1. Investment requirements for energy facilities

The shift from supplying certain future electricity demands from nuclear- to coal-generating facilities would result in some capital cost savings, since fossil fuel utility plants are not as capital intensive.[61] Reliance in making these calculations has been on the Bechtel model's coefficients for coal and nuclear facilities (including associated transportation costs) adapted to our high- and low-energy scenarios. The results are shown in Table 26.

The variation in capital costs between the nuclear and coal options using the model is not large. For example, cumulative 1975-2000 construction costs and associated transport construction costs are calculated to be about $1,126 billion (in 1975 dollars) for the high-scenario nuclear option and $1,093 billion for the corresponding coal-fired option—a difference of only 3.8 percent. The difference for the low case is 2.9 percent. The estimated required capital investments seem feasible under any of these options when compared with projections for total net private domestic investment for the same period.[62]

If business fixed investment each year is about 10 percent of GNP, total annual fixed investment would rise from $149 billion in 1975 to $332 billion in 2000, with a cumulative total over the 25-year period of about $6,100 billion. Investment requirements for energy facilities would be about 16-17 percent of total fixed investment for this period.

2. Additional cost of generating electricity

The decision of a utility manager to build a nuclear- or coal-fired generating

TABLE 26. Cumulative Capital Outlays for Energy Facilities and Associated Transportation 1975-2000
(billions of 1975 dollars)

	Energy facilities	Transport costs	Total
High demand (126 q in 2000)			
Nuclear option	677	449	1,126
Coal option	629	464	1,093
Low demand (101 q in 2000)			
Nuclear option	556	311	867
Coal option	517	325	842

facility will depend on the cost differential between the two systems. The difference in costs is sensitive to estimates of capital costs and to the assumed escalation rate of fuel costs over the rate of inflation. Alternative cases are calculated for various fuel escalation rates using levelized costs discounted to present values, as shown in Table 27. Results of these and other cases for decision making are shown in the paper on comparative costs in Volume III.[63]

The additional cost of electricity due to a moratorium is calculated for the 1985-2010 period using a simplified, undiscounted approach described in a separate paper in Volume II.[64] Several alternative cases have been calculated with different fuel escalation and fixed capital charge rates. The reference assumptions are a price increase for both coal and uranium at an annual rate that is 2 percent higher than the inflation of the economy, and a 12 percent fixed capital charge rate. As underlined in Table 28, the estimated cumulative increase in electric power costs (calculated in 1975 dollars) for the 25-year period would total about $420 billion in the high-demand case, and $314 billion in the low-demand case. Several other cases have been calculated for the low demand and the high demand at various assumed fixed capital charge and fuel escalation rates.

Several yardsticks are available for placing the economic burden (however it is estimated) in perspective. Starting with the aggregate economic indicators, the U.S. gross national product in 1985 is expected to reach $2.1 trillion and disposable personal income some $1.5 trillion. Under our projections of economic growth we expect a GNP of $4.0 trillion and personal disposable income of $2.9 trillion in the year 2010.[65] (These calculations are in constant 1975 dollars.) Since the impact of higher electricity costs will ultimately fall on consumers—directly in terms of higher residential electricity rates and indirectly through higher prices for consumer goods and transportation—these increased costs can be measured against personal disposable income. Under the reference assumptions, the added costs would average about two-thirds of 1 percent of this income, and the real value of goods that consumers could purchase would be reduced by an equal amount.

A second yardstick for comparison is the recent increase in total U.S. electricity prices which, from mid-1973 to mid-1975, averaged about $7.5 billion per year.[66] Given differences in size of the U.S. economy during the period of the moratorium, and the gradual escalation of the burden expected under the moratorium, the economic impact would not be so serious or so disruptive as that

TABLE 27. Effect of Fuel Escalation Rates (Above Inflation Rate) on Differences Between Cost of Nuclear- and Coal-Generated Electricity

Assumptions on net fuel cost increase (per year)	Percent cost advantage (disadvantage) of nuclear over coal	
	Nuclear over coal without scrubbers	*Nuclear over coal with scrubbers*
Coal 0%, nuclear 0%	9	18
Coal 0%, nuclear 2%	−1	8
Coal 0%, nuclear 4%	−12	−4
Coal 2%, nuclear 2%	17	24
Coal 2%, nuclear 4%	4	10
Coal 2%, nuclear 6%	−11	−5
Coal 4%, nuclear 4%	26	31

Note: Percent difference = [(coal cost − nuclear cost)/nuclear cost] x 100. Base case assumes 5 percent inflation and 11 percent operating discount rate (6 percent net discount rate).

TABLE 28. **Additional Cumulative Cost of Electricity Due to a Moratorium (1985-2010) for Alternative Fuel Escalation and Fixed Capital Charge Rates**
(billions of 1975 dollars)

Case	Levelized effective fixed capital charge rate	Fuel escalation rate				
		2% coal 2% U	*2% coal 3% U*	*3% coal 2% U*	*3% coal 3% U*	*3% coal 4% U*
		Mixed low-sulfur and high-sulfur coal*				
Low demand	7%	362	256	602	497	358
	9%	342	237	583	478	339
	12%	314	208	554	449	310
	15%	285	179	525	420	281
High demand	7%	484	341	810	667	479
	9%	458	316	784	641	453
	12%	420	277	746	603	415
	15%	382	239	708	565	376
		High-sulfur coal				
Low demand	7%	346	241	577	470	331
	9%	334	228	562	457	318
	12%	314	209	543	438	299
	15%	295	190	524	418	279
High demand	7%	463	320	773	630	442
	9%	446	303	756	613	425
	12%	421	278	730	587	399
	15%	395	252	705	562	373

*Assumes incremental requirements for coal in case of a moratorium will require two-thirds of plants without scrubbers and one-third with scrubbers.

experienced following the OPEC embargo. We estimate that the moratorium would increase electricity prices some 8-10 percent over the period compared to what they would otherwise be.

Regional Impacts

The calculated burden of a nuclear moratorium on electricity prices will vary widely between geographic regions in the United States, depending on the regional availability of oil and coal and the cost of transporting these fuels to the consuming centers. At one extreme the Northern Rocky Mountain and Northern Great Plains states are low-cost, low-sulfur coal resource areas.[67] In these regions electric generation based on coal will be less expensive than the nuclear option for a wide range of alternative assumptions about future coal and nuclear generating costs.[68] This is illustrated in Table 29. From an economic standpoint, then, adverse economic impacts of a moratorium are likely to be minimal in these areas. Indeed, there would be positive benefits. These would follow not only from the expansion of the coal industry but also from the probable in-migration of industries which are heavy users of electric power.[69]

For the New England region, however, the opposite is true. Not only is New England distant from low-sulfur coal but also both transportation and capital construction costs are relatively high. In recent years New England has been paying from 50 to 70 percent more for coal than has the nation as a whole.[70]

Electric utilities in this region now operate largely on high-cost imported oil. The impact of the oil price escalation which followed the OPEC embargo further disadvantaged New England industries in those instances where power costs are a significant share of total manufacturing costs. Here, nuclear generating costs will remain lower than those of coal or oil systems for a wide range of cost assumptions.[71]

It is not surprising, then, that New England now has a higher percentage of nuclear power generation than any other region, and that long-term forecasts anticipate 70 percent dependence on nuclear power in the future.[72] Nuclear power appears to be the only way this region can overcome its competitive disadvantage in manufacturing and use of energy. Further migration of New England manufacturing industries to other regions would follow a nuclear moratorium: adjustment to the resulting economic dislocations would require a long period.

Southern California is similar to New England in that it too is a high-cost energy importing region. However, Southern California's future energy supply will be assisted by the flow of Alaskan crude oil and possibly natural gas. Although Southern California is not assessed in detail in this study, we have noted that according to the medium production/medium energy-use scenario developed by Rand Corporation in a study for the state as a whole, about three-fifths of

TABLE 29. Regional Comparison of Coal Versus Nuclear Power Plants for Alternate Assumptions

(preferred mode of electricity generation, based on cost per kWhr)

Assumptions	Region 1	Region 2	Region 3	Region 4	Region 5
1. Base case Lifetime, 1985-2015	N	N	N	N	C
2. A relaxation of requirements for SO_2 scrubbers.	N	N	N	TU	C
3. Nuclear plants cost an additional $200/kW over indicated values.	TU	N	N	TU	C
4. Coal costs do not rise while nuclear fuel costs increase at a net 2 percent per year.	TU	TU	TU	TU	C
5. Coal costs rise 2 percent (net) annually and nuclear fuel costs rise 4 percent annually.	N	N	N	TU	C
6. Coal costs rise 2 percent (net) annually while nuclear fuel costs rise 6 percent (net) annually.	TU	TU	TU	TU	C
7. No inflation, and coal costs increase at 2 percent annually and nuclear fuel at 4 percent annually.	C	TU	TU	TU	C

Typical regions
Region 1—Midwest
Region 2—Northeast and Southern California
Region 3—Florida and Texas
Region 4—Appalachian Mountains and Southern Great Plains
Region 5—Northern Rocky Mountains and Northern Great Plains

Matrix code
TU—Tossup (if within 10 percent)
N—Nuclear (favored)
C—Coal (favored)

California's electricity in the year 2000 is expected to come from nuclear generation.[73]

In contrast, the East North Central (Great Lakes) states would be much less disadvantaged by a nuclear moratorium than would New England. The former region has its own large resources of high-sulfur coal and is close to Appalachian coal sources. Moreover, Western low-sulfur coal for utility consumption is transported as far east as Illinois and Ohio. While the generating costs for the Great Lakes region will rise in case of a moratorium, the increase should approximate the national average.[74]

Although nearly two-thirds of the region's utility generation is expected to depend on nuclear facilities by the end of the year 2000, favorable economic factors such as low-cost water transportation on the Great Lakes and nearness to raw materials and markets would seem to indicate that the East North Central area is not likely to be regionally disadvantaged by the moratorium.

Additional and more detailed regional studies are required if the specific consequences of a nuclear moratorium are to be examined. For areas where the composition of regional fuel supplies is likely to be changed radically by a moratorium, assessments of regional dislocations and local problems as well as benefits are needed.

Coal Industry Impacts

An expanded future role for coal in the event of a nuclear moratorium is by no means assured. Environmentalists who oppose the continued expansion of nuclear-fueled electric generating plants generally oppose the rapid expansion of domestic coal output. They are troubled by the environmental problems that accompany strip mining and note that the removal of sulfur, etc., from coal cannot be commercially feasible without the development of new technology. They are also concerned that there is insufficient water in the Western coal areas to permit rehabilitation of mined land. However, in our analysis we have assumed that these underlying questions have been resolved and that environmental issues will not seriously limit coal production.

Under either the high- or low-energy option, the domestic coal industry will undergo rapid expansion after 1985. Our two energy demand estimates imply the amounts of coal as shown in Table 30.

By translating quadrillion Btu into approximate tonnages and considering future lower Btu rates, we derive estimates of coal production (see Table 31). On the basis of our consultation with coal experts, we believe that about two-thirds of coal mined in 2000 and 2010 will be from Western sources. This represents a major shift from 1985 when two-thirds of the nation's coal supply will be from Eastern sources.[75]

One key question is whether the required rates of expansion are unrealistic because of potential but foreseeable restraints on production. In response to the OPEC-generated energy crisis in the fall of 1973, coal production has expanded moderately, reaching an all-time high of 637 million tons in 1975, 6 percent higher than 1974.[76]

According to an estimate of the Bureau of Mines, the coal reserve base of the United States was 437 billion tons in 1974.[77] This tonnage is in place and near enough to the surface to be mined by conventional underground or surface techniques. We assume that at least 50 percent of the identified reserves can be recovered. At our estimated production rate for the year 2000, the United States theoretically has a 200-year supply—provided, of course, that a commercial solution is found to the problem of sulfur removal.

The federal government owns about 40 percent of the nation's coal reserves. Nearly all of this coal is west of the Mississippi River, and most of it is low sulfur.[78] There has been a leasing moratorium since 1973, pending development of an acceptable leasing plan for these reserves. Hence, expansion of Western coal potential depends, in part, on the action of the federal government.

Our postulated rates of expansion do not appear to be pushing any upper physical limits possibly until after the year 2000. The Project Independence study found that expansion of coal production to 1.5 billion tons by 1985 was possible.[79] This would have been an expansion of 150 percent in 11 years, or 8.7 percent annually. Our estimate of coal needs in the high case does not anticipate a requirement for 1.5 billion tons until 1994. On the other hand, our high estimate, 4.8 billion tons in 2010, appears formidable when compared with the present rate of coal production.

Bureau of Mines capital investment estimates vary widely. For three strip mines, capital investment per annual ton of production capacity ranges from $6.12 to $12.72, with the lowest investment being for Northern Great Plains coal. For underground mines, capital investment estimates vary from $23.83 per annual ton of production capacity to $33.34 per annual ton.[80] Assuming a need for about 1.5 billion additional annual tons of coal by 2000, with two-thirds surface Western and one-third underground Eastern, the capital requirement would be about $16.5 billion. We believe this to be a feasible capital sum.

A second key question concerns price changes. If the Project Independence findings on the impact of proposed rates of expansion on coal prices are reasonably valid (p. 106 of that report), expansion at anticipated rates in our scenarios should not have more than a moderate impact on prices. A second study covering Western coal indicates that with expansion of output up to 25 percent per year the increase in the price of Western bituminous coal (measured in 1974 dollars) delivered to Chicago would be about 14 percent between 1974 and 1982; for subbituminous coal the price increase would be about 28 percent over the same eight-year period.[81] These are modest price increases (1.65 and 3.13 percent annually), postulated for far higher rates of expansion than in our scenarios. We therefore believe that the physical expansion proposed would not, in itself, result in rapid price increases.

In the short run, coal prices have proved to be volatile because it takes time—four to five years—to open new mines and reach volume output. Following the OPEC oil embargo in the fall of 1973, coal prices rose dramatically in the face of a relatively fixed short-term supply. In the longer run, prices in the spot market fell sharply, beginning in late 1974. Most coal industry studies anticipate Western low-sulfur strippable coal to be extremely supply elastic in the long run, at a price of about $5 per ton at the mine. This is the kind of price behavior one would expect in a competitive industry with relatively large reserves. There is, of course, the possibility that coal prices might escalate after 1980 if a nuclear moratorium were declared. Certainly, temporary price escalations could be expected which might persist for as long as five years. However, long-run equilibrium would

TABLE 30. Estimates of Future Coal Requirements
(quads or 10^{15} Btu)

	1985	2000	2010
Low demand			
Nuclear option	16.3	17.7	26.3
Coal option	16.3	34.3	57.3
High demand			
Nuclear option	16.6	31.2	49.0
Coal option	16.6	51.2	93.8

TABLE 31. Estimates of Future U.S. Coal Requirements
(10^9 tons)

	1985		2000		2010
Low demand					
Nuclear option	0.71		0.78		1.15
Coal option	0.71		1.50		2.94*
Annual percent increase (coal option)		5.1		5.8	
High demand					
Nuclear option	0.73		1.37		2.51
Coal option	0.73		2.63*		4.81*
Annual percent increase (coal option)		9.0		6.1	

*Average tonnages for 2000 and 2010 have been increased 17 percent to account for Western coal having about three-fourths the Btu content of Eastern coal (22.8 x 10^6 Btu/ton is the average heat value used up to annual production of 2.0 x 10^9 tons).

return; coal is a competitive industry and, sooner or later, supply comes into balance with demand. The energy supply scenarios used in this analysis indicate that coal production would increase about 9 percent per year on the average between 1985 and 2000 to meet the increased demand implied by a nuclear moratorium. (We have derived this percentage by using the highest coal demands in the high-demand scenarios.)

We estimate that for each billion tons of additional coal mined annually as a result of the moratorium, about 87,000 miners would be required, assuming 70 percent is surface- and 30 percent is deep-mined.[82] Supporting industry such as transport and coal equipment would require additional workers.

Nuclear Industry Impacts

The nuclear industry consists of several distinct sectors: (1) reactor manufacturers, (2) architect-engineering construction firms, (3) specialized component manufacturers, (4) utility companies, and (5) nuclear fuel processors. The anticipated economic impact of a domestic moratorium on nuclear power plant construction would vary widely among the sectors.

Of the total construction costs of a large nuclear electric plant, only about 18 percent goes for the nuclear steam supply system, the primary item supplied by the reactor manufacturers. Other major equipment items include turbine generators, condensers, cooling towers, pumps, instruments, and electric plant equipment. These equipment items come from a wide variety of sources, but some of the major items are supplied by the reactor manufacturers. The largest share of the cost, in the range of 30-50 percent, goes through the hands of the architect-engineers and constructors, often a single firm.[83]

The four active reactor manufacturers also produce capital equipment for fossil fuel plants in the electric utility industry.[84] They would undoubtedly continue to do so in the event of a nuclear moratorium. There would be some idling of specialized production equipment as a result of the changeover to a nonnuclear future, and probably a somewhat slower rate of growth for the electric utility industry because of higher electricity prices. While it is difficult to measure nuclear-related employment in the reactor manufacturing industry, one estimate of temporary unemployment is that it would affect about 16,000 workers.[85]

Most of the architect-engineering construction firms participating in the nuclear industry are large and diverse; their services would be needed for the construction of alternative means of providing electric power. There are smaller firms heavily involved in the nuclear industry which could lose perhaps 50 percent of their business.

It is difficult to estimate the impact of a moratorium on suppliers of special components. Nuclear power plants need computers, cranes and hoists, filters, gauges, meters, radiation monitors, neutron sensors, pumps, seals, shielding materials, tubing, valves, etc. Most of the companies supplying such components serve a number of industries. Some would receive partial offset business from other utility plant construction; however, the smaller, highly specialized suppliers would not and therefore might have difficulty surviving.

Utility construction and operating companies would experience some employment effects from a moratorium. One study estimates 11.5 man-hours/kW for nuclear plant construction and 8 man-hours/kW for fossil fuel plants.[86] Nuclear power plants also require more operating employees than fossil fuel plants. Hence there would be some (perhaps 20,000) decrease in the size of the construction labor force, and some cutback on engineering personnel.[87]

The nuclear fuel cycle sector would be gradually affected, faced by the no-growth future and the long-term replacement of nuclear plants. Since a nuclear plant requires a new set of fuel elements every three years, the supplying of these elements would continue at a diminishing rate. In addition, a portion of the international market is supplied by the United States, which also provides enrichment services.

A slowdown of the nuclear enterprise, resulting in the probable loss of 50,000 jobs for the nuclear industry alone, represents a smaller adjustment than U.S. industries have successfully made many times. A more serious effect would be the long-run costs for restarting a domestic nuclear program should the moratorium policy be reversed (see export discussion which follows). A moratorium could also have serious impacts on efforts to maintain a highly competent group of engineers and nuclear scientists for work in crucial R&D fields, particularly the breeder program.

International Economic Effects

We have addressed two major international effects of a domestic nuclear moratorium: (1) foreign exchange costs of electing the oil import option rather than domestic coal to make up the energy deficit and (2) probable consequences on the nuclear fuels and nuclear power equipment industries resulting from international developments caused by a domestic moratorium.

Foreign exchange costs would be greatest if imported oil instead of domestic coal were used to fire fossil fuel plants under the nuclear moratorium. Under this option our supply scenarios for the year 2000 show utilities using 16.6 q (low-energy case) or 20.4 q (high-energy case) of oil annually. Assuming these are the import requirements, this would mean an average of 18.5 q of oil by 2000 to meet utility needs. Using $25 per barrel (1975 prices), about $97 billion would be required in the year 2000 for total U.S. annual oil imports, of which $83.3 billion would be for the utility industry. Under this scenario the import bill in 2000 might account for the same proportion of total imports as it did in 1975 (roughly one-fourth, which is a feasible ratio).

To calculate the $25 per barrel price in 2000, we have assumed a net fuel increase of 2 percent annually through 1985 and 3 percent per year thereafter. The prices quoted, in 1975 dollars, do not take general U.S. inflation into account. We have not attempted to construct an export price index for the year 2000. Our conclusion is based on the assumption that oil import prices will not repeat their spectacular escalation of 1973-1975.

The volumes of oil involved are not so large as to suggest disruption of the international petroleum markets, given the existing large shut-in capacity in both the Middle East and other OPEC countries and the expected increases in world oil production between now and the year 2000. However, the world petroleum supply-demand balance will almost certainly be more stringent in 2000 than it is today. Price is therefore an area of uncertainty in our calculations. An announcement by the United States of a 30-year nuclear moratorium would, in itself, immediately strengthen the OPEC bargaining position. If oil imports expand as we have suggested earlier, as much as 55-60 percent of total U.S. petroleum supplies could come from foreign sources, and one-third of electricity generation might be fueled from this source under the high oil import option.

The impact of the 1973 OPEC oil embargo has sparked proposals for a large strategic stockpile, starting with 150 million barrels in 1973 and increasing thereafter to 1 billion barrels in 1982.[88] If a 1 billion barrel stockpile were available, this would represent only about three months of oil imports at the level calculated for the year 2000. Hence a prolonged embargo could have serious economic consequences despite the existence of an oil stockpile, since alternative supply arrangements (coal gasification, exploitation of shale oil, etc.) would take several years to put in place.

Since U.S. foreign policy has stressed the peaceful uses of atomic energy, we must consider the international consequences of a nuclear moratorium. In 1954 the United States embarked on an "Atoms for Peace" program, and began to establish the framework for making nuclear materials and equipment available to other nations under appropriate safeguards.[89] This philosophy was continued in the establishment of the International Atomic Energy Agency and in the treaties of nonproliferation (NPT).[90] As nuclear power developed, commercial nuclear steam supply systems were exported for use in foreign reactors. The process governing exports includes agreements for cooperation, long-term enrichment service contracts, and export licensing of materials and equipment. The U.S. position as the world's leader in commercial applications has been an important lever, allowing us to play a leading role in establishing international controls.

In the future, continued U.S. exports of nuclear fuel and power reactors are expected to contribute to the solution of the energy supply problems of many countries. In particular, nuclear plants allow countries to achieve a greater degree of fuel independence as opposed to increased reliance on petroleum imports.

The United States has exercised leadership in international nuclear affairs, but it is difficult to see how we could continue such leadership in the event of a moratorium. U.S. reactor manufacturers are multinational corporations which already operate nuclear-related production facilities abroad. With all of the reactor orders and a large share of the component business coming from abroad in case of a moratorium, foreign government pressure might cause major production facilities to be moved overseas. In the past, such pressure has played a leading role in moving multinational companies abroad.

How much business is involved in related exports? U.S. nuclear power export

TABLE 32. Projected U.S. Nuclear Power Exports as Percent of Projected Total U.S. Exports
(billions of 1974 dollars)

	1980	1985	1990	1995	2000
Total nuclear exports Low/high	2.3/2.4	3.5/3.9	5.3/6.1	7.4/8.8	7.9/9.9
Total U.S. exports*	121.8	145.2	173.3	206.7	246.6
Nuclear as percent of total	1.8/2.0	2.4/2.7	3.1/3.5	3.6/4.3	3.2/4.0

*Based on assumed real growth rate of 3.6 percent per year.

activities already have resulted in significant revenues for the United States. Through 1974 export revenues for nuclear power plant equipment were estimated at approximately $0.8 billion and total enrichment revenues at $0.7 billion (in constant 1974 dollars).[91] By 1985, projected annual U.S. nuclear power exports are estimated to run between $3 billion and $4 billion, increasing by 2000 to between $8 billion and $10 billion. Through the turn of the century, projected cumulative U.S. nuclear power exports are estimated to be between $120 billion and $140 billion.[92]

Projected nuclear power exports are expected to have a significant indirect beneficial effect on U.S. exports. Maintenance of the U.S. position in the international nuclear market will be a clear indication of our continuing ability to compete in world markets for high-technology goods and services.

Estimates of the range of installed nuclear power plants abroad are based on an ERDA report.[93] Case Y, the middle estimate of that report, was used to project foreign nuclear plant growth. Assumptions with respect to the likely U.S. share of such business lead to the conclusion that nuclear equipment will be a major export in the future. If nuclear power plant equipment grows to 3.6 percent of U.S. exports by 2000, this industry will almost certainly become a leading export industry similar to the aircraft and computer industries today.

The cumulative 1975-2000 exports are estimated by ERDA at between $120 billion and $140 billion.[94] Power plant equipment (measured in dollars) is the largest single sector of this industry group; the loss of half these potential exports would amount to $60-70 billion over a 25-year period. There would also be losses of exports for other high-technology equipment.

In sum, it would appear technically feasible for the United States to accommodate to a nuclear moratorium, but to do so would cause losses in real personal incomes, losses in potential foreign exchange earnings, and regional economic dislocations.

5 Environmental Implications

There is no known energy supply alternative that is totally without some environmental impact. Clearly, then, the environmental implications of a U.S. nuclear moratorium must be discussed in terms of *alternative* impacts. For example, a switch from expanded nuclear power to a substituted coal electric system will result in a reduction in radiation emissions and waste storage problems at the expense of increased atmospheric sulfur dioxide, sulfates, and particulates.

In this section the alternative environmental implications are compared on the basis of four potential types or levels of impact. The first of these relates to actual and potential international and global problems, and the second to major accidents and human safety. The other two considerations are the long-term health effects and the land area which is disturbed. The environmental implications of proceeding on a path of expanded nuclear power on the one hand, and of shifting to coal for the generation of electricity on the other, are evaluated for each of the four types of potential impacts.[95]

Global Implications

A primary potential impact of proceeding with nuclear energy development is the possibility of an international proliferation of nuclear weapons. On the other hand, a major shift to coal might induce large-scale global climate change as the concentration of carbon dioxide in the atmosphere increases. A moratorium by the United States alone would not decrease the likelihood of proliferation, and it would only marginally influence a change in global climate. If, of course, a moratorium in the United States led to a worldwide moratorium, the global effects would be markedly different.

1. Proliferation and use of nuclear weapons

We are unable to determine the effects of a *U.S.* nuclear moratorium on the international proliferation of nuclear weapons. We believe that the effect of a moratorium adopted only by the United States would be marginal and secondary: marginal because reactors would be available from other countries, secondary because of the influence of the United States on world nuclear energy policy (including decisions by others to follow suit).

It is no longer possible for a single nation to influence significantly the possibility of proliferation through a unilateral capacity to supply nuclear power systems. On the other hand, the extent to which the U.S. influence on worldwide nuclear policy would be diminished by its withdrawal from nuclear power development could result in less rigid international regulation and inspection.

2. Possible climate change induced by additional atmospheric carbon dioxide

The ultimate constraint on the burning of fossil fuel may be the climatic impact from atmospheric CO_2 buildup.[96] This, of course, is a global problem; what the United States does during the next 30-50 years is likely to contribute little to total global atmospheric levels. Nevertheless, increasing reliance on fossil fuel by such a large consumer as the United States poses a prospect of severe climatic shifts that cannot, in principle, be dismissed. The extent to which a nuclear moratorium would aggravate the buildup of CO_2 must therefore be examined.

Carbon dioxide in the atmosphere affects the thermal radiative balance of the planet and through this balance the global climate. On the basis of the best atmospheric models now available, a doubling of the atmospheric CO_2 would result in a global average surface temperature increase of 1.5-2.4°C, with greater increases in the high latitudes. Although models of the type used in these studies predict present global climate surprisingly well, a number of significant variables are not included. Consequently, the results must be regarded as preliminary until additional information and more reliable climatic feedback mechanisms can be properly included.

During the past hundred years, the annual global production of CO_2 by burning fossil fuels has grown nearly fiftyfold. It now stands at 18×10^9 tons, which is about one-tenth the amount accounted for by the annual net primary fixation of carbon by terrestrial plants. This production appears to have caused an increase in the concentration of CO_2 in the atmosphere. Since 1958 observers at the Mauna Loa Observatory in Hawaii have monitored atmospheric CO_2 content, and the 1975 measurements show an average CO_2 concentration of 330 ppm (in the latter part of the nineteenth century it was 290-295 ppm). The measurements show annual increases for each year, averaging about 0.7 ppm during the late 1950s and early 1960s and up to 1.0 ppm or more in recent years.

The cumulative production of CO_2 since the end of 1957 and the observed increase in CO_2 are plotted in Figure 8. The upper set of points indicates the increase in concentration of CO_2 in the atmosphere that would have occurred if all CO_2 produced from fossil fuels and cement since 1957 remained airborne. The lower set of points represents the observed increase in atmospheric CO_2 concentration at the Mauna Loa Observatory.

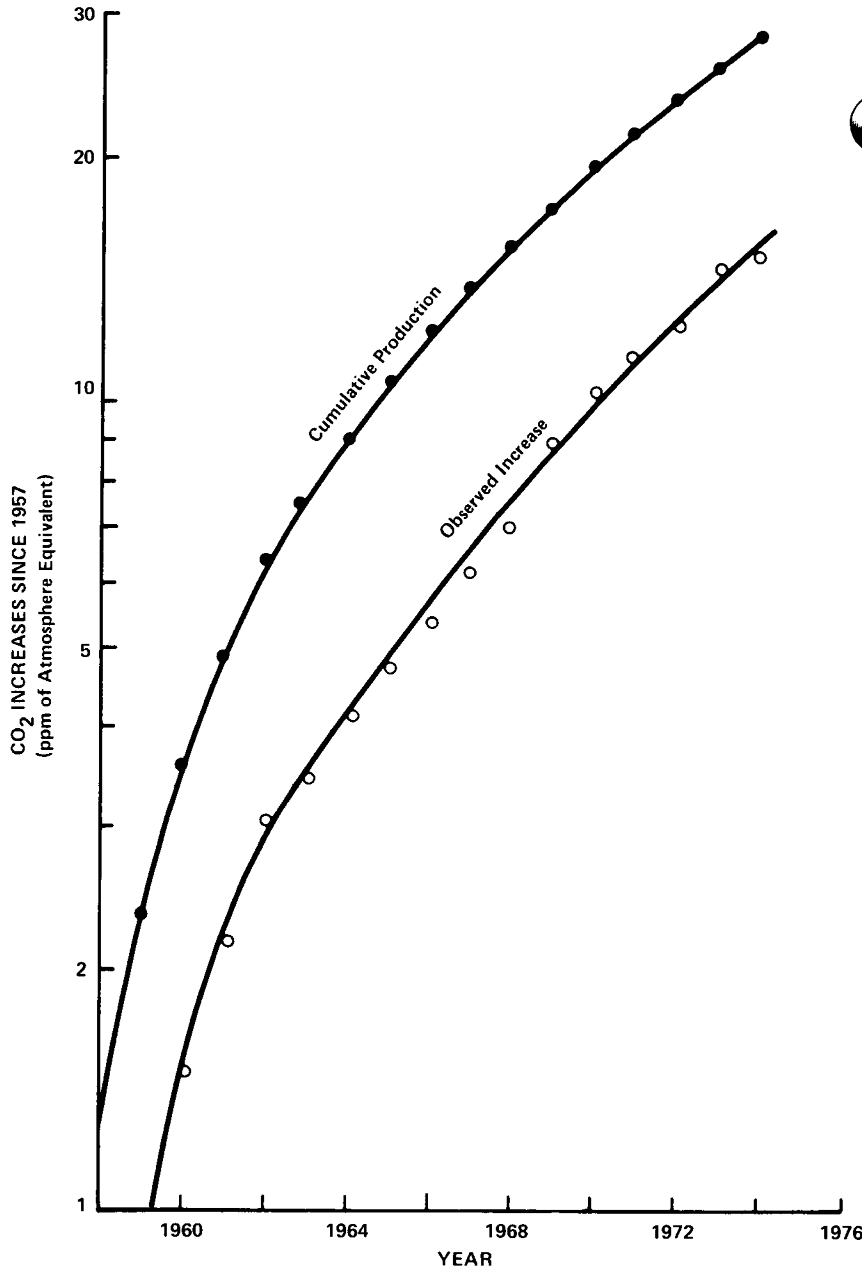


Figure 8 Cumulative CO_2 production and observed increase in the atmosphere.

Nearly one-half of the CO_2 produced from fossil fuels and cement seems to have found its way into reservoirs other than the atmosphere, and it is important to understand the nature of these reservoirs and their capability for continued CO_2 storage. Probably of greatest significance is the need for better understanding of the exchanges between the atmosphere and the ocean surface. The varying behavior of the oceans as a CO_2 sink places a large uncertainty on the future concentration of CO_2 in the atmosphere even if the fossil fuel usage is accurately predicted.

The biota also exchanges CO_2 with the atmosphere in large amounts which vary from season to season and year to year. If the size of the "long-term" biosphere (essentially long-lived woods) is decreased, the effects of fossil fuel burning may be amplified; if storage of CO_2 in trees is increased, the fraction remaining in the atmosphere would be correspondingly reduced.

What would be the effect of a U.S. nuclear moratorium on the atmospheric CO_2 buildup? The United States now uses only one-third of the world's energy. Moreover, during the next 30 years the rate of energy demand increase in many parts of the world is likely to be greater than that in the United States. Thus the fraction of atmospheric CO_2 contributed by the United States will most likely drop whether or not the United States uses nuclear power. The U.S. contribution to the buildup of atmospheric CO_2 is hardly decisive.

We have estimated that the international use of energy, excluding the United States, will reach 589 q by the year 2000 and 1,595 q by the year 2025. U.S. energy use is estimated to be approximately 15 percent of total world energy use in the year 2000 and 7 percent in the year 2025 (IEA lower scenario of 101 q in 2000), or 18 percent in the year 2000 and 10 percent in the year 2025 (IEA higher scenario of 126 q in 2000). Table 33 presents the estimate of CO_2 production that will occur with these scenarios.

It is evident that the global production of CO_2 is more sensitive to the fraction of global energy produced from nuclear (or other nonfossil) sources than it is to either the level of energy use in the United States or to the size of the U.S. nuclear component. For example, in the year 2025 (with the U.S. low energy demand of 126 q per year) the U.S. production of CO_2 is increased only 3×10^9 metric tons by the substitution of fossil fuel for the nuclear contribution. The increase is ten times (30×10^9 metric tons) as much if the world as a whole were to depend on nuclear power for only 5 percent of its energy demands instead of 35 percent as might be the case by 2025.

Almost any reasonable scenario for future global energy demand yields continued increases in atmospheric CO_2, but the resulting concentrations do not appear to reach levels that will cause severe climate alterations before 2000. However, little complacency should be derived from this, since continued energy demands during the first few decades of the next century will push atmospheric CO_2 concentrations to levels which warrant serious concern, even for the low energy growth case. The inertial effect in energy supply systems makes it clear that decisions made now on the nuclear/nonnuclear issue will have an impact reaching many years into the future. The alternative energy scenarios in Figure 9 illustrate the potential difficulty with CO_2 in the twenty-first century.

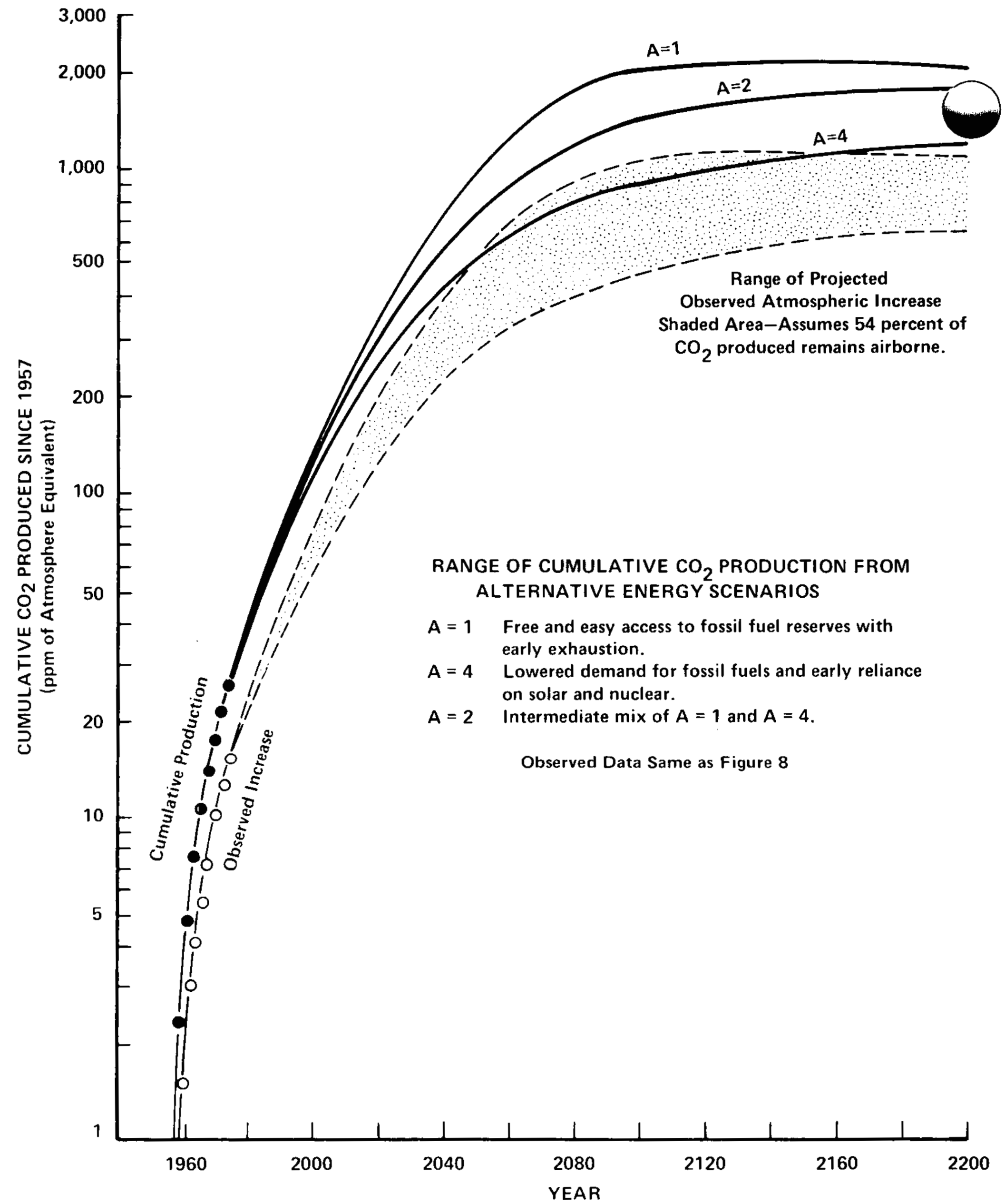
These projections suggest that the time when atmospheric CO_2 concentration will become crucial is early in the twenty-first century. The figure suggests an increase of 62-73 ppm over the 1958 value of 315 ppm by 2000. The resulting

TABLE 33. Projected World CO_2 Production (2000–2025)

			CO_2 production in 10^9 metric tons/year*			
			U.S. nuclear		*U.S. nonnuclear*	
Year	**World energy strategy (% nuclear)**	**Level of U.S. energy use (q/year)**	World	U.S.	World	U.S.
2000	20	101	37	5	38	6
		126	38	6	41	9
2000	5	101	43	5	44	6
		126	44	6	47	9
2025	35	126	73	5	76	8
		170	75	7	80	12
2025	5	126	104	5	107	8
		170	106	7	111	12

*1974 world CO_2 production = 18×10^9 metric tons. 1974 U.S. CO_2 production = 4.3×10^9 metric tons.

Figure 9 Projected cumulative CO_2 production and projected observed atmospheric CO_2 increase since 1957.



atmospheric concentration of 375-390 ppm may well be a threshold range at which climate change from CO_2 effects will be separable from natural climate fluctuations. An increase of 150-225 ppm by 2025 (concentration of 465-540 ppm) should certainly result in recognizable climate change if such changes are ever to occur. The consequences of an increase of this magnitude in atmospheric CO_2 make it prudent to proceed cautiously in the large-scale use of fossil fuels.

In comparing estimates of heat released to the atmosphere from energy usage to the temperature rise from increased levels of CO_2, consider a *tenfold* increase in energy release. This will still place the heat generated by man at only one-thousandth of the solar insolation reaching the earth's surface. If all else remains constant, this would change the black-body temperature of the earth by about 0.06°C compared with estimates of ~2°C for a *doubling* of CO_2. Thus, as first approximation, the CO_2 effect from burning fossil fuel appears far more significant than the direct heat effect.

Even the most conservative world energy scenarios indicate increases in CO_2 which approach a doubling of atmospheric concentration by 2050.[97] A U.S. nuclear moratorium with its resulting increased reliance on fossil fuels may not have much direct impact on CO_2 buildup in the atmosphere, but should other countries follow our lead a doubling of CO_2 concentration could occur even sooner.

Major Accidents and Safety

The impact of a U.S. nuclear moratorium includes trading the risk of accidents in the nuclear fuel cycle for those in the coal-electricity cycle. As the United States increases its dependence on coal, the decreased probability of a reactor accident with a U.S. nuclear moratorium would be exchanged for an increased probability of a major mining tragedy.[98]

1. Reactor accident probabilities and implications

Both our higher- and lower-energy futures and their dependence on nuclear reactors, with and without a nuclear moratorium, are used to estimate reactor-years of operation for each scenario. To supply the electricity in the high energy demand scenario with nuclear supply, an estimated 880 reactors will be required in 2010 with an accumulated 13,000 reactor-years by that time. For lower demand and a nuclear moratorium, only 147 reactors will be required; and an accumulated 4,450 reactor-years will be experienced by 2010. Table 34 summarizes the probabilities of accidents involving a serious core melt (with a release of a significant amount of radioactivity) for each of the energy scenarios. The probabilities are taken from the Rasmussen study and are based on pressurized water reactor (PWR) accident modes 1-7 and boiling-water reactor (BWR) modes 1-4.[99] It should be recognized that in using the Rasmussen probabilities we have violated a stricture in that study *not* to apply them to future reactors, because improved technology should reduce the probabilities.

2. Mining accident implications

Fossil-fueled generating plants do not have the potential for the same level of catastrophic effects that nuclear plants have. However, the accidents associated

TABLE 34. Expected Number of Reactor Accidents* from Cumulative Reactor-Years†

	Nuclear supply case		Coal supply case
Year	*High energy*	*Low energy*	*Both high and low energy*
1975	(228) 0.011	(228) 0.011	(228) 0.011
1985	(1105) 0.054	(1105) 0.054	(1105) 0.054
2000	(5980) 0.306	(5598) 0.286	(2855) 0.142
2010	(12956) 0.671	(11138) 0.576	(4447) 0.221

*Accidents involve a core melt and a release of a significant amount of radioactivity and are based on PWR modes 1-7 and BWR modes 1-4. Only 23 percent of BWR sequences involve breach of aboveground containment.

†Cumulative reactor-years in parentheses.

with coal mining are so much more frequent than in other mining operations that an evaluation of the implications of an energy scenario more dependent on coal requires an examination of coal mining accidents.

Future accident rates for coal mining will depend on many factors; for example, legislation may result in a significant improvement in the accident rate. Currently, the accident rate of coal mining seems unnecessarily high when compared with that of other mineral industries. Workers in primary nonferrous smelters and refineries, for examples, suffer ten times fewer fatal injuries per million man-hours than do coal miners. Workers in the petroleum and natural gas, metal mills, nonmetal mills, and coke industries experience injury rates on the order of eight times lower than those of their counterparts in the coal industry.[100]

Rates of injury in the coal mining industry vary dramatically, not only by mining technique but also by coal company. Surface mining injury rates have been spectacularly lower than underground mining injury rates. In general, coal companies whose underground mines are safer than others also operate safer strip mines and vice versa.[101]

The simplest method of projecting future injury rates for mining coal is to extrapolate historic trends while making some assumption about the future demand and use of coal. The total number of injuries that will actually occur depends primarily on three factors: the nation's commitment to safety in underground mines, the percentage of coal that will be produced in surface as opposed to underground mines, and the rate of coal consumption. The projections included here assume that historic rates of improvement in coal mining safety continue, that the mix of surface mining and underground mining for the period through 2010 remains the same as it is today (though we concede that the surface mining fraction will likely increase considerably), and that the rate of coal consumption follows from the IEA energy scenarios developed earlier. Based on these assumptions, future coal mining injuries for the various scenarios are estimated in Table 35.

Long-Term Health Effects

The generation of large quantities of electric power by almost any means produces by-products which may be unpleasant or injurious. Scenarios which depend heavily on nuclear fuels result in one type of risk to public health; dependence on coal for electric generation creates another. These potential impacts on the health of large segments of the population are examined in the following on the basis of the various energy scenarios developed earlier in this report.[102]

TABLE 35. Estimated Number of Coal Mining Injuries per Year*

	Nuclear supply case		Coal supply case	
Year	*High energy*	*Low energy*	*High energy*	*Low energy*
1985	8058 (82.2)	7922 (80.7)	8058 (82.2)	7922 (80.7)
2000	7430 (59.4)	4215 (33.7)	12285 (98.3)	8165 (65.3)
2010	7162 (51.3)	3844 (27.5)	13714 (98.3)	8378 (60.0)

Note: Assumptions: (1) Historic rates of improvement in coal mining safety continue, (2) mix of surface mining and underground mining remains the same as it is today, (3) rate of coal consumption follows from energy scenarios.

*Fatal injuries are given in parentheses.

1. Impacts from radiation

Radiation exposure can originate from sources outside the body or from material taken into the body. External exposure results from radiation emitted by radioactive sources at some distance. Internal exposure results from inhalation of radioactive gases or fine particulates and from ingestion in food and water.

The potential radiation exposure resulting from nuclear power has been the subject of many studies and has resulted in the promulgation of regulations designed to reduce emissions to the lowest practicable level. Radiation exposure from activities associated with power generation results primarily from the power generation and fuel reprocessing steps.[103]

Two nuclides—tritium (^3H), in the form of tritiated water, and krypton (^{85}Kr), a chemically inert noble gas—are considered to be the major contribution to the radiation environment important to public health. Both are released either in the course of power production or at the time fuel elements are disassembled for reprocessing. Both eventually become distributed worldwide so that international generation of nuclear power, rather than that of any particular country, governs the level of environmental burden.

The average air concentration, ~15 picocuries (pCi) of ^{85}Kr per cubic meter of air (1970 level), results in an exposure level of ~0.0004 mrem per year per person. The total atmospheric burden of ^{85}Kr from the testing of nuclear weapons is small compared to that now released and anticipated from the nuclear power program, assuming 410 Ci/MWyr.

The present level of ^3H in the environment (water and food) is about 500 pCi per liter of H_2O or per kilogram of food, giving a dose rate of 0.04 mrem per year per person. The estimated environmental burden from naturally occurring processes is 20-85 megacuries (MCi) of ^3H; power-produced ^3H is estimated to reach the natural production rate sometime between 1980 and 1985.

In evaluating the public health impact of radioactive releases from nuclear power sources, the risk of injury is assumed proportional to dose. The relevant dose is the average per capita dose to the tissue of interest. To determine the public health implications of nuclear power, the annual dose in millirems per person is obtained by multiplying the dose commitment per unit of electricity generated by the estimate of total capacity in place during the period being considered. Table 36 was constructed using a value of 8×10^{-4} mrem per person per gigawatt (GW) and the nuclear capacity required in each scenario at a given time. The values presented are estimates of the average dose for the entire population of the United States and include that from both ^{85}Kr and ^3H as well as other radionuclides contributing smaller amounts to the total dosage. Radiation exposures of 1 mrem per year per person are considered negligible under present criteria.

To gain perspective on the magnitude of exposure, consider the total dose

TABLE 36. Estimated Annual Whole-Body Dose of Radioactivity
(millirems)

	Nuclear supply case		Coal supply case
Year	*High energy*	*Low energy*	*Both high and low energy*
1975	0.022	0.022	0.022
1985	0.14	0.14	0.14
2000	0.41	0.36	0.14
2010	0.70	0.52	0.12

level in various areas of the United States (the dose from cosmic rays varies considerably with altitude):

At sea level (30-40° latitude), 40 mrems/yr = average of 40/8,760 = 0.0046 mrem/hr. In or near mountains (Colorado), 120 mrems/yr = average 120/8,760 = 0.0136 mrem/hr. Difference = 0.009 mrem/hr.

Thus a person who lives on the seacoast accepts an increased increment of radiation risk when he spends three or four days in the mountains.[104] This is comparable to what he would experience from the higher-energy nuclear supply scenario for 2010. Our estimates do not include possible exposures that would result from core meltdowns, or contributions from mine tailings.

2. Coal electric generation

If a major portion of electric generation is supplied from combustion of coal instead of from nuclear reactors, the amount of air pollution affecting public health becomes far more dependent on the level of controls adopted with regard to sulfur dioxide and nitrogen oxides emissions than it does on whether or not there is a nuclear moratorium.[105] A moratorium which requires heavier dependence on coal could result in *less* air pollution if more stringent (expensive, but achievable) controls are enforced than would be the case of meeting energy

Figure 10 Comparison of pollutant standards, background levels, man-made exposures, and health effects. (From Chester Richmond's testimony presented to the Committee on Science and Technology's Subcommittee on Environment and the Atmosphere, March 1976, Oak Ridge National Laboratory, ORNL/TM-5277.)

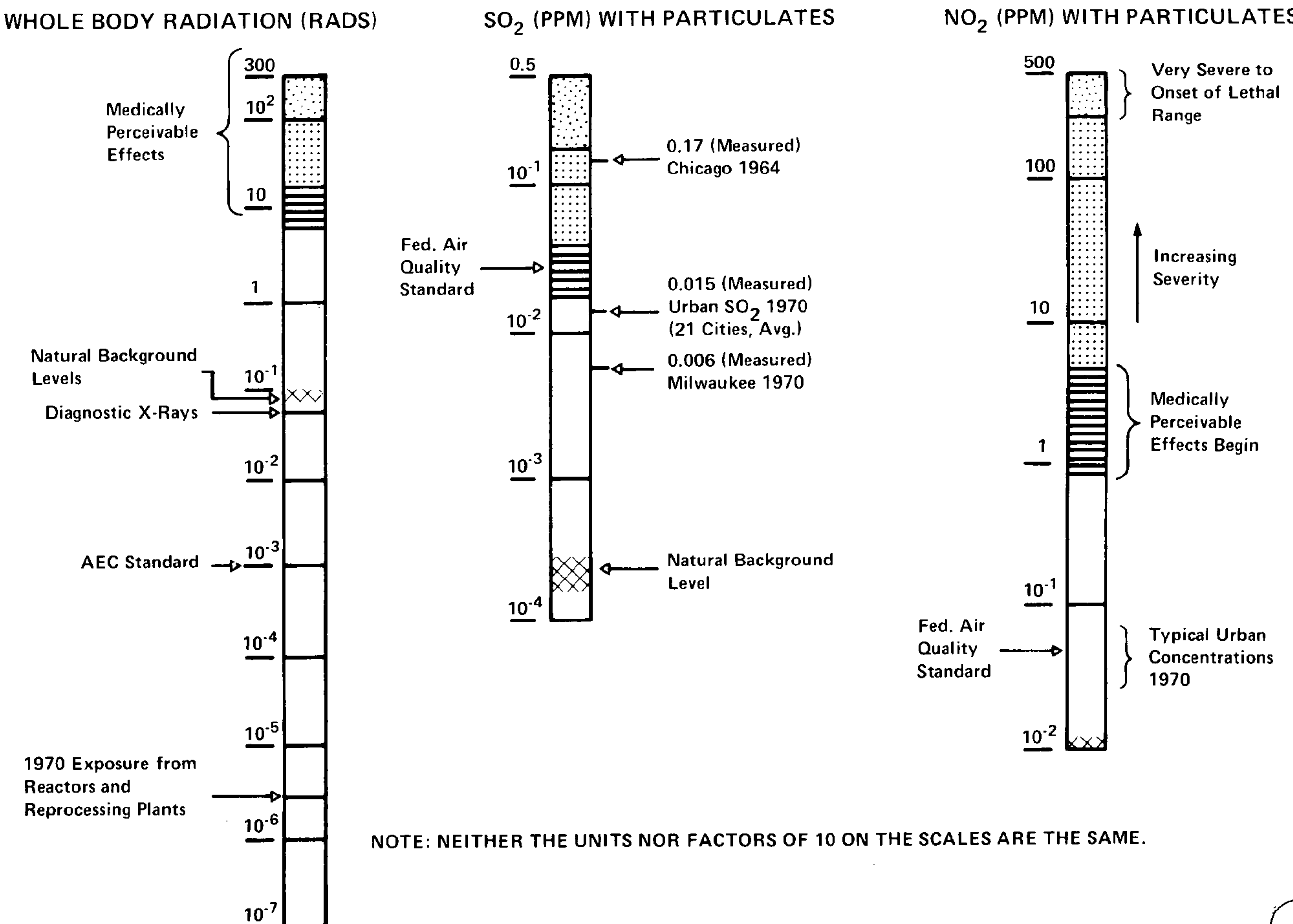


TABLE 37. Selected Impacts Due to Sulfate Pollution
612 MW Coal-Fired Electric Base Load Capacity
(percentage increase in parentheses)

Control options (see notes)	Case I—Rural site		Case II—Urban site	
Aggravation of heart and lung disease in thousands of person-days/year				
High-sulfur coal (3%)	256.0	(0.241)	755.0	(3.09)
New source perfm. stand*	45.9	(0.043)	137.0	(0.56)
Scrubbers†	26.5	(0.024)	79.2	(0.32)
Scrubbers with physically cleaned coal‡	10.6	(0.010)	31.7	(0.129)
Chronic respiratory disease in thousands of cases				
High-sulfur coal (3%)	25.4	(1.61)	74.9	(20.6)
New source perfm. stand*	4.6	(0.29)	13.6	(3.76)
Scrubbers†	2.6	(0.167)	7.9	(2.16)
Scrubbers with physically cleaned coal‡	1.1	(0.067)	3.1	(0.87)
Premature deaths				
High-sulfur coal (3%)	14.3		42.2	
New source perfm. stand*	2.6		7.6	
Scrubbers†	1.5		4.4	
Scrubbers with physically cleaned coal‡	0.6		1.8	

Notes: These estimates are based on the model by North and Merkhofer.[107] The power plant is assumed to be 612 MW with an 80 percent load factor and a generating efficiency of 38 percent. Output is 4.28×10^9 kWhr per year. Siting and ambient conditions are:

Case I—Rural. Plant 520 km upwind. Population at risk is 50 million, ambient SO_4 concentration is 16 $\mu g/m^3$.

Case II—Urban. Plant 60 km upwind. Population at risk is 11.5 million, ambient SO_4 concentration is 16 $\mu g/m^3$.

*New source performance standards (1.2 lb SO_2 per 10^6 Btu of input).

†Scrubbers with 3 percent sulfur coal assumed to remove 90 percent of SO_2 (5 percent deterioration in generating efficiency assumed).

‡Scrubbers with 3 percent sulfur coal which has been physically cleaned.

demands with nuclear power assuming only a continuation of present pollution controls on fossil fuels. Obviously for the same control strategy the minimum coal-burning scenario will give the minimum SO_2 and NO_X pollution. Figure 10, taken from testimony by Chester Richmond, compares pollutant standards and background levels for radiation, SO_2 emissions, and NO_X emissions.[106]

The figure shows the ranges where medically perceivable effects begin for each, and the relationship between these ranges and present control standards. There is reason to hope that by the year 2000 nationwide emissions of SO_2 from energy systems may be significantly lower than at present, regardless of the energy scenario selected. As pointed out above, routine radioactive emissions from nuclear power plants have a negligible impact on public health.

The prevailing view is that sulfates formed from SO_2 rather than SO_2 itself represent the primary health hazard associated with SO_2 emissions (or, indeed, with air pollution from coal-fired plants). The National Academy of Sciences' study on *Air Quality and Stationary Source Emission Control* made a rule-of-thumb estimate that a doubling of SO_2 emissions would result in a 10-40 percent increase in nationwide urban ambient sulfate concentrations.[107]

The actual increase in health problems from power plant generated sulfate pollution is highly dependent on siting policy. Table 37 illustrates the importance of atmospheric dilution as well as control levels enforced.

Two plant locations were chosen: (1) a "rural" plant located on the Ohio-West Virginia border, 520 km upwind of the Boston-New York-Washington populated area, and (2) an "urban" power plant 60 km upwind of the New York metropolitan area. The exposed population in the first instance is assumed to be 50 million people; in the second, 11.5 million.

The specific examples in Table 37 suggest two observations which are probably valid for coal-fired plants in general: (1) the environmental impact of coal-fired plants due to sulfate pollution can be made relatively small, but is probably not trivial; (2) from an environmental point of view, the control and siting strategies that are followed for coal-fired plants are of far greater importance than a nuclear moratorium decision per se.

The most serious health impact of NO_X emissions is probably related to the formation of photochemical oxidants. The reaction mechanisms are complex and only partially understood. Evidence presented by the National Academy of Sciences Committee on the Relationship of Emissions to Ambient Air Quality suggests that a major effect of NO_X emissions may be an increase in rural levels of oxidants.[108]

The situation is somewhat analogous to the conversion of SO_2 to sulfate. Through such mechanisms local problems become regional problems. The impact on rural as well as urban areas will be amplified with remote siting of power plants. Nitrogen dioxide, another conversion product of nitric oxide emissions, is currently less a national pollution problem than was once supposed. Nevertheless, the increase in projected NO_X emissions could represent a public health hazard of as yet undetermined proportions. As was the case with SO_2, there is *risk* of a significant increase in nationwide NO_X emissions toward the end of this century, with or without (but particularly with) a moratorium. It seems possible that if stringent controls are actively enforced, emissions could be substantially *lower* in all scenarios than are presently being experienced. With the *same* control assumptions, NO_X emissions would be 10-20 percent higher in the case of a moratorium (year 2000).

In order to develop our estimates of the emissions of the five "criteria" air pollutants (SO_2, NO_X, particulates, hydrocarbons, and CO), we have drawn heavily on the accounting system developed by Brookhaven National Laboratory for the Council on Environmental Quality and ERDA.[109] The model, which is described in *Sourcebook for Energy Assessment*, basically involves the use of emission coefficients (for each pollutant) for individual activities in the energy system from extraction to end use. The BNL model in effect assumes that by 2000 all coal plants are equipped with devices that remove 90 percent of the SO_2 from coal of about 2.6 percent sulfur content; particulate control in power plants is also improved, but this effect is overshadowed by industrial emissions which are unaffected by the moratorium. Hydrocarbon and CO emissions are related mainly to automobiles, and, though much lower than now, they are little affected by a moratorium.

Table 38 gives the projections of the emissions of the five criteria air pollutants for the nuclear cases and moratorium-coal cases as calculated by the Brookhaven model.

In comparing the nuclear scenarios to the nonnuclear scenarios, it is noted that all five of the "criteria" air pollutants show a very modest increase when emphasis is shifted toward coal. This effect is greatest in the cases of SO_2 and NO_X emissions. The difference between the high and low energy demand scenarios is comparable in magnitude for the SO_2 and NO_X emissions to that achieved in going from the moratorium to the nuclear case. This result is based on

TABLE 38. Estimated Air Pollution Emissions for A.D. 2000*
(millions of tons per year)

Pollutant	Present	Nuclear supply case: *High energy*	Nuclear supply case: *Low energy*	Coal supply case: *High energy*	Coal supply case: *Low energy*
Sulfur dioxide†	20	12	9	15	12
Nitrogen oxides‡	23	27	22	34	28
Particulates**	5	12	11	13	12
Hydrocarbons††	14	6	5	7	5
Carbon monoxide††	108	24	21	25	22

*From Brookhaven Energy Systems Model calculation for IEA scenarios.

†The Brookhaven National Laboratory model assumes 90 percent removal of sulfur from 2.6 percent coal in coal-fired steam electric plants. Dominant contributions are from coal-fired steam electric plants and coal for industrial process heat and steam.

‡Current standards for electric utilities were assumed. Dominant sources are coal-steam electric and transport sector, particularly trucks and buses. Contribution of automobiles is insignificant.

**Increase in emissions due primarily to increase in emissions from coal used in industry for process heat and steam. Fifty percent precipitator efficiency is assumed with coal of 10 percent ash.

††Reductions primarily due to improved emission control from automobile fleet.

the use of pollution control equipment, as assumed in the BNL model, that goes beyond what is required by the EPA New Source Standards for SO_2.[110] Should present practices be maintained through this period, then SO_2 emissions with a moratorium would be about twice the emissions without the moratorium.

Land Impacts

The primary difference in land-use impacts between the nuclear supply scenario and the nuclear moratorium scenario comes from the relative magnitude of ore extractions required for uranium and coal.

The land-use impacts are usually more localized than are the air pollution impacts. People directly affected are deeply concerned because the land-use costs are geographically distant from those who reap the benefits.

1. Land disturbed in uranium mining

For current light water reactors (LWRs) without plutonium recycle, a ton of average uranium ore mined today (0.208 percent U_3O_8 equivalent) yields 730 million Btu of heat. At present, about 60 percent of total uranium production comes from open pit mining operations and 40 percent from deep mines.[111] In the case of open pit uranium mining, about 250 acres of land is affected for each quad of energy supplied. On the other hand, with underground mining (based on a 9-ft average thickness of uranium seams and a 75 percent fraction extracted) 55 acres of surface is affected to produce 1 q of uranium energy.

On the assumption that the fraction of uranium supplied from surface mines grows to 80 percent in the future, the disturbed land associated with uranium requirements for electric generation in 2000 for the various scenarios is given in Table 39.

2. Land disturbed in coal mining

In contrast to the 730 million Btu provided by a ton of uranium ore, bituminous coal provides an average of 24 million Btu per ton and Western subbituminous coals and lignite about 15-18 million Btu per ton. Thus to provide a quad of energy will require many more tons of coal than uranium ore, and a much larger impact on land area is expected. The national average for strip-mined coal is 15.2 acres per 10^{12} Btu. This value (land-use coefficient) varies widely from one U.S. mining region to another, from a low in the Powder River Basin of 0.8 acre per trillion Btu of coal to 33.8 acres in West Virginia.[112]

The greatest land-use impacts are associated with surface mining of coal. Although the area broadly affected by subsidence from underground mining is larger than areas required for surface mining, the effect on the surface is generally less pronounced. Direct surface disturbance by underground mining (excluding roads and coal storage facilities) amounts to about 0.3 acre per 10^{12} Btu of coal.[113]

The fraction of coal mined underground has been declining consistently since the mid-1950s, when it represented about 75 percent of the total. Until 1969 the decline was gradual, averaging about 1 percent per year. The Mining Health and Safety Act appears to have temporarily accelerated the decline, and currently only about 50 percent of our coal is produced in underground mines.[114]

The impact of present new mine development and expansion on the relative proportions of underground and strip capacity is difficult to assess. A recent survey of the development plans of firms with 60 percent of the nation's coal output shows slightly greater expansion of strip over deep mine capacity. However, the ratio of *net* new capacity may be quite different. For example, fully two-thirds of the planned deep capacity may be for replacement, while the fraction of strip capacity for replacement is likely to be smaller. The prevailing view in the coal industry is that a major increase in coal production will be accompanied by a substantial shift to strip mining (70 percent of capacity in the later years of the century is one estimate)[115]; the environmental and, in particular, land-use impact of strip mining may thus be a major issue.

The impact of strip mining varies substantially by region—indeed, by site—thus making generalization exceedingly difficult. A simple calculation of different regional mining strategies indicates that relatively modest changes can have a large effect on estimates of land disturbed. In the high energy demand scenario in the year 2000, approximately 52 x 10^{15} Btu must be derived from

TABLE 39. Land Requirements for Electric Transmission and Fuel Production—A.D. 2000
(all entries in thousands of acres)

	Nuclear supply case		Coal supply case	
	High energy	*Low energy*	*High energy*	*Low energy*
Transmission and distribution right-of-way	20,800	16,600	20,800	16,600
Uranium mining				
20% deep	0.34	0.30	0.12	0.12
80% surface	6.2	5.4	2.2	2.2
Coal mining				
30% deep	94	51	155	101
70% strip (a)	332	180	548	356
(b)	98	53	162	105
(c)	61	37	118	76

(a) 14% Western, 35% Midwestern, 51% Appalachian (1970 distribution).
(b) 50% Western, 25% Midwestern, 25% Appalachian.
(c) 60% Western, 20% Midwestern, 10% Appalachian.

coal. Under such conditions, the area disturbed each year by strip mining could be several times the current rate of about 70,000 acres—or it could be only modestly larger than today in case of no moratorium and dependence on Western coal.[116]

Table 39 shows the variation in acreage which will be required in 2000 for production of coal for each of the scenarios. The assumption of 70 percent production from surface mining is arbitrary, but the variation in land requirements (with and without a moratorium) will be much the same as any other reasonable proportion of production from strip mining.

An additional consideration is land required in the transmission and distribution of electric energy. According to the *Sourcebook for Energy Assessment*, 17,200 acres is required for each 1,000 MW plant.[117] Multiplying by the electric capacity required in each scenario, the total land area which must be dedicated to transmission and distribution can be estimated. These areas dwarf those required for fuel production. Of course, the area dedicated to rights-of-way is not totally removed from use by society for other purposes; cattle can be grazed and some crops can be grown under transmission lines; lawns, streets, and sidewalks are commonplace under distribution lines. But the land is used differently from that dedicated to uranium or coal mining; it is removed in perpetuity while the acreages being disturbed by mining are annual incremental amounts and will usually be returned to other uses. The huge requirement of land for transmission and distribution is nonetheless impressive.

6 Alternative Long-Range Energy Futures

Two different perceptions of the long-range future support the opposing views with regard to the role of nuclear energy. All agree that ultimately we shall need a nonfossil energy source. Those who favor continued nuclear development look to the fission breeder and fusion technology as the backbone of the ultimate, or asymptotic, system. Those who do not usually regard various embodiments of solar energy as occupying this central position.

It is not yet clear that a choice can be made between these alternatives. Nevertheless, a fundamental issue related to the nuclear moratorium is: What is gained, what is lost, if our society rejects nuclear energy and relies primarily on the solar option in the era extending beyond this century when fossil fuels can play only a minor role? Many additional questions remain or are emerging for both alternatives, or any mix of alternatives. We do not pretend, therefore, to answer this basic, probably unanswerable, question. In what follows, however, we shall try to delineate the issues without coming to clear-cut conclusions about the ultimate tradeoffs. In Volume II of this report, separate, detailed studies of the long-range solar and nuclear futures are presented.[118]

The Solar Option

With regard to the solar option, the primary question is: How can an affluent, complex society exist entirely on solar energy (and its immediate derivatives)? In [illegible], can we *afford* solar energy as our primary energy source? Any discussion of this question is obviously hindered by the paucity of hard engineering data. We cannot operate, or responsibly conceive the operation of, the energy systems for a planet of 10-15 billion people on the basis of promises alone. We can, however, speculate.

Certain critical components of a solar system *may* exhibit rather sharp inflections in the cost of marginal supply as demand increases. Two examples come to mind: solar electricity and biomass. The inflection in solar electric costs may come as (1) intermittent solar sources (terrestrial photovoltaic, solar thermal electricity, wind, wave power) are required to stand alone with their own storage (these matters are discussed in a separate paper in Volume II) and (2) more expensive reliable sources are brought on line (such as electricity from biomass).[119]

The sharp increase in biomass costs may occur as the opportunity costs of additional land and water resources increase, as returns from marginal fertilizer applications diminish, or as we shift to more intensive modes of production that may require large amounts of capital (e.g., algae culture).

Direct thermal applications of solar energy may exhibit rather analogous cost behavior. Thus, for a given type of load (such as residential heating), increasing the fraction of total solar heat above a certain percent is likely to result in a disproportionate increase in the capital cost of the solar system.

Going from residential to industrial heat loads may also present profound cost challenges for solar systems. In general, however, direct thermal applications, particularly where the end-use temperatures are relatively low, appear to suffer comparatively fewer constraints.

The result of these capacity-cost relationships is that the unit cost of solar energy systems may be more heavily dependent on aggregate energy demand and the pattern of demand than would be the case with nuclear. It is thus not surprising that pioneering studies of nonnuclear futures emphasize energy conservation and are particularly sensitive to the possibilities of "second-law analysis." Compared to longer-term analyses of nuclear systems, solar system analyses may require more refined demand studies. Indeed, the dominant problems of analysis may actually be on the demand side despite the massive uncertainty, in an absolute sense, surrounding supply technologies. In general, solar energy and conservation are almost certainly indissolubly related: a complete solar society would tend to be a low-energy society.

It is probably premature to cost the present solar technologies and attempt to compare the cost with that of nuclear systems. This would require using the results of an R&D program only recently undertaken. Present costs are hardly relevant; possible future developments are still obscure. On the basis of what we now know, however, the cost of *some* components of a solar energy system, such as solar electricity, appears to be higher than that of their nuclear counterparts. For example, photovoltaic cells now cost $250/ft^2; even if their cost is reduced thirtyfold, photovoltaic electricity remains very expensive compared to what we believe nuclear energy will cost. In the conventional wisdom, this alone would warrant dismissal of solar electric options, particularly if, as may be the case, the cost differential involves factors of two to four more.

It may be worthwhile, however, to examine the implications a change to a solar system would have for the economy as a whole. Conceivably a doubling or even tripling in the price of electricity or industrial process heat would have only a modest effect on aggregate economic performance. And since the economy is likely to continue to grow, albeit more slowly than in the past, it is difficult to sound apocalyptic about a projected per capita income in the twenty-first century that might be 10 percent less than it otherwise would have been. Of course, solar systems may cost very much more than we anticipate, but in any case the issues may revolve around the reliability and security of the system and problems of transition. The question again arises of what we gain in this transaction by giving up nuclear power. If, in fact, we simply substitute an equivalent amount of central-station solar electricity for nuclear electricity, we may gain relatively little.

The Nuclear Option

The problems embraced by a nuclear system (in this analysis only the fission breeder is considered) take on a somewhat different cast. Ultimate physical and economic constraints are less pressing (though there are constraints on the rate of deployment). Of more concern are the perceived hazards of nuclear power. But the central concerns are probably the sociopolitical consequences of adopting the nuclear option.[120]

Implicit in most official analyses of long-term nuclear power policy is the assumption of a long period of social peace and institutional stability; one cannot simply abandon a nuclear reactor the way one can abandon a coal-fired plant. But such a long-term projection cannot be based on historic experience; few, if any, societies or institutions have continued without violent lapses over the kind of time period subsumed here. Profound qualitative societal changes will be necessary if we can look forward with confidence to the kind of stability that will permit the necessary long-term meticulous stewardship of a nuclear system. A less-convincing critique of nuclear power and its accompanying all-centralized electric future is related to the vulnerability of such a system to social or political instability. This, however, is not necessarily an "antinuclear" argument. It is as much directed against conventional central-station electric generation; obviously, central stations are more vulnerable to social chaos than are dispersed systems.

In this connection the following quotation from Robert Heilbroner[121] is relevant:

> I would call attention to a matter of some significance. It is that, even among my severest critics, I have noted a surprising acquiescence in my diagnosis of the gravity of the human plight. Whatever my mistakes of fact, however fanciful my speculations, it has become plain that my vision of a major and protracted crisis—a crisis slated to deepen and intensify rather than to lessen or disappear—is a premonition shared by many.

Perhaps in light of this we should pay more attention to avoiding major perceived risks and less to optimizing "surprise-free" futures. One risk-avoidance strategy may be to encourage decentralization of much of the energy system and to encourage a diversity of energy sources, perhaps through significant government intervention in the marketplace. But if we value the principle of diversity of supply, it would seem to require tortuous casuistry to base a rejection of nuclear power on this principle.

When comparisons are made between nuclear and nonnuclear futures, a number of rather arbitrary "linkages" are made by both opponents and proponents of nuclear power. One is a linkage between nuclear power and high energy consumption. There is no reason that this should necessarily be the case for an energy system which includes nuclear power. Indeed, if nuclear power is as expensive as its critics claim, there will be powerful incentives to conserve.

A Solar-Nuclear Option

It is an unfortunate symptom of the polarization of the nuclear debate that usually the only long-term paradigms under discussion are extreme and illusionary—a "full" commitment to solar or a "full" commitment to nuclear. The debaters tend to regard middle ground as essentially uninteresting. Nevertheless, by examining the middle ground we may reduce the scale of the nuclear enterprise and this may, in turn, reduce the intensity of some problems associated with it. At the same time such a course could avoid the most costly and regionally disruptive aspects of a full solar economy. We may find, for example, that various configurations of nuclear systems might provide the best available forms of storage for a solar energy system. On the other hand, biomass-derived fuel, while probably potentially too limited to supply storage for solar electric systems together with its other priority applications, may be cost competitive with nuclear hydrogen for many applications (such as transportation or industrial cogeneration of process heat and electricity). With a deliberately hybrid instead of fully nuclear paradigm, we may find that the number of required reactors will be considerably less than current projections, since it would be only one among several important energy technologies. Of course, reliance on solar energy for any significant fraction of the ultimate system will depend on the success of solar R&D programs.

We have not in this study examined a "most plausible" or "most reasonable" mixed scenario. Instead, we have looked at rather extreme nuclear and solar energy systems having characteristics selected to bring out systems problems or inconsistencies that might not be evident in less extreme scenarios.

If we concede that the long-term physical and economic constraints on a full nuclear commitment are tractable, we are left with the more difficult question: Can nuclear power be "socially" acceptable if it is to be deployed, essentially forever, on a substantial scale? In the following section we try to envisage the requirements for a socially acceptable asymptotic nuclear future.

Acceptable Nuclear Future

We have not identified any physical constraints that invalidate the asymptotic breeder system, provided that one accepts geologic disposal of wastes.[122] However, nuclear energy is *potentially* hazardous. Possible dangers include diversion, sabotage, proliferation, and reactor accident. As long as the whole system is small and its duration is short, these hazards appear tractable. However, they take on formidable proportions when the nuclear system dominates, and is expected to last essentially forever. We have, therefore, tried to visualize improvements, some technological, some social, that could reduce to acceptable levels the probability of harm from diversion, sabotage, and accident. We do not propose a "fix" for proliferation, which some view as the major potential hazard, of nuclear energy.

1. Nuclear energy "Phase I"

Nuclear energy is likely to develop in two phases—Phase I, based on burner reactors, and Phase II, the asymptotic nuclear system, based on breeders. Because uranium is limited, Phase I cannot last very long. Roughly speaking, a 1,000 MW(e) LWR with recycle requires about 4,000 tons of natural uranium during its 30 years of operating life. The amount of uranium available to the United States at costs that can be afforded in an LWR is usually estimated to be 3×10^6 tons. Thus, prima facie, we have enough uranium to support about 25,000 reactor-years of LWRs—say 800 reactors for 30 years. This period—which, to be sure, may be longer or shorter than 25,000 reactor-years depending on the accuracy of our estimates of uranium supply – we designate as "Phase I."

It is likely that Phase I will be played out without an actual occurrence of any of the possible nuclear catastrophes. Obviously, quantitative estim[illegible] cannot be given for diversion, sabotage, or proliferation. As for accidents, if [illegible] accepts the Rasmussen estimate of 5×10^{-5} as the probability of a meltdown in a PWR, then during all of Phase I there is a probability of about unity for one meltdown. However, the probability that this will breach aboveground containment is lower, about 1 in 4 (for BWR the probability of meltdown is lower, and of breach of containment higher, but we believe PWR is emerging as the dominant reactor type). As Rasmussen reminds us, incremental improvements are likely to reduce these probabilities. We would therefore consider the likelihood of a serious incident in Phase I to be quite small, assuming that the improvements dictated by experience are indeed incorporated into the present generation of reactors.

2. Nuclear energy "Phase II"

Phase II, the asymptotic future based on breeders, presumably will last much longer than Phase I. For Phase II, three additional requirements may be necessary: physical isolation, separation of generation of nuclear power from its distribution and marketing, and a professionalized nuclear cadre. We consider each of these in turn:

The likelihood of diversion, sabotage, and damage from an accident can probably be reduced if the asymptotic nuclear energy system is confined to a finite number of energy centers and waste disposal sites—100 centers and six waste sites occupying a total of 5,000 sq miles. These areas, and only these areas, would be committed to high-level radioactive operations. Such centers would require tight security, possibly comparable to the wartime security imposed on Oak Ridge and Hanford. All lines of communication would be internal; thus diversion of fissile material would be difficult, and transport accidents would be minimized. The centers would further possess logistic capabilities (fire departments, radiological monitoring capability, general engineering expertise) much larger and more elaborate than those customarily available at isolated single reactors.

The demands for expertise and security as well as extreme longevity (both because the wastes must be looked after and because the nuclear system can never be simply abandoned) at the nuclear energy centers are probably incompatible with the present fragmented structure of our electric utilities. It may be desirable, therefore, to place the *generation* of nuclear electricity in the hands of a special Nuclear Energy Authority (NEA)—possibly although not necessarily a governmental body—that would be responsible for the secure and safe generation of nuclear electricity into perpetuity. Distribution and marketing of electricity would continue to be carried out by existing utilities.

Two long-term requirements of the nuclear system seem to be inevitable: tight security and responsible, dedicated expertise. The former is necessary if we are to cope with threats of sabotage and diversion, the latter to ensure the highest order of quality control and to cope with, and to avoid, serious malfunctions of the system that would release large amounts of radioactivity. A special nuclear cadre—perhaps roughly analogous to the Coast Guard—may be required to man the ultimate nuclear enterprise. By keeping the cadre relatively small, one minimizes the chance that necessary security measures would intrude on the rest of the society. Thus the asymptotic nuclear enterprise would possess a degree of *insulation,* in somewhat the sense that the Strategic Air Command or the Coast Guard is set apart: the demands imposed by the society on these entities are obviously greater than the demands made on the society as a whole.

Some elements of Phase II have been much better thought through than others. Thus, we feel confident that nuclear energy centers ought to be a pr[illegible] element of the asymptotic nuclear energy system. On the other hand, much further consideration must be given to the exact institutional changes that may be necessary if nuclear energy based on breeder reactors is to be accepted as a permanent prime energy system.[1 2 3]

The Nuclear Moratorium and Phase II

It is difficult to assess the impact of a moratorium on the achievement of Phase II. On the one hand, a moratorium would "wipe the slate clean" and give us a chance to devise a fully rational nuclear system. On the other hand, the experience we will be gaining during Phase I will be invaluable for planning a more rational Phase II. A moratorium that proscribed nuclear energy might, in the end, lead us to repeat mistakes made in Phase I.

There are steps that can be taken now that would ease the transition to a fully rational Phase II. Probably the most important would be to adopt siting practices in Phase I that make achievement of Phase II easier. Two such actions are: (1) require all new reprocessing plants that are now pending to be located in existing nuclear energy centers such as Hanford, Oak Ridge, Savannah River, and Idaho Falls; (2) require any breeder reactors to be built in existing or prospective centers.

Final Observations

Beyond the issues already touched on here, there are important, value-laden questions which we have hardly examined. Nevertheless, we offer the following speculations about the underlying tradeoffs between solar and nuclear:

Nuclear seems to be a larger and cheaper electricity source than solar: i.e., for a given expenditure of land and of money, nuclear can supply more electricity than can solar. This is particularly true if the overall system is so large as to require full storage. Moreover, if biomass is used widely for portable fuel, the demands on land and possibly water resources become formidable: such a society would almost surely be a low-energy society.

The institutional changes suggested here for Phase II of a nuclear system may be unacceptable. Institutional changes of this sort would not be required for solar.

On the other hand, insofar as solar may impose an intermittency on our pattern of living, an all-solar energy system would seem to be far from a totally "free" society. What may ultimately be at issue is freedom in the use of time. The nuclear society, with its high energy potential, allows us to use our time without regard to energy availability. The price we pay for this freedom is the necessity to organize and manage the nuclear system so as to avoid recognized potential hazards.

These observations are broad, possibly broader than the foregoing analysis justifies. Nevertheless, we believe there is an essential element of truth in such basic, almost philosophic, comparisons. At the very least, we have identified issues whose further clarification would contribute to the current debates on the shape of our ultimate energy system.

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