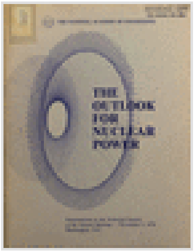

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Contents

Nuclear Power Reliability and Safety in Comparison to Other Major Technological Systems:

Need for Nuclear Power Worldwide: World Regional Energy Modeling

WOLF HÄFELE*

SUMMARY

Based on a 5-year study of the International Institute for Applied Systems Analysis, Laxenburg, Austria, this paper identifies the factual basis of today's energy situation, stressing the need for and difficulties in long-term supranational energy supply strategies.

The bases are two scenarios--defined by close to observed trends of population and economic growth--that indicate a conceivable energy demand range until 2030. These scenarios are quantified for seven comprehensive world regions by way of a highly iterative model set designed at IIASA to study long-term, dynamic, and regional/global aspects of large-scale energy systems.

The results illustrate the need for the world to use all available, and high-cost, energy sources. Nuclear and solar technologies replacing fossil resources will fully have to come to bear after 2030. Before, the weight will have to change from primary to secondary energy supply, e.g., to synthetic fuels production from coal. Resource allocation and trade flows will in general be restricted by production ceilings. Thus, prudent political and economic decisionmaking is in order for the world and its regions to ensure a satisfactory long-range energy supply.

INTRODUCTION

Nationally, there are numerous schemes and programs for planning the energy future. They provide a wealth of detail and a fairly short, or at best medium-term, planning horizon of up to about 15 years. After all, detailed measures *must* have a relatively short time frame in order to be feasible.

Innovation, however, that is to say major changes in an existing infrastructure, involves much longer periods of time. Compare, for example, the evolutions of various primary energy carriers in the energy market. Figure 1 is a logistic representation showing the S

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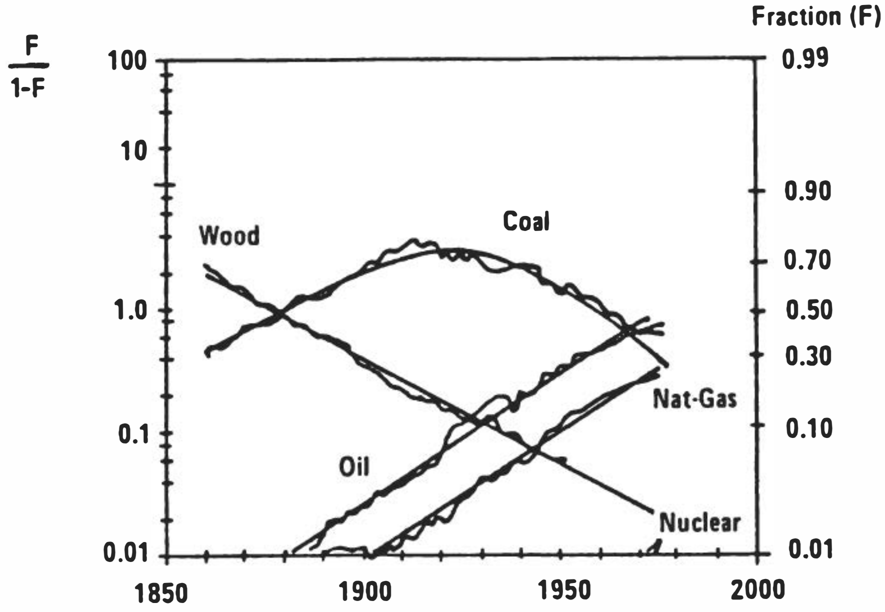


FIGURE 1 World: primary energy substitution.

curves of energies penetrating the market (from share 0 to share 1) as straight lines. Their behavior is remarkably regular,[1] extending over more than a century. This is just to underscore the need for a *long-range* view once changes in the energy supply structure are at stake. If one takes into account that the life of a power plant averages 30 years, the time bracket to consider for innovation may well be 50 years. But there is also other evidence. Consider the dwindling of cheap (known) fossil reserves. Consider the impact of tapping energy sources on the world climate and on man's environment, which is not well understood. These and other aspects all suggest a long-range perspective.

Looking at the energy problem from this angle, one is confronted with several difficulties:

- We are not prepared, either analytically or via control of the market mechanisms, to come to grips with the interplay of short- and long-term aspects.
- International interdependence will have increased considerably in 50 years from now. This will not come as a surprise, since already today 50% of the crude oil in the Federal Republic of Germany, for example, originates from one single area, the Persian Gulf. Yet we will have to do better in viewing the world as a whole.
- There is a severe lack of input data, required for standard energy planning tools, with respect to the 50-year time frame and the way the world will then look geopolitically. Or what about elasticities, for example, i.e., the change in percent in the demand for a given secondary energy as a function of percentage changes in various determinants, such as prices or gross domestic product? Whereas most large-scale econometric models now in use in the United States assume availability

of elasticity inputs in one form or another, for long-range investigations such elasticities cannot be obtained.

For these reasons, medium- and long-term strategies of energy supply are difficult to deal with, both in terms of substance and methodology.

An attempt at formulating long-term global energy supply strategies has been undertaken at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, an East-West venture supported by scientific institutions of 17 nations, which is concerned with problems of civilization in a long-range and globally comprehensive fashion. Initially, IIASA's Energy Systems Program gave much thought to a qualitative understanding of the energy situation and a breakdown of the problem into feasibile subsets. This then enabled the program to proceed to a synthesis by quantitative analysis and integration of many special studies into a global and long-term energy supply and demand picture.

The tool chosen is the writing of internally consistent scenarios: the greatest possible number of necessary conditions is identified and used to narrow down the scope of subjective judgment. To support the effort, a set of computer models is relied upon. The principle guiding this approach is plausibility. Two basic scenarios are constructed, marking the range between plausible upper and lower bounds. But since there is only one reality in store for us, the scenarios are valued as guidelines toward conceivable energy futures and their outcomes as indicators and not as predictors. With the ordering forces of the market having lost much control, such guidelines are indispensable. This above all holds for the oil market, where prices and obtainable quantities have come to be simply vehicles of political action, irrespective of the market mechanics. They will work again properly, leading to the necessary investments, only when confidence and trust in the market are being restored.

TWO SCENARIOS

For some steps in the description of the energy problem, it is useful to consider global overall figures like the following. The world today consumes about 8 TWyr/yr of energy, i.e., commercial energy. (Note that 1 TWyr/yr fairly accurately corresponds to 1 billion tons of coal equivalent [tce] per year.) The average per capita consumption then amounts to 2 kWyr/yr (see Figure 2). About 70% of the people of the world, however, live on much less than the average, and a considerable number of them on only 0.2 kWyr/yr per capita. A conceivable addition of 0.3 kWyr/yr from burning wood and manure figures high in this context. About 22% of the world population use 2-7 kWyr/yr per person, the Europeans among them. The remaining 6% enjoy a per capita energy use of 7-12 kWyr/yr. If, as in Figure 3, one assumes a doubling of the world population in the coming 50 years--a change Keyfitz[2] considers rather conservative--and in an increase in the per capita average to 3 or 5 kWyr/yr, the world's energy demand rises to 24 or 40 TWyr/yr, respectively. This consideration, though so simple, helps assessing the efficiency and capacity required for future energy systems. Their

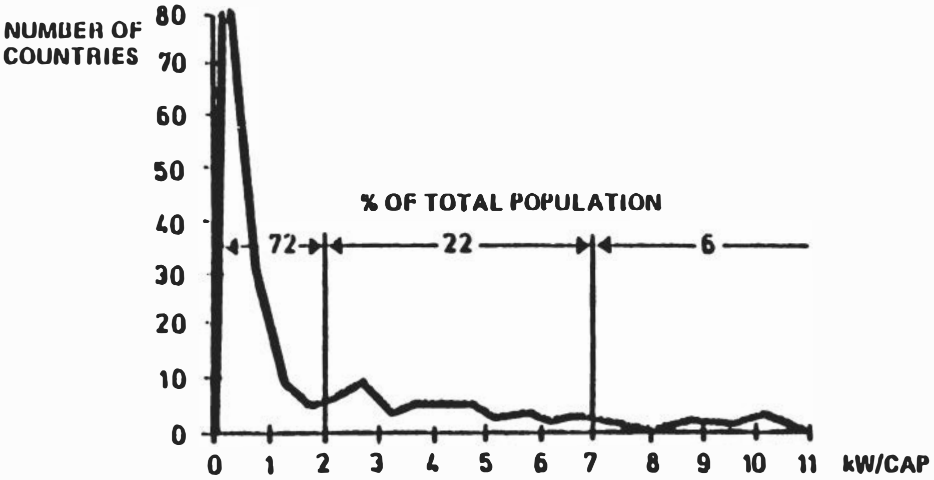


FIGURE 2 Per capita commercial energy consumption in the world, 1975.

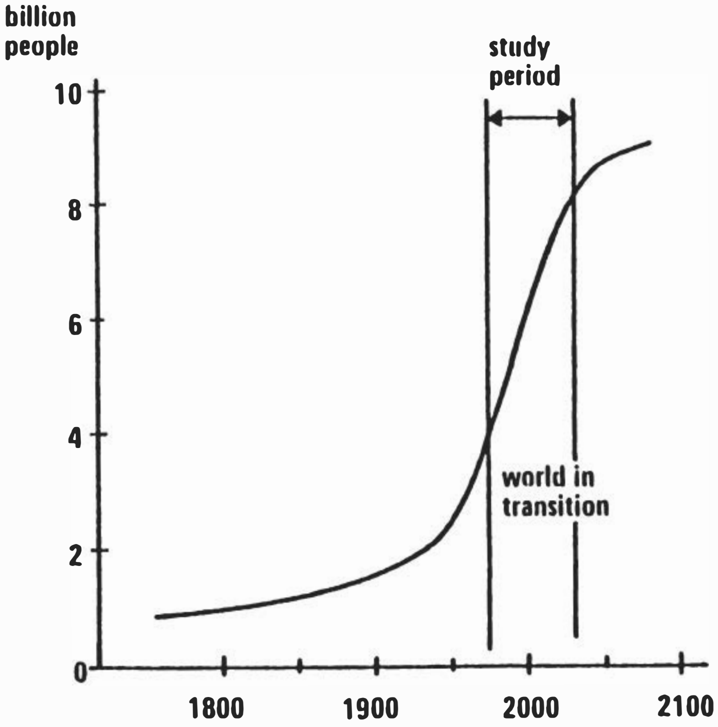


FIGURE 3 World population: historical and projected.

magnitudes often turn out to lie between expectation and observed reality, a thought that will come up again later.

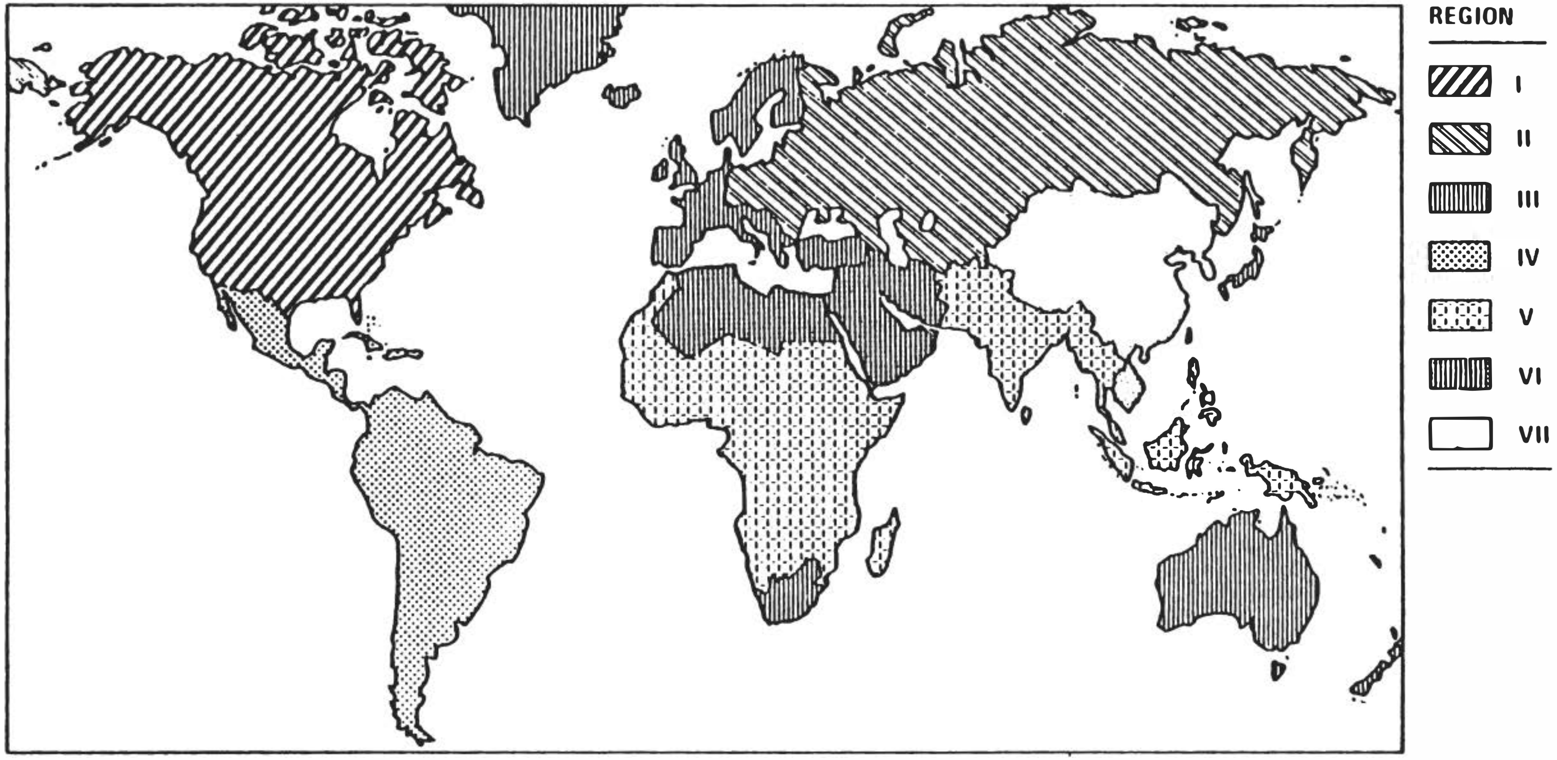
Unfortunately, it appears that such rough guidelines are not sufficiently detailed for real-world decisionmaking, and one is tempted to go back to the national framework. This cannot be done here, however, since it would impair the globally comprehensive vision of the problem. IIASA, in seeking a way out of this dilemma, has identified seven *regions* that describe the world as a whole. In this way, typical regional differences are accounted for and regional interdependencies identified (Figure 4). These regions differ above all by their states of economic development and the availability of resources and, to a lesser extent, by geographical conditions. Regions I, III, and II correspond to the so-called first and second worlds: the industrialized North. Regions IV, V, VI, and VII represent the developing third and fourth worlds, with widely differing national structures. To each world region a set of mathematical models is applied separately. This IIASA set of energy models is depicted in Figure 5, with the larger computer models shown in boxes.

Assumptions on population and economic growth in the various regions enter the model MEDEE, which calculates final energy demand in considerable detail, i.e., the use of energy by the final consumer. The model output, a set of secondary energy demands such as electricity, heat, gas, etc., is the input to the supply model MESSAGE. This linear programming model allocates specified quantities of primary energy, such as oil, gas, coal, uranium, etc., to the generation of secondary energy over a period of 50 years. It produces optimal discounted costs and, most important, takes into account various constraints, providing in this sense an optimal supply mix of primary energies in a region. The resulting requirements for direct and indirect investments in energy generation are accounted by the model IMPACT. The model uses an input-output approach to identify the effect these requirements may have on a given economy. The aggregated investments are then fed into the MACRO model, which helps assess the macroeconomic implications of changes in the ratio of energy consumption and investments. With a quasiformalized procedure linking international trade between the world regions, a first-order approximation of input data for MESSAGE is obtained. Another output, to be derived from the model results, is prices and elasticities.

While all the models in the set in their present form have been developed and applied at IIASA, their origins vary. MEDEE orginates from the University of Grenoble, MACRO is founded on work in Canada and the United States, and IMPACT and the world trade procedure come originally from the Siberian Power Institute at Irkutsk. The model MESSAGE has been completely developed at IIASA.

In the light of the explications above, it is crucial to merit the iterative character of the modeling procedure. The findings described below could in no way have been obtained from one run through the modeling loop. Rather, the procedure is in steps, so that interfaces can be installed in between them for iterative modification until a consistent analysis is obtained. Thus there is indeed room for assumptions and judgment in the light of the underlying mental model.

Two scenarios have been constructed that are defined by two basic development variables, population and gross domestic product (GDP).



I	(NA) NORTH AMERICA
II	(SU/EE) THE SOVIET UNION AND E. EUROPE
III	(WE/JANZ) W. EUROPE, JAPAN, AUSTRALIA, NEW ZEALAND, S. AFRICA, AND ISRAEL
IV	(LA) LATIN AMERICA
V	(Af/SEA) AFRICA (EXCEPT NORTHERN AFRICA AND S. AFRICA), SOUTH AND SOUTHEAST ASIA
VI	(ME/NAf) MIDDLE EAST AND NORTHERN AFRICA
VII	(C/CPA) CHINA AND CENTRALLY PLANNED ASIAN ECONOMIES

FIGURE 4 Seven world regions.

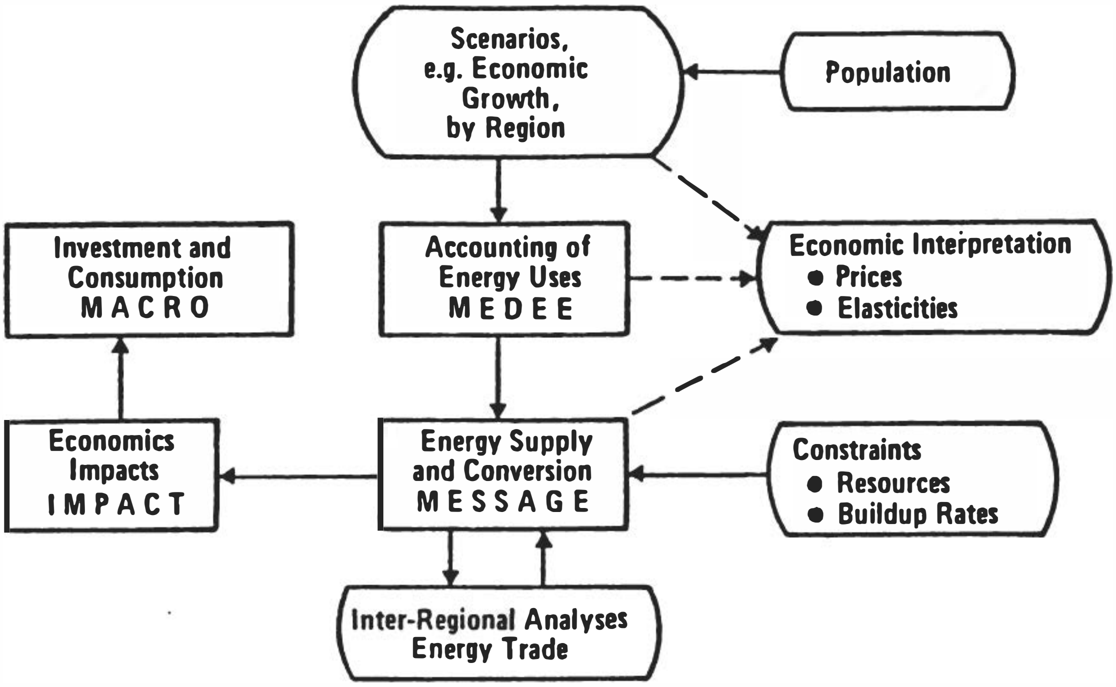


FIGURE 5 IIASA's set of models for energy strategies.

Both scenarios, High and Low, are rather conservative, representing moderate departures from observed trends cases. In either scenario, population is assumed to grow to 8 billion in 2030 (and would then taper off to a sustainable level). The basic difference is in GDP projections: one scenario assumes a relatively low economic growth, fairly large advances in energy end-use technology, and a rather positive attitude towards energy saving of those concerned. The other scenario assumes a modestly high growth. The less conservative assumptions made on the supply side in both scenarios include effective and timely decision-making and implementation, as well as due regard for the needs of the developing countries.

In all, these assumptions are rather optimistic, marking the bounds for what may be maximally feasible, while the real world experience may turn out to be more sobering.

ENERGY DEMAND

Let us now look more closely at how energy demand is dealt with in the two scenarios. To this end, it is useful to consider the economic evolution of the regions in terms of percent of per capita GDP.

Table 1 gives the per capita GDP and its yearly growth rates used in the High and Low Scenarios, 1975-2030. In the Low Scenario, the per capita GDP growth for North America (Region I) goes down to 0.7%/yr, and that for Europe (or more exactly, Region III) comes to be only 0.9%/yr. Both values are meant to approximate zero economic growth.

TABLE 1 1975 Per Capita GDP and Growth Rates for Two Scenarios to 2030

Region	GDP Per Capita ($) 1975	Growth Rate of Per Capita GDP (%/yr) High Scenario 1975-2000		Low Scenario 1975-2000	
		High Scenario 1975-2000	High Scenario 2000-2030	Low Scenario 1975-2000	Low Scenario 2000-2030
I	7,046	2.9	1.8	1.7	0.7
II	3,416	3.6	3.2	3.1	1.9
III	4,259	3.0	1.8	1.7	0.9
IV	1,066	3.0	2.4	1.6	1.9
V	239	2.8	2.4	1.7	1.4
VI	1,429	3.8	2.8	2.4	1.2
VII	352	2.8	2.4	1.6	1.4

The highest growth rate, by contrast, is that for Region VI (Middle East and Northern Africa) from now to the turn of the century (3.8%/yr). The Soviet Union and the Eastern European countries (Region II) have generally high values but otherwise follow the decreasing trend.

Gross *regional* products (GRP) are obtained by multiplication of the GDP growth rates by regional population figures. (The population data here are from Keyfitz.) In the OECD countries, GRP annual growth rates, 1975-2030, range between only 2% to 3%; the evolution assumed follows the general decreasing trend.

More important than the economic data are the related values of energy demand, however. An adequate definition of energy flows from the source to consumption differentiates at least between primary energy and secondary energy, as well as energy use (see Figure 6). The latter term in fact comprises what is called energy services, resulting in a fine piece of pottery, a warm room, or adequate illumination for reading. This energy service can be consumed, other than energy itself, which follows the law of conservation. Use of energy has to do with the negative entropy or negentropy (or information) content of energy. This rather abstract quantity, equivalent to the use of capital or work or to the impact of know-how, can completely or partially be consumed or substituted: the piece of earthenware may break, the room may cool down, and the light photons are absorbed.

The point here is that the relationship between energy consumption--which depends on the level of a given economic activity--and the economic activity itself is *not* unambiguous and straightforward. No wonder the issue is in the center of controversy today. It surfaces in the discussion on energy coefficients, that is the percentage of energy growth required per percent of GDP growth. And as we will see in a moment, differentiation of final energy and primary energy is very important in this context.

The *final* energy-GDP coefficients for Regions I, II, and III center around 0.8, but those for Regions IV, V, VI, and VII are around 1.5, which demonstrates the need for the developing countries still to build up their infrastructures. By the way, more energy is needed at first to build a railway system than to ship by it computer printouts later, which may stand here for the most recent sophisticated accretion of GDP.

To argue this point in a convincing and credible manner, lots of details are necessary. MEDEE, the model for assessing long-term energy demand, is meant to do so. It does in fact account for the great diversity of end-use categories and their interdependencies. Figure 7 summarizes the relevant results. The final energy-GDP coefficient is assumed to go down to as low as 0.3 for the industrialized countries, but to only slightly less than 1.0 for the developing countries.

The respective coefficients of *primary* energy and GDP, on the other hand, may differ completely, both in quantity and in quality (see Figure 8), where ε_p for Regions I, II, and III in 1975 was close to 1.0 but clearly above 0.8. This is due to conversion losses at the level of secondary energy generation and to electricity generation in particular. Considerable losses arise from coal liquefaction, which plays a major role in both scenarios for Regions I and III, as will be seen later. This then may well cause the primary energy-GDP coefficient to rise to values higher than 1.0.

It is not possible here to treat these energy demand calculations in greater detail. One point merits special attention, however. The demand for *liquid* secondary energy carriers, such as heating oil or gas, is shown to be a much more severe bottleneck than is widely assumed. Therefore, it is attempted in both scenarios to limit the use of liquid fuels to practically nonsubstitutable applications, such as for transportation, feedstocks, and petrochemicals. Table 2 shows this use of liquids in percent. The shares vary between about 50% today and more than 90% in 2030. Therefore, it becomes more and more necessary to substitute district heat and electricity for heating oil and gas. As a consequence, there is a continuous steep increase in electrification (Figure 9).

Such demand considerations lead to a per capita *primary* energy demand in the scenarios as in Table 3: a world average of 3 or 4.5 kWyr/yr, respectively, in 2030--similarly as was noted above--instead of 2 kWyr/yr per person as of today. While the per capita consumption ratio of Regions I and III, compared to Regions IV and V, improves by a factor

TABLE 2 Use of Liquids: Percent of Liquid Demand Used for Transportation and Feedstocks

Region	1975	High 2030	Low 2030
I	74	94	91
II	65	100	100
III	52	86	76
IV	69	90	89
V	58	91	88
VI	74	94	91

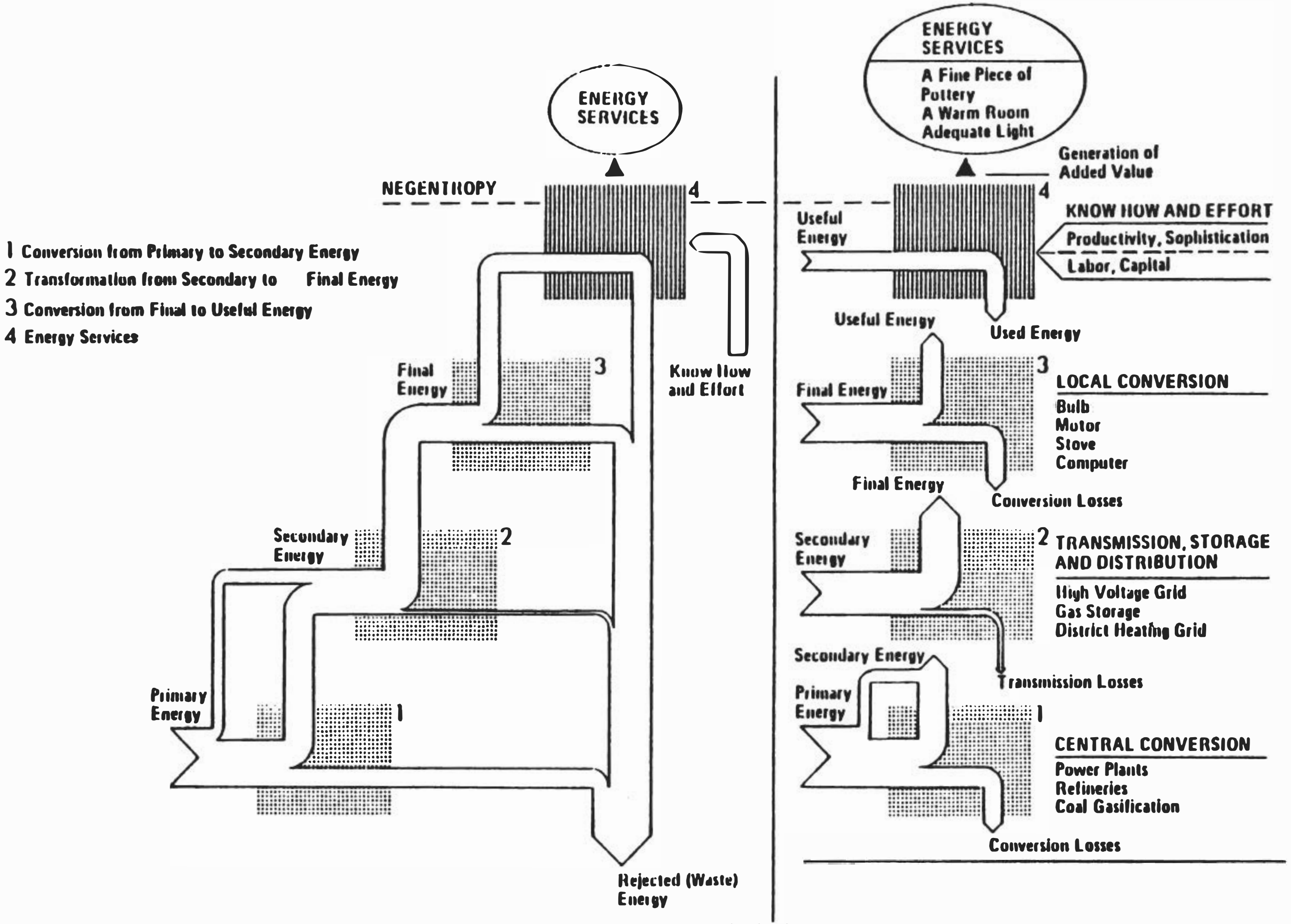


FIGURE 6 Energy flows: definition of terms.

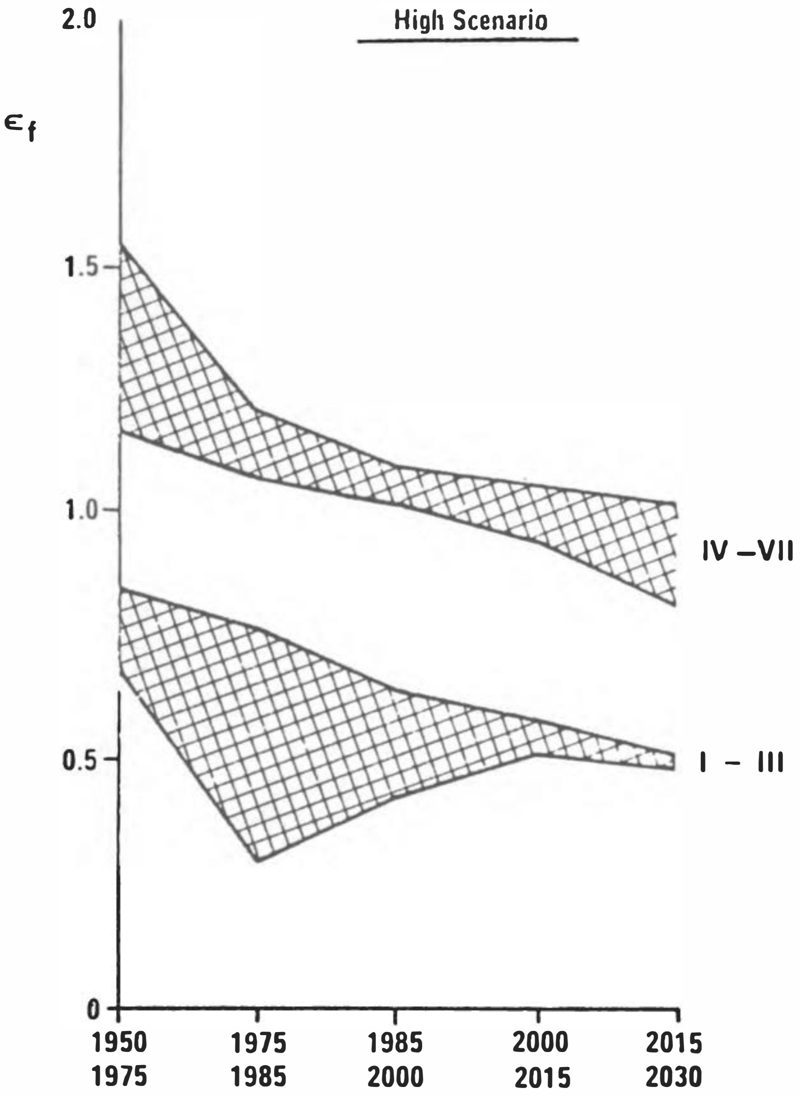


FIGURE 7 Final energy-GDP coefficient.

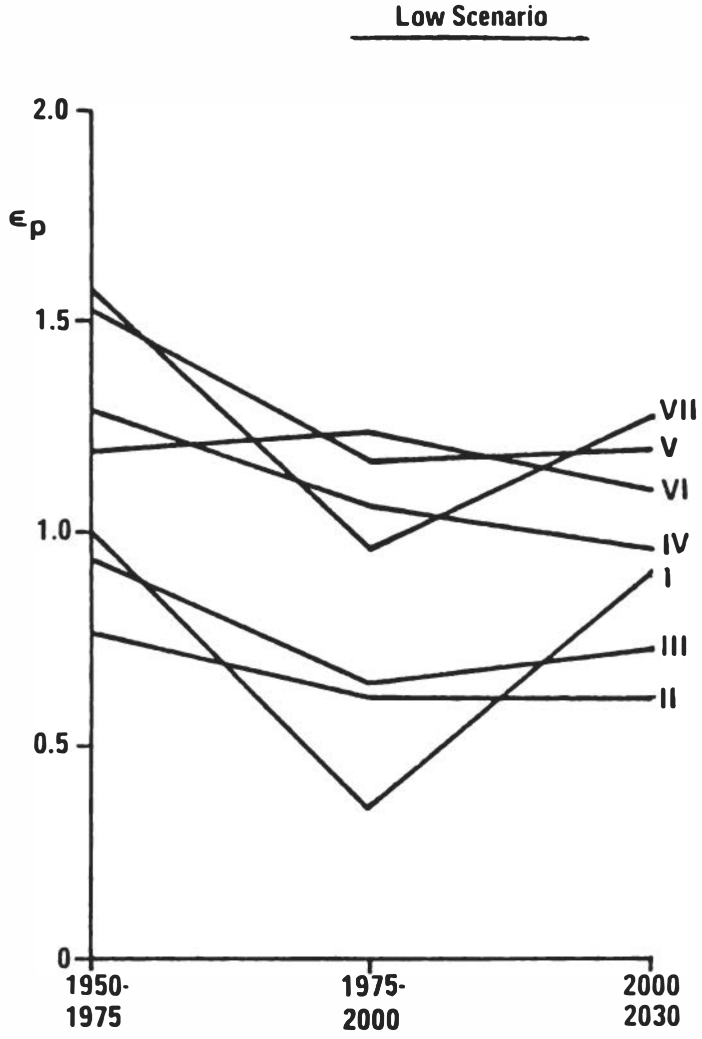


FIGURE 8 Primary energy-GDP coefficient.

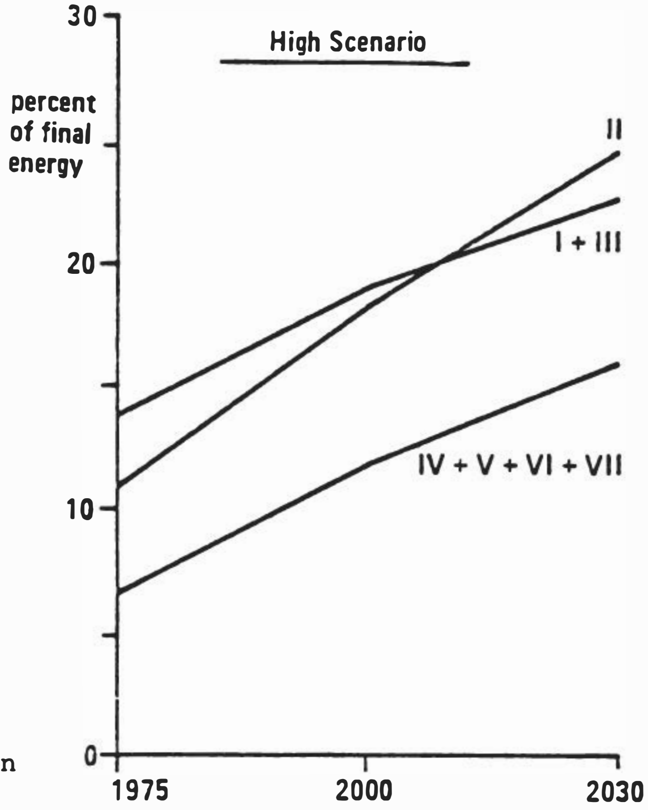


FIGURE 9 Electrification 1975-2030.

of about 2, considerable inequities between developed and developing countries remain, and the gap continues to be a problem far into the next century. The *global* primary energy demand is projected in Table 4, with 22 TWyr/yr in the Low Scenario and 36 TWyr/yr in the High Scenario.

Mind you, it is easily possible to obtain still lower as well as higher values if the scenario assumptions are slightly varied. One way

TABLE 3 Primary Energy Per Capita (kWyr/yr per capita)

Regions	1975	High 2030	Low 2030
I + III	6.2	12.2 (2x)	8.2 (1.3x)
IV + V	0.4	1.9 (4.8x)	1.1 (2.9x)
WORLD	2.1	4.5 (2.2x)	2.8 (1.4x)
Ratio $\frac{I + III}{IV + V}$	16.2	6.4	7.5

TABLE 4 Primary Energy Projections (TWyr/yr)

Regions	1975	High 2030	Low 2030
I + II + III	6.8	20.5 (3.0x)	13.9 (2.1x)
IV + V + VI + VII	1.5	15.2 (10.5x)	8.5 (5.8x)
WORLD	8.2	35.7 (4.3x)	22.4 (2.7x)

of comparison tried at IIASA is a 16 TWyr/yr scenario that retains the 2 kWyr/yr per capita average of world energy consumption. An increase in energy use in the developing countries must accordingly be offset by a negative energy consumption growth in the industrialized world. Table 5 describes this case for the seven world regions.

There is at present quite some agitation to promote a negative or zero energy growth for other reasons than energy supply difficulties.[3] Yet the impact this movement will have on our way of living cannot be grasped. At the other end of the spectrum, however, there are world energy consumption estimates of clearly more than 40 TWyr/yr. The political concept of the New Economic Order, for example, pronounced by the UN group of the 77 at UNCTAD conferences, leads to such higher energy demand values.[4] But this is not out of focus with an observation above that the link between energy and economy is not naturally a closed one. In this light, the energy demand figures of the High and Low Scenarios fall well within the mid-range of today's projections.

TABLE 5 Per Capita Primary Energy Consumption, a 16-TW Scenario, 1975-2030 (kWyr/yr per capita)

Regions	Base Year (1975)	2000	2030
I	11.27	9.1	8.0
II	5.10	7.2	6.2
III	4.03	3.6	3.2
IV	1.06	1.8	2.8
V	0.23	0.5	0.7
VI	0.96	2.2	3.6
VII	0.51	1.0	1.2
WORLD	2.1	2.0	2.0

ENERGY RESERVES AND ENERGY RESOURCES

A clear distinction must be made between reserves and resources. Reserves, being resources that are explicitly known, can be mined at economic conditions. Resources then are considered to include reserves *as well as* a resource base: this resource base is presumed to exist with a certain probability by way of geological evidence, but its exploitation is not evidently economic. Both categories continuously vary in quantity, the ultimate difference between them being technology. North Sea oil is a case in point. There, with the technology of floating platforms at hand, the resources have become reserves. Consider, however, that such technology has become feasible only after 1973.

Estimations of resources traditionally differ from each other. Geologists apparently tend towards cautious estimates. Economists, on the other hand, guided by the role of price increases, proceed from a *de facto* unlimited resource base. Inherently different definitions apply for coal and gas, with coal being usually estimated on a geological basis and oil with a view to maintaining a certain reserve-production ratio. Resource assessment is difficult, therefore, especially if assumptions on future conditions are involved, as in the present scenario.

While all this commands caution, one must come up with numbers for the scenario definition. The estimates in Table 6 of ultimately recoverable fossil resources should be looked at this way. They are grouped by three price categories. Coal, oil, and gas of the cheapest category ($25/t or $12/boe, respectively) make up about 1,000 TWyr. Simple calculation shows that for 40 TWyr/yr this amount would be used up in 25 years, and one comes to realize that this is where the public's concern about resource scarcity originates. Realistically, Categories II and III must also be included in the count, leading altogether to about 3,000 TWyr. Also, it seems more appropriate to assume the world's fossil energy use of the next five decades to average about 15 TWyr/yr, which makes the situation appear less tense. Of course, more details,

TABLE 6 Ultimately Recoverable Resources. Coal I: $25/t, II: $25-50/t; Oil, Gas I: $12/boe, II: $12-20/boe, III: $20-25/boe

Resource	Coal (TWyr)		Oil (TWyr)			Gas (TWyr)		
Cost Category	I	II	I	II	III	I	II	III
I (NA)	174	232	23	26	125	34	40	29
II (SU/EE)	136	448	37	45	69	66	51	31
III (WE/JANZ)	93	151	17	3	21	19	5	14
IV (LA)	10	11	19	81	110	17	12	14
V (AF/SEA)	55	52	25	5	33	16	10	14
VI (ME/NAF)	<1	<1	132	27	n.e.	108	10	14
VII (C/CPA)	92	124	11	13	15	7	13	14
WORLD	560	1,019	264	200	373	267	141	130

in particular with regard to regional differences (see Table 6), were used in the modeling, as in the case of energy demand. But, even at this summary level, large differences are obvious between different qualities of coals, oil, and gas. For example, oil recovery in Saudi Arabia or in Alaska or in the North Sea do not easily compare. It shows that the 3,000 TWyr in Table 6 are not a soft cushion to rest on.

Besides fossil resources, energy supply from renewables is getting much attention, nourishing wide hopes. If one neglects the large-scale use of solar energy temporarily, one finds the potential of the remaining sources to be limited. Much explanation would be needed to fully prove this statement. Since this is not possible here, a summary of the estimated potential of renewables is given in Table 7. It differentiates between what is theoretically or technically possible and what may actually be feasible. The realizable potential of renewables appears to be about 10 TWyr/yr, a figure much lower than the expected demand. The average energy densities of renewables, on the other hand, are 0.1-1.0 W/m^2 (Figure 10). With an indicative energy density of 0.5 W/m^2, this implies that 20 million km^2 of land will be needed for harvesting the realizable potential of 10 TW--an area about as big as all the agricultural land in the world!

Another matter is the *large-scale* use of solar energy, the annual average density of which may be 20-40 W/m^2, and whose area requirement is relatively smaller. Extensive investigations[5] have shown that the need for land is bound to complicate solar use in some such cases, but

TABLE 7 Estimated Potential of World Renewable Energy Supply

Source	Potential Technical	Realizable	Constraint
Forest and fuel farms	6.0	5.1	ecological climatological
Solar panels Soil storage Heat pumps	5.0	1.0	economic technological
Hydropower	2.9	1.5	ecological social
Wind	3.0	1.0	economic
OTEC	1.0	0.5	ecological climatological technological
Geothermal	0.2	0.6	economic
Organic wastes	0.1	0.1	balanced
Glacier power	0.1	0	technological
Tidal	0.04	0	computational
TOTAL	20	9.7 TW	

might be resolved in general. A much greater long-term problem may be capital cost and energy storage. An overriding concern is the tremendous demand for material needed to cover such areas. The minimum material density is generally estimated to be 10 and 100 kg of concrete and iron per square meter.

The solar growth rates in Figure 11 are inferred on this basis. With a hypothetical doubling of world concrete and iron production to be invested in solar power plants, between 250 and 1,500 GW(th) could be installed per year. Therefore, and for other supporting reasons, the *growth rate* rather than the solar power potential appears to be a leading constraint on large-scale solar power application over the next 50 years. This, of course, assumes optimistically that capital cost and storage requirements can be met.

Now a few words about nuclear energy. In the present context, the question is above all the magnitude of what nuclear energy can at best

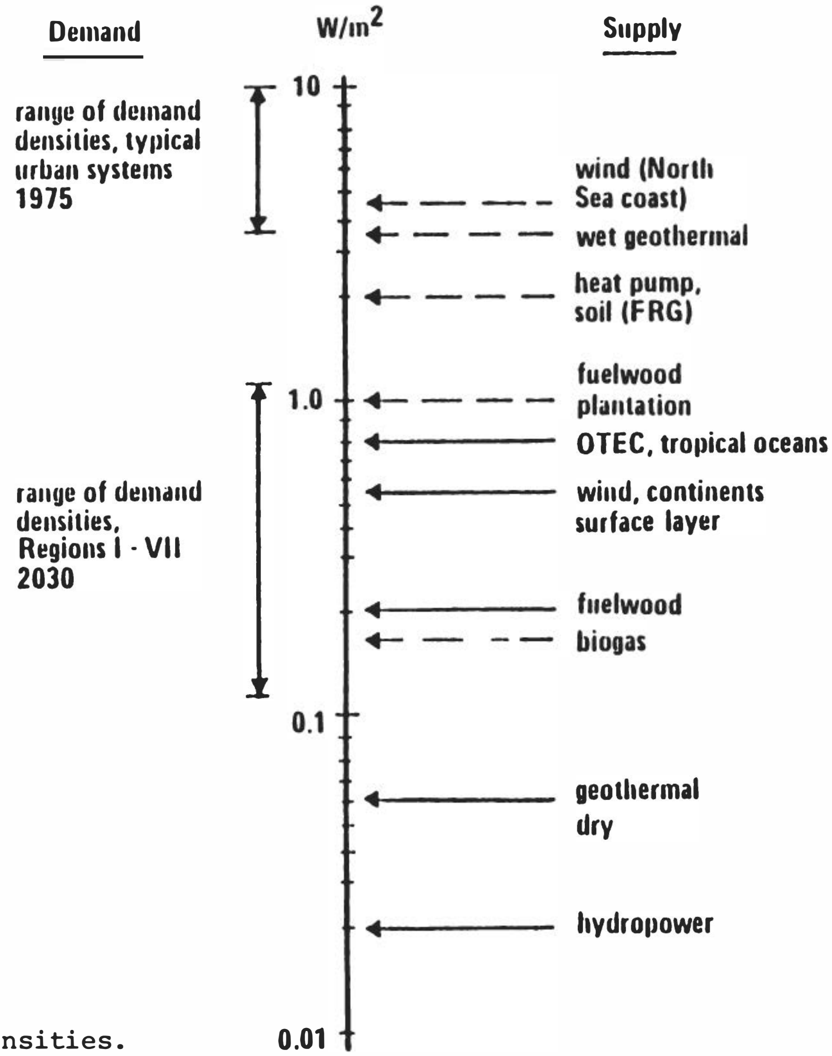


FIGURE 10
Energies densities.

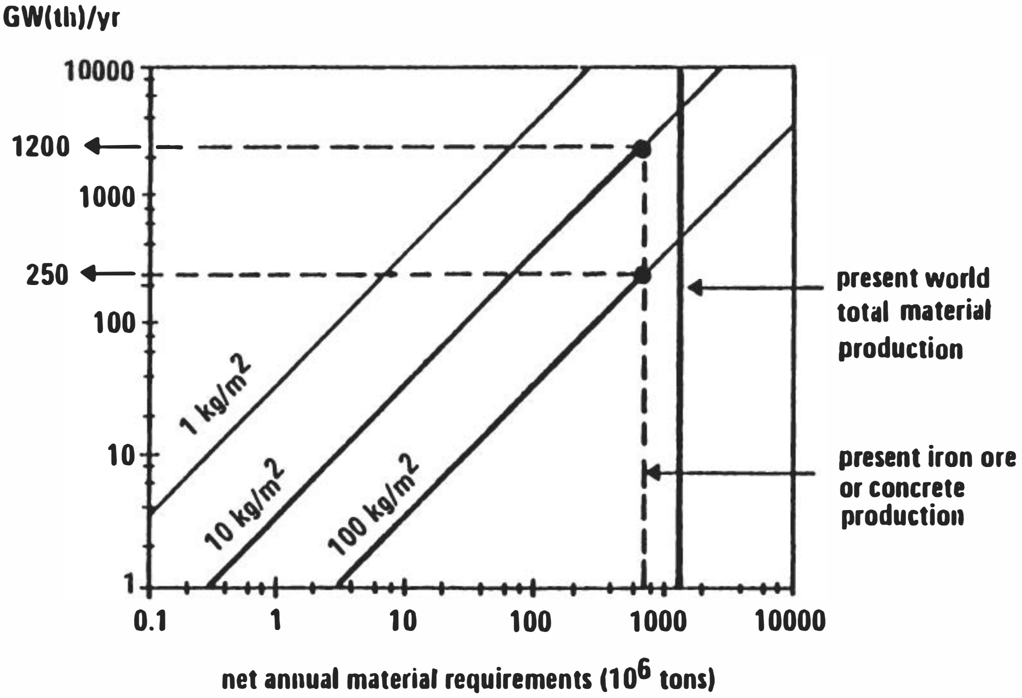


FIGURE 11 Material requirements: solar conversion systems of various net densities.

contribute by 2030, all institutional and societal issues put aside. There is only a vague answer to it. Detailed studies--not discussed in the present context--indicate a worldwide realistic upper limit of 10 TW of installed electric capacity. It is trivial to show that the maximum could be less. To 10 TW(e) installed capacity, a (commercial) primary energy consumption of 17 TWyr/yr would correspond. (Note that TWyr/yr always implies annual calorific input to produce power.) At such a growth rate, the sensitive parameter is the natural uranium requirement, e.g., of light water reactors. For example, the International Fuel Cycle Evaluation (INFCE) considers that 4.3 million tons of natural uranium at prices up to $130/kg are available in the Western world today. For the world as a whole and with worldwide prospection at the present U.S. level, one could consider uranium resources of, say, 20 million tons--but this number should be taken as a working hypothesis rather than as established fact. This large amount would be used up by about 2020, however, if light water reactors (LWR's) or other nonbreeders were the only nuclear technology deployed. Therefore, breeders must play their part in time. For example, the plutonium from LWR's could be fed into fast breeder reactors (here LMFBR's, see Figure 12) and be used as breeder inventory that is not consumed but breeds more fuel. A once-through of 20 million tons of natural uranium would lead to about 24,000 tons of Pu, which means that the 17 TWyr/yr in question could be produced for a virtually unlimited period of time. However, this possible reactor strategy presupposes fostering now an intensive buildup of

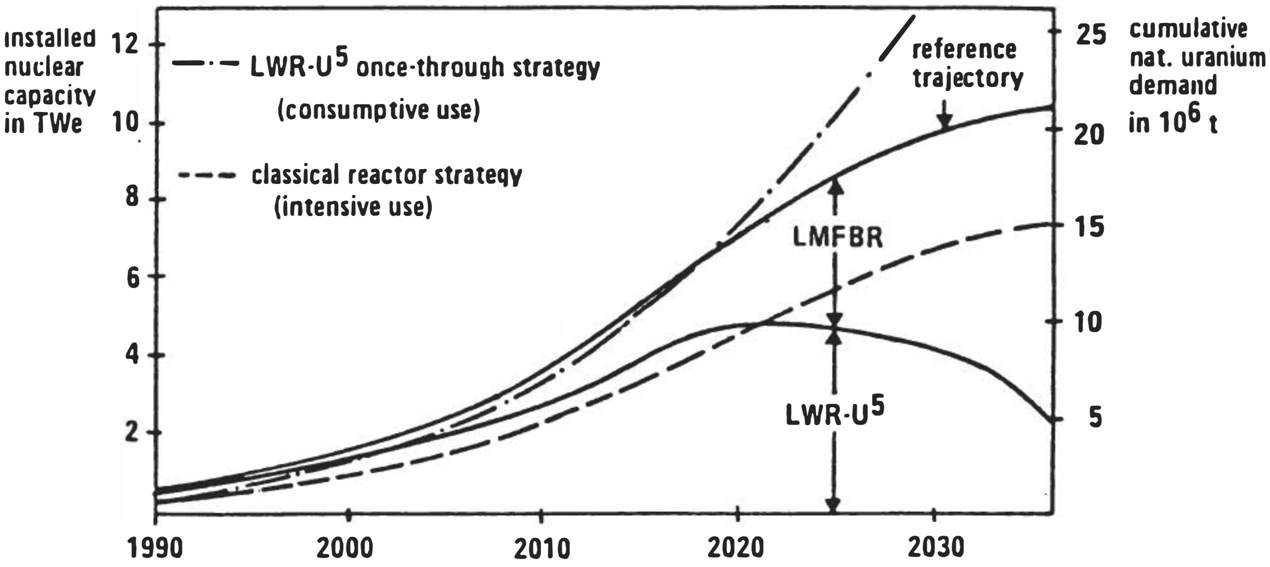


FIGURE 12 The classical reactor strategy.

fast breeder reactors that would become operative on a large scale by the turn of the century. There are, of course, various other possibilities besides this reactor strategy, but all of them require breeding.

In this respect it is useful to realize that the fusion reactor of the future, based on the present design, will also be a breeder reactor. Granting the central fusion process of energy release in the plasma to be typically different from the process of nuclear fissioning, there are yet remarkable parallels between fusion and fission breeders in strategic energy planning and reactor operation: lithium in fusion corresponds to U-238 (and Th-232) in fission breeding, and tritium in fusion to plutonium (and U-233) in fission. In both cases, there are radioactive inventories and radioactive wastes. Both types of breeders today are geared to electricity generation. Lithium as well as uranium plus thorium resources are similar in size, either one yielding an energy output of about 20 kWh/g. In spite of these qualitative similarities, a technically mature fusion reactor could offer considerable quantitative advantages over the fission breeder.[6,7] Technical maturation of fusion reactors, however, will still continue far into the twenty-first century, and no more than 2-3 TWyr/yr from fusion are to be expected in 2030. Its share will possibly increase thereafter.

Table 8 attempts to summarize the world's resources, indicating what the potentials as well as the constraints are in producing and using these resources. The data are rather optimistic. Much more would have to be said if time permitted.

ENERGY SUPPLY STRATEGIES

Where do resources come in in IIASA's set of energy models, attempting to simulate the energy demand-supply situation? Figure 5 identifies

TABLE 8 Resources, Production Potentials, and Constraints

Source	Production (TWyr/yr)	Resource (TWyr)	Constraints
Wood	2.5	∞	Economy--environment
Hydro	1-1.5	∞	Economy--environment
Total	6-(14)	∞	Economy--(nature)
Oil and Gas	8-12(?)	1,000	Economy--environment--resources
Coal	10-14(??)	2,000(?)	Society--environment-economy
Nuclear			
Burner	12 for 2020	300	Resources
Breeders	≤17 by 2030	300,000	Buildup rates--resources
Fusion	2-3 by 2030	300,000	Technology--buildup rates
Solar			
Soft	1-2	∞	Economy--land--infrastructure
Hard	2-3 by 2030	∞	Buildup rates--materials

resources in the lower right oval as an input to MESSAGE. Several extensive LP runs of the MESSAGE program for the seven world regions lead to --within the defined context--optimal energy supply strategies. For the purposes of this presentation, the globally aggregated supply is of interest.

Figure 13 shows the evolution of the primary energy mix by 2030. It is to be taken with a grain of salt, but note the slightly reducing share of gas and the overall fairly constant share of oil together with synthetic fuels, e.g., methanol. Within this band, oil is increasingly

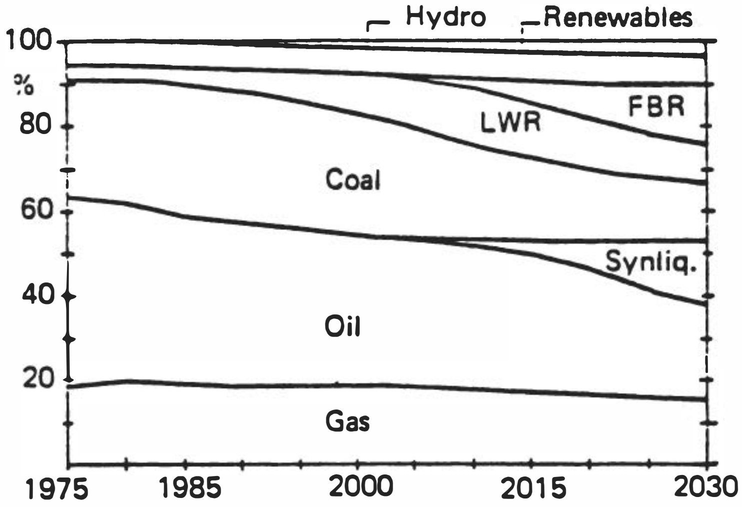


FIGURE 13 World: low demand, primary energy or equivalent.

replaced by synthetic liquids after 2000. One such source is autothermal coal liquefaction, assumed to increase the need for coal. Together, such and the traditional uses of coal lead to a rather uniform overall share of coal in the primary energy market, with the traditional share decreasing steadily. This decline is offset by a rise in nuclear energy for electricity generation. Among the various nuclear shares, that of the fast breeder increases quickly after the turn of the century. The rest of the primary energies remain fairly small until 2030, but let me repeat that solar and fusion could take on greater importance later. These results relate to the *Low* Scenario. In terms of primary energy market shares, the mix for the High Scenario does not differ significantly. But, of course, what we are after above all in this context is the *absolute* contributions of the various primary energies in the year 2030.

They are listed in Table 9. Indeed, oil production does not seem to decrease at all. It appears rather high, providing about 6.83 TWyr/yr in 2030 in the High Scenario. So does gas production, contributing 4 times the value of today. All nuclear energy production, of nonbreeders (nuclear 1) as well as breeders (nuclear 2), amounts to 8.1 TWyr/yr, that is about 23% of the total energy supply in the High Scenario, and yet the number is far from the theoretical 17-TW potential. Most remarkably, these primary energies are topped by a coal production of almost 12 TWyr/yr, or about 13 billion tons of coal equivalent per year. Solar, which is just about 0.5 TWyr/yr in 2030, is a more or less ad hoc input to MESSAGE since the program rejected solar contributions at the estimated cost levels. Solar may at best be 2 TWyr/yr perhaps, but surely not more. Hydropower, too, may figure higher in 2030 than indicated by, say, 50%. In relative terms, the contributions of both solar and hydro appear rather small; absolutely speaking they are enormous, and even more so are the absolute numbers for the other primary energies.

One may wish to react to these incredible quantities by reducing energy demand to values lower than in the Low Scenario. But, in doing so, one is brought to face the problems that were discussed under the heading of a 16-TW scenario. In particular, a clarification would be needed as to the regions and the manner and the extent in which the energy demand should be reduced.

The present scenario approach offers the advantage of confronting us directly with the huge orders of magnitude that are required. This is unlike a national approach, which may allow one to escape into imports if futures appear too dim. When treating the world as a whole, as is done here, one must explicitly specify where imports for certain world regions could originate. As far as hopes for oil are concerned, extraction must be assumed to materialize somewhere in the world. National difficulties can no more be dismissed or exported to the abstract level of the global market, given a worldwide perspective.

Indeed, questions of oil import were very important for our regional calculations. Thus Region VI, largely though not fully identical with OPEC, appears to play a dominant role still by 2030. It cannot be expected that this region will endeavor transferring its wealth of oil into inflationary capital, as would be the case if it simply complied with import requests as they are received. Rather, it is sensible to

TABLE 9 Two Supply Scenarios, Global Primary Energy: 1975-2030 (TW)

		High Scenario		Low Scenario	
Primary Source	1975	2000	2030	2000	2030
Oil	3.62	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.95	11.98	3.93	6.45
Nuclear 1	0.12	1.70	3.21	1.27	1.89
Nuclear 2	0	0.04	4.88	0.02	3.28
Hydro	0.50	0.83	1.46	0.83	1.46
Solar	0	0.10	0.49	0.09	0.30
Other	0.21	0.22	0.81	0.17	0.52
TOTAL	8.21	16.84	35.65	13.59	22.39

expect a limit on the region's oil production, here assumed to be 33 million barrels a day.

The block diagram in Figure 14 illustrates the oil export-import situation for all regions in 1975 and 2030, according to the High Scenario. One GWyr/yr, the unit given, corresponds to about 14,000 barrels a day. Region IV (South America) and Region V (South East Asia and Africa) also were exporters in 1975, supplying Region I (North America) and Region III

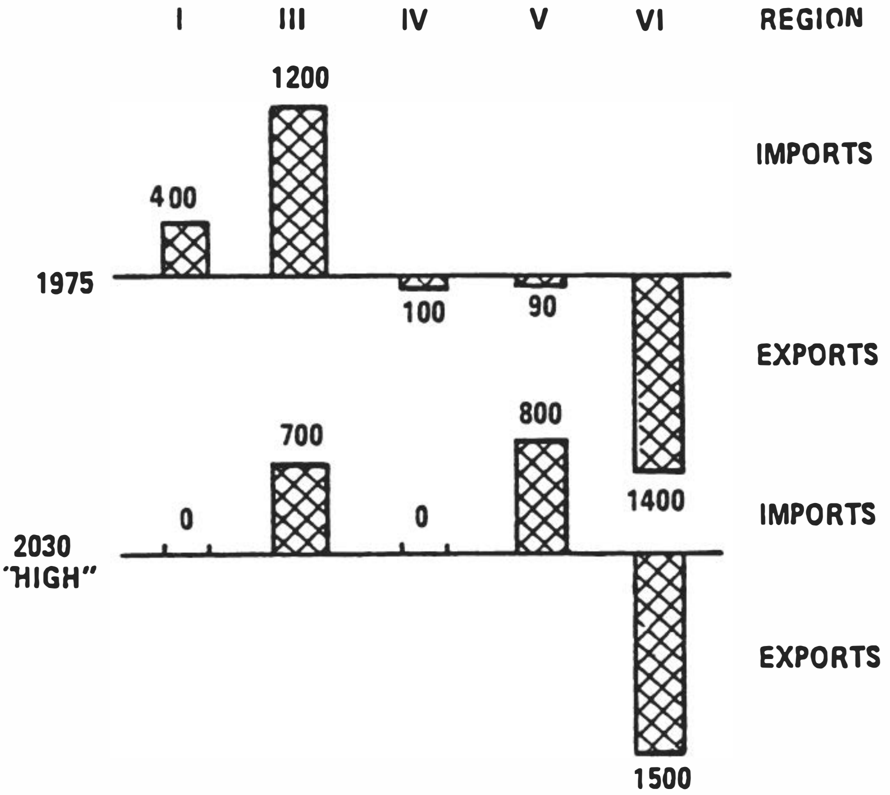


FIGURE 14 Oil trading regions, 1975 and 2030 (GWyr/yr).

(Western Europe, Japan, and Australia). In 2030, the High Scenario indicates for Region I oil self-supply and thus no need for import, in spite of the absolute increase in the region's energy demand; and for Region III, a reduction in imports, largely on account of autothermal coal liquefaction. The remainder should help alleviate the most severe energy needs of Region V. However, it is plain to see that Regions I and III will, on account of their purchasing power, still import more than is foreseen by the scenario, at the disadvantage of the developing Region V.

One understands from the above that the main factors determining resource allocation and trade flows are first of all production ceilings and the possibility of increases in the production rate. The resources themselves are not actually exhausted by 2030. Compare the cumulative oil consumption by 2030 in Table 10: it is 68% in terms of Price Categories I and II, but only 1% of highest-cost oil, which is oil shales and tar sands. For natural gas the ratios are 49% and 0%, and for coal, 61% and 0%. In other words, out of a world total of about 3,000 TWyr of resources only about 900 TWyr will have been used by 2030. This is, of course, the relatively cheap and clean resources, having less impact on the environment than others. With an annual requirement of about 40 TWyr, for example, the rest of about 2,000 TWyr would last for another 50 years. After what we know today and what we can now anticipate for the future, the main constraint of the coming five decades will be production ceilings, with resources constraints coming to bear in the following half century. By that time a transition to nuclear and solar will be inevitable.

This exercise in how supply schemes affect resource allocation demonstrates the usefulness of the scenario approach, by which anticipated

TABLE 10 Cumulative Uses of Fossil Fuels, 1975 to 2030, High Scenario

	Total Resource Available (TWyr)	Total Consumed	
		TWyr	%
Oil			
Conventional (Cat. I + II)	464	317	68
Unconventional (Cat. III)	373	4	1
Natural gas			
Conventional (Cat. I + II)	408	199	49
Unconventional	130	0	0
Coal			
Cat. I	560	341	61
Cat. II	1,019	0	0

events are put into a chronologically meaningful order. Still, one should remember that it is scenarios we are dealing with here, and not predictions.

COAL IN EUROPE

As was shown in Table 9, the highest absolute shares in 2030 in both scenarios are those of coal production. They are worth looking into in more detail, given the present selling difficulties in coal and one at best short-term trend toward coal use, other than burning, for power generation. But at IIASA, short-term and long-term are put into different boxes, which, in the context of coal use, means that one needs a long-term perspective to clarify matters. Although quantification is difficult, it is possible to derive to this end actual technological implications from the scenarios.

Calculations have been made for all regions, and in particular for Western Europe in Region III. It appears that Western Europe does *not* have enough indigenous coal to meet an earmarked requirement of 14,000 million tce in 2030. Thus it would have to drive coal mining to the extreme of, say, about 500 million tce, and import the rest. This, in principle, could come from the United States, but means that they would have to mine 2,000 million tce for their own needs plus 900 million tce for Europe!

In short, the insights gained from these calculations make coal a scarce resource after the turn of the century. It figures high in world trade and is likely to be processed by various new technologies, in order to substitute oil as a liquid secondary energy carrier.

Autothermal liquefaction, among the various coal conversion processes, is a process by which carbon atoms are transformed into hydrocarbons, such as methanol. A greater conversion efficiency than the present 25%-29% would be desirable but requires, e.g., exogenous addition of large amounts of hydrogen (see Figure 15). Such an advanced process would require only one-third of carbon needed in present autothermal processes, and the energy content of the resulting methanol would at equal parts be derived from hydrogen and carbon. This throws new light on the possible coupling of methanol production with nuclear or/and solar, serving to produce electrolytic hydrogen, for example. The overall constraining factor for such systems would be capital cost.

One cannot conclude a discussion on coal without touching on the CO_2 problem. The natural CO_2 content of the world's atmosphere compares to the release from burning about 500 TWyr of coal. With a fossil energy production of about 900 TWyr by 2030, suggested by the High Scenario, a doubling of the atmospheric CO_2 content has to be expected, and an impact on the climate lasting longer than for centuries. Climatologists agree that an uneven warming of the earth's atmosphere would result, with a minor variation of the average, but large changes (about 10°C) in polar areas and partial melting of the polar ice caps. At the present state of the art, there is no conception of what this will mean for actual climate patterns, nor how certain the development is to occur: experts

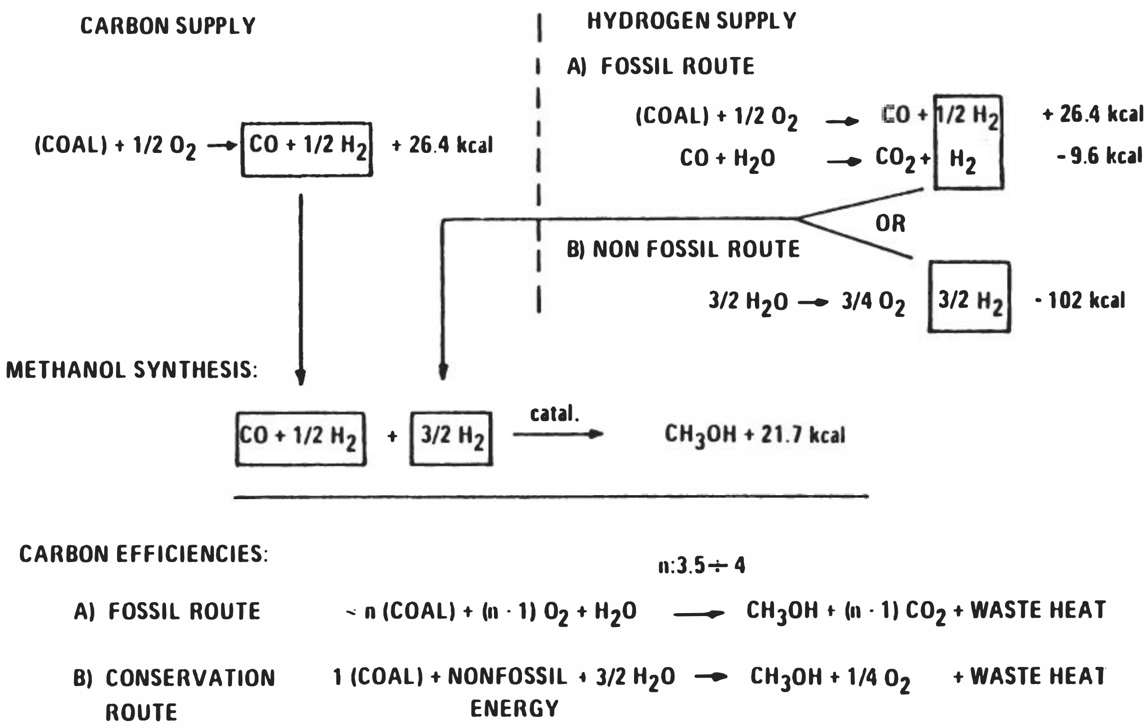


FIGURE 15 Methanol production routes.

can only appeal to decisionmakers for highly flexible global energy strategies.[8] The prudent use of the carbon atom as discussed above may serve as an example.

CONCLUDING REMARKS

The foregoing considerations were meant to bring light into the complex interplay of medium- and long-term facets of the energy problem. It appears that, if due regard is given to both types of aspects, it is well possible to point out ways for remedying the energy situation. The problems involved are only partially a matter of substance and can be largely overcome if political and economic measures are guided by prudence and willpower. The considerations discussed are founded on a 5-year study of IIASA's Energy Systems Program, with contributions from scientists from the USA and USSR and 15 other countries in East and West. The study is being documented in a 1,000-page volume on "Energy in a Finite World--A Global Systems Analysis," which is due to appear at the beginning of 1980.

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Risk and Democracy

DAVID L. BAZELON *

I would like to discuss with you the role of the courts in regulating risks generated by modern science and technology. I think our role is important, but often misunderstood. And the judicial perspective has significant consequences for engineers and other experts who contribute to public decisions about risks, such as licensing a nuclear power plant. We are among the many professions who have some rethinking to do. This is an unprecedented era of technological promise and peril. With mobility comes staggering auto accidents, plane crashes, traffic jams, and air pollution. And with the miracles of energy come the risks of coal mining accidents, nuclear reactor accidents, and even atomic terrorism.

Nobody is satisfied with existing regulation of risks. For each regulation, some claim it is too lax, while others claim it is too strict. We all hear the current call for "deregulation." But the Three Mile Island review commissions highlight the need for more effective regulation. The District of Columbia Circuit Court's caseload now involves challenges to federal administrative action relating to matters on the frontiers of technology. What level of exposure to known carcinogens is safe for industrial workers? Shall we ban the *Concorde* SST, Red Dye Number 2, or Saccharin? How can society manage radioactive wastes from nuclear reactors?

Let me tell you first that the courts cannot and do not answer such questions, even when posed as challenges to administrative actions. None of us knows enough to resolve issues on the frontiers of nuclear physics, toxicology, and other specialties informing the NRC, EPA, or FDA. Courts also lack the political mandate to make the critical value choices that ultimately are reserved for the public. These decisions must be made by elected representatives or public servants legally accountable to Congress and the people.

If the courts do not resolve technical disputes or value conflicts about technological changes, what *are* the courts' roles? Of course, there are individual nuances and shifting historical trends, but,

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in brief, the judicial responsibility is to assure that an agency's decisionmaking is thorough and within the bounds of reason. The agency's decisional record must disclose the evidence heard and policies considered. This will permit quality checks through effective peer review, legislative oversight, and public education. Only if the decisionmakers disclose assumptions, doubts, and points of controversy can experts in universities, government, and industry evaluate the technical bases of the administrative action. Only then can they scrutinize the agency's factual determinations, bring new data to light or challenge faulty assumptions.

Full disclosure of the reasons for a decision is also essential to legislative and public review. Congress and ultimately the people must make the critical value decisions about such questions as what level of radiation emissions can be accepted in the face of incomplete medical knowledge. So disclosure is essential to permit politically legitimate oversight of agencies' implicit value choices.

Courts stand outside both expert and political debate. They can help to ensure that a complete and orderly administrative record is discovered. Courts can guarantee that all relevant information was considered and addressed. Further, courts can accustom decisionmakers to the discipline of explaining their actions. Finally, courts can assure that all persons affected had an opportunity to participate in the decision.

I had always thought that scientists and engineers understood this judicial function. But in recent weeks I have been surprised to find that this is news to many. Perhaps the advantages gained through the judicial tasks are also not widely known, although they benefit everyone, including decisionmakers themselves. For if the decisionmaking process is open and candid, it can expose gaps, stimulate the search for better information, and reduce the risk that important information will be overlooked or ignored. An open process can inspire more confidence in those who are affected. Above all, an open process protects the credibility of decisionmakers from claims that they are covering up incompetence, ignorance, or damaging information.

What consequence does this all have for you, who serve as leaders or advisors in industry or government? Part of the disclosure requirement I have described falls on the agency decisionmakers that Congress made responsible for licensing nuclear power plants, approving waste disposal plants, and the like. Yet there is an equally important implication for your role. If your advice and plans are to provide adequate support when, for example, the NRC approves an operating license application, you too should disclose your assumptions and doubts, as well as the risk levels you estimate. Unless you explain the basis for your engineering judgments, the agency record to be reviewed by the court, and ultimately by your peers and the public, simply will not do the job.

Understandably, many believe that complete disclosure of risks is unwise. I have heard experts say that they would consider not disclosing risks that, in their view, are insignificant in order to avoid the danger of needlessly alarming the public. It may well be that popular fears about risks from atomic energy are irrational. Public fears about nuclear plant meltdowns may in fact be disproportionate to the seriousness of the threat, when discounted by its probability. A sense of the public's irrationality may have led the Information

Director of the French Atomic Energy Commission to observe that publication of precautions against risks "frequently has little other effect than to heighten [public] feelings of insecurity." He concluded that "there is nothing to be gained" through public debates on particular nuclear power controversies.

Many of you here may agree with this sentiment. But I believe that this view is unacceptable in our country. It is also unrealistic when it comes to nuclear power. Nondisclosure does not eliminate public fears. Indeed, it can exacerbate them. The fact is, the public is already afraid. Loss of public confidence is cited by the Kemeny Commission as one of the worst problems with the nuclear power industry and its regulators. Alvin Weinberg, a founding father of the Nuclear Age, I think rightly warns that nuclear power will be rejected politically not because people "will actually be hurt," but because "people will be scared out of their wits."

In other ages, and other cultures, the decisions of a wise man, or shaman, would resolve all doubts. But so long as we remain a democracy, the judgment of the people will prevail. And as Thomas Jefferson said, "if we think them not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them, but to inform their discretion." The genius of our system is its checks on centers of accumulated power. For this system to survive, experts must disclose their knowledge about promises and perils from technological advances. Special knowledge will undoubtedly, and rightly, give experts an important voice in political value choices. But to protect themselves, and the country, experts cannot, and should not, arrogate the decisions to themselves. Public confidence, I submit, is possible only if experts accept the difficult tasks of explaining what they know and do not know, and how they balance risks and benefits.

This message may be somewhat unfamiliar to engineers who have more experience with decisionmaking in the private sector. After all, your concerns traditionally have been to develop effective applications of scientific advances, as cheaply and as safely as possible. But today, the consequences of your judgments are of unprecedented magnitude and major public concern. Strictly private decisionmaking is no longer possible. Instead, value judgments and technical decisions deserve and require peer and public review.

Consider the selection of safety systems at a nuclear power plant. Making a plant "as safe as possible" may call for redundant safety systems and multiple fail-safe strategies to shut down the plant at the first sign of malfunction. Yet safety features of this kind are costly to install and even more expensive to employ. I am told that somebody decided that safety could be purchased for a lesser price at Three Mile Island. Perhaps the safety protections there were in fact adequate. Perhaps the crisis was generated "only" by the press. But the danger came far closer than anyone had predicted, and public fears were understandably aroused. The crisis mentality might have been avoided had the public been better informed about the trade-offs behind the safety design.

Implicit in that design are value judgments that may be hidden unless deliberately exposed to view. This is the case with cost-benefit analysis in general. It calls for controversial quantitative valuations of human life and health. It also too often presumes to compare the incomparables. How do we compare low-level, long-term radiation exposure with the benefits of nuclear power? Perhaps most troubling for our purposes, a cost-benefit calculus framed for private decision-making may significantly depart from the demands of public decision-making. A private firm is likely to consider only privately borne costs and call the rest "externalities." If a public decisionmaker relies solely on that private cost-benefit analysis, the entire range of costs and risks may not be revealed to all and sundry.

I do not know if it is true, but it is said that engineers may have disincentives to disclose design defects to their private employers. A defect identified means a new cost to the manufacturer. It may even cause the loss of a contracting bid. The drive to produce the cheapest design in the shortest possible time may eliminate needed safety checks. The DC-10 is perhaps the most notorious recent example of private competitive pressures shortchanging safety. Public pressures can also push hardware faster and farther than it is ready to go. Witness the current experience with the space shuttle, whose designers kept costs down by eliminating component testing but are now back at the drawing board. I do not mean to imply bad faith or incompetence. I just mean to point out that time and profit pressures may interfere with the caution crucial to public safety. The Kemeny Commission concluded that we have a mind-set problem. Infrequent accidents have produced optimism and confidence. But however infrequent, the magnitude of possible harm demands an independent and vigilent concern for safety. And only full disclosure can assure that a particular mind-set does not preclude external safety checks.

The need for disclosure may call for a change in a basic engineering approach. Countless innovations have been perfected privately by engineers through trial and error. But the blowups of experimental railroad boilers of yesteryear never posed the magnitude of public risk now present if a 747 plane crashes or a nuclear reactor malfunctions. With public consequences of this sort, an engineering assessment of general theoretical feasibility, if relied upon, may not be enough to instill public confidence. Moreover, an agency does not have the leeway to conclude that an unresolved issue can be worked out later, if the statute demands adequate evidence now.

Consider the problem of nuclear waste disposal. Many engineers believe that the solution is within reach--in theory. It has taken the industry a long time to take the problem seriously, even though it has been the public's major concern about nuclear power for years. This problem came to my attention in a case in our court, *Natural Resources Defense Council* v. *Nuclear Regulatory Commission*. I became concerned because the NRC had relied exclusively on vague assurances by agency personnel that nuclear waste disposal problems as yet unsolved would be solved. Our court reversed the agency's decision in order to permit a fuller inquiry. My objection was not founded on any disagreement with the conclusion that nuclear waste disposal can be managed. Nor did I criticize the NRC for failing to develop fool-proof solutions to the problem. What I found unacceptable was the almost cavalier treatment of the issue by the agency, and its apparent refusal to come to grips with the limits of its knowledge. The commission gave no serious response to criticisms brought to its attention. No technical oversight within the agency was demonstrated, and no peer review by the expert community at large was possible.

In this case, perhaps better known under the name of *Vermont Yankee,* the Supreme Court unanimously rejected our decision. That Court concluded that we had imposed on the agency procedures not required by law. Nevertheless, the Court returned the case for us to determine whether the record supported the substantive conclusions of the NRC. In so doing, the Court reaffirmed the fundamental requirement of full disclosure on the record. This includes thorough exploration of uncertainties, even if engineering practice would otherwise leave a problem alone until it demanded practical solution.

I was heartened by a thoughtful letter I recently received on this subject from a professor of nuclear engineering at a midwestern university. He wrote that the value system of the engineer includes acceptance of "an uncertain level of risk" because his decisions must be quick to be cost-effective. He said that compared to other risks associated with nuclear power, the waste disposal problem is "minute" to the engineer. Yet this professor acknowledged that others view the level of risk from a different set of values. For example, some seem to feel that any risk is too much. He concluded, and I quote,

> I believe that now the technical community is learning that their value system and that of the public [do] not coincide, and sometimes [do] not even seem to overlap. I also believe that it has been the courts that have mostly impressed this on them.

When public values are called into play by engineering decisions, disclosure of known risks and unresolved problems is the only course that will protect public decisionmaking.

I have been told about a final engineering trait that poses problems for public decisionmaking. That is the profession's general aversion to taking public stands on safety issues. This is not only a problem for engineers. A prominent professor of medicine recently criticized his profession for its silence throughout the Three Mile Island incident. No one in the medical profession corrected the media story that the radiation leaks were no worse than those from a single X-ray shot per person. Apparently, this view neglects the more serious cumulative effect of the leaks. I certainly do not know enough to judge the severity of the health risk. But erroneous palliatives will not diminish whatever risk there was. In fact, some are now charging that better medical precautions should have been mobilized to counteract whatever danger the radiation posed. In addition, the mental stress from uncertainty is perhaps the most serious health effect from the Three Mile Island incident, according to the Kemeny Commission. The medical profession's failure to take a leadership role must in part be blamed on both counts.

Engineers may be particularly reluctant to speak out about indeterminate risks because they would rather be silent than misstate the risks. But engineers must realize that decisions will be improved, and public understanding enhanced, if experts reveal exactly what they *do* know. Industry disincentives may, however, contribute to engineers' reluctance to "go public." I do not need to remind this group of the Bay Area Rapid Transit engineers who were fired after their safety concerns about the system's automatic train control became public.

But I do not believe that fear of reprisals causes the engineering profession's reticence. A more dominant problem is that loyalties to employers and other concerns can cause us to ignore broader public needs. The engineering profession's duty to the public is acknowledged in its ethical canons. But I do not believe that duty has been dealt with adequately. The Code of Engineering Ethics, approved by the Engineering Council for Professional Development in 1974, calls upon engineers to advance the profession by "serving with fidelity the public, their employers, and clients." However admirable a sentiment, this principle provides no structure to direct the engineer who notes a divergence between public and private interests. A number of engineering societies have adopted what looks to be a more instructive guidepost, as part of a statement on "employment guidelines." This statement directs the professional employee to withhold plans that do not meet accepted professional standards and to present clearly the consequences to be expected if that professional judgment is not followed. Adm. Hyman Rickover, the father of the nuclear submarine, put a similar view quite succinctly. He very recently urged all in the nuclear field to "face the facts and brutally make needed changes, despite significant costs and schedule delays."

None of this is easy. The costs and delays from brutal honesty and reevaluation will make your life harder, as they make life more difficult for a great many other professionals. Disclosure may scare people. It may scare the public to hear, as the Kemeny Commission has reported, that engineers have not designed sufficient safety checks for many foreseeable human errors in operating nuclear power plants. But nondisclosure violates a partnership with the public that engineers have entered by ushering in a new day in technological capabilities. If technological progress is to coexist with democracy, I believe that its creators must rethink their methods and their communication with the public. At the same time, judges, regulators, and other participants in public decisionmaking must reexamine our roles against the backdrop of the ever-evolving technological landscape. However difficult, we must criticize ourselves to avoid "hardening of the arteries" in our professional conduct and moral sensibilities. We need self-regulation, not just governmental regulation, to harness newfound tools for human ends.

Nuclear Power Reliability and Safety in Comparison to Other Major Technological Systems: Space Program Experience*

GEORGE M. LOW†

My purpose this morning is to provide an overview of reliability and safety in the space program, as an introduction to subsequent discussions on reliability and safety in the nuclear power industry.

To begin, let me review my credentials to speak on this subject. I am an aeronautical engineer with 27 years experience in NASA and its predecessor agency, NACA. My entire career--until quite recently when I became associated with RPI--has been in the fields of aeronautics and space, where reliability and safety are always of paramount importance.

I know about complex systems and how they are designed, built, and operated. I had hands-on experience in every facet of the business when I became Apollo Spacecraft Project Manager after the Apollo fire. But I do not know about nuclear systems, except in a most superficial way.

I will describe how we handled safety and mission success in spaceflight, especially in Apollo. But I will not conclude that what we did in Apollo also applies to nuclear power plant safety. That can only be done by those who understand nuclear systems and their operation much better than I do.

A moment ago I mentioned the Apollo fire. In a way that fire was our own "Three Mile Island," only the immediate consequence was much worse in that three men died. As a result, however, we had a much better Apollo: There are those who even believe that without the fire we could not (or would not) have done everything that was necessary to make Apollo an eventual success. Much of what I will have to say here this morning reflects the lessons learned from the Apollo fire. I believe that Three Mile Island can have a similar beneficial effect on the nuclear energy program; and I hope that Three Mile Island will be a catalyst to strengthen our nuclear industry, and not to destroy it.

I prepared the substance of this paper in May 1979, long before the report of the President's Commission on the accident at Three Mile Island (Kemeny report) was issued.

Yesterday that report did become available, and I studied it in some detail. I was impressed by the fact that many--perhaps most--of the

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*Based on testimony before the Committee on Science and Technology, U.S. House of Representatives, May 24, 1979.

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commission's findings relate directly to subjects I will cover in my remarks.

As a result I *now* believe that many of the lessons learned in Apollo apply substantively to the safe operation of nuclear power plants.

SIMILARITIES AND DIFFERENCES

There are many similarities between Apollo and a nuclear system, but there are also many differences. Let me characterize some of both.

Both Apollo and a nuclear power plant are very complex high-technology systems. Both involve machinery, substances, and environments that are inherently dangerous to life. Both grew up with safety being of paramount concern, with the full realization that when the chips are down, safety must come first. Both involve constant interaction and interrelation between man and machine.

It is now quite clear that the Three Mile Island accident involved many complex and interrelated factors: the design of the system and its instrumentation, the reliability of various components, and the qualification of the operators. More often than not, a combination of events--rather than a single factor--is also responsible whenever an accident occurs in flight.

Apollo safety had many dimensions: our greatest effort went into assuring the safety of the "operators"--the astronauts and the ground crews--for they experienced the greatest exposure; of equal concern, but much more limited in scope, was the safety of the population at large, for the exposure of the public was limited to the launch and reentry phases of flight. By contrast, in nuclear systems, the safety of the public is *the* safety problem of highest concern.

In Apollo, also, we devoted as much emphasis to mission success as we did to safety, because the very existence of the program depended on achieving the objective of reaching the Moon. Yet "mission success" in the nuclear business is taken for granted and becomes an economic factor rather than a safety factor.

In Apollo we designed, built, and operated a single system, and that system was under the control of a single set of vendors, suppliers, contractors, and government people. In the nuclear power business there are several reactor suppliers and many different designers, suppliers, and operators of the total system. I believe that this difference is especially important when it comes to the design and operation of the complete system--the plumbing, the piping, the valving, and the electrical controls--and the components used in that total system.

In Apollo there was essentially one customer, while in the nuclear power industry there are many.

Finally, whereas NASA is a single action-oriented agency, with clear lines of authority, and with individual responsibility assigned at each level of the organization, the same is not true in nuclear energy, where NASA is replaced by a combination of the NRC and the utilities.

Because the differences I have just described are significant, some of the elements that were essential in the space program may not bear a direct relationship to nuclear safety. Nevertheless, it may be useful to list how we achieved safety in space--primarily in Apollo. To do this, I will concentrate on two aspects of the space program: design and test; and operations.

DESIGN AND TEST

Apollo was designed for a specific mission: to land men on the Moon and return them safely to Earth. The design stretched the state of the art, not because we wanted to do that, but because we had to in order to accomplish the goal. We used large quantities of propellants, nearly 3,000 tons of oxygen, hydrogen, and kerosene, and a few more exotic ones; new materials were stretched beyond normal limits and designed for extreme light weight; computers and electronic systems were used in novel applications leading the state of the art; automated systems and sequences were carefully balanced with human operations.

The underlying design philosophy was to use redundancy wherever possible, and to provide the simplest possible interconnections among various systems. Together these made for a very forgiving design: many things could go wrong (and often did) without endangering the mission or the safety of the crew. We recognized that components would fail--statistically there were too many of them for this not to happen--and then designed the system so that a component failure could be tolerated.

I should make an important point here: the operators of the system--in our case the astronauts and the flight controllers--were involved in the design from the very beginning. They asked some of the most important design questions and helped formulate sound design solutions. They placed special emphasis on the design of the instrumentation--the measurements--in an effort to provide unambiguous signals for subsequent operations. In that way we were assured that our systems would not fool or confuse the operators at a critical time.

We established design standards that all of our systems had to meet and developed rigid procedures to assure that they were met. We allocated reliability budgets. We analyzed the design for possible failure modes and effects, sneak circuits (latent electrical paths that can cause unwanted functions to occur), and single-point failures. We placed all changes under the most rigid of controls. Emphasis was on formality and discipline at every step along the way.

Manufacturing and assembly were also carried out to exacting standards. Individual parts were bought only if their pedigree was known. We specified how to solder, how to crimp wires, and controlled the process of plumbing. Every part of the system was known, its manufacture specified, and the people who performed intricate functions were specially tested and certified.

The proof of the system came from the test program. Everything was tested: piece parts, components, subassemblies, and complete systems. Parts identical to those to be used in flight were subjected to prescribed overstress conditions. In addition, each flight component was acceptance tested to at least the worst case conditions of flight. Environmental testing was performed under simulated conditions of vibration, acoustics, shock, temperature, corrosive contaminants, and many more.

We made enormous investments in test facilities so that we could indeed simulate the environments of space, and made sure that all components were qualified for flight. We made a deliberate decision to have test facilities owned by the government, and to have government people involved in the test program. This had several advantages: the vendors and contractors did not have to invest in duplicate test facilities; there was uniformity in test procedures and specifications; and we had a direct overview of the reliability of critical components and systems.

Of course, without standardization and configuration control, the test program would have been meaningless. Components that were flown were identical to those that had been tested. There were no substitutes.

Formality, discipline, and rigor were the key words in the test program. Test specifications were prescribed in advance, test results were audited and certified, all anomalies were reported, and all failures had to be understood and corrective action taken.

We established an intricate network to report problems and failures to all involved in the geographically dispersed Apollo system. No failure was too small to report. I remember receiving midnight calls about a test failure at some distant contractor's plant, if that failure might in some way be related to the hardware to be flown on the next flight.

In every phase of design, manufacture, test, and operations, we held formal reviews, audits, and inspections. There were dozens of them, and they became a way of life: Preliminary Design Reviews, Critical Design Reviews, Design Certification Reviews, Customer Acceptance Readiness Reviews, Flight Readiness Reviews, Launch Readiness Reviews, and Safety Assessment Reviews. In these reviews all failures were reported, and actions taken to resolve them were discussed. All levels of people from contractors and government participated. Formal paperwork was submitted, audited, and approved. Responsibilities and authorities for saying "yes" or "no" were clearly understood.

It is important to recognize that these reviews were prescribed and carried out by the people responsible for getting to the Moon. All were highly motivated engineers who wanted to get on with the job. But we organized ourselves in a way to have the right kind of internal checks and balances to assure safety and mission success. With a single exception, we did not have outsiders looking over our shoulders, prescribing what we should do, telling us how to do it. (This does not mean that we didn't call on outsiders for advice--we often did.) At each step along the way, we had to balance risk and gain, we had to make the decisions that would allow us to meet our objectives on schedule and within cost, and at the same time be safe and successful.

The single exception I just alluded to was the Aerospace Safety Advisory Panel, a group chartered by the Congress to take an outside look at how we were doing. The panel held its own reviews, assured itself that NASA was doing its job, and reported directly to the NASA Administrator as well as the Congress.

But I want to emphasize again that, as Apollo Spacecraft Program Manager, I felt fully responsible for the engineering of the spacecraft *and* for its safety. Although I endorse safety audits and inspections, these can only work as adjuncts to an already safety-conscious organization. Safety cannot be forced from the outside--it must come from within.

OPERATIONS

Although safety must be designed into a system, the ultimate responsibility for safety is in the hands of the operators. This is why, in manned spaceflight, we insisted upon operator input in the design, and this is also why we placed major emphasis on the selection, qualifications, training, and motivation of the operators.

We began with highly motivated people--astronauts, flight controllers, and the launch team. When they came to us, they had the basic knowledge to understand the fundamentals--the physics if you will--of the systems they were going to operate. Almost without exception, all were engineers; without exception, all were highly competent.

How we selected the astronauts is well known. The ground control teams were selected from among our best engineers and were motivated by the fact that many flight controllers had moved on to top executive positions in NASA. Theirs was not a dead-end job; it was the beginning of an exciting career.

Operators spent years learning about the specific systems they were to control, participated in tests and simulations, and knew the workings of their systems oftentimes better than even the designer. They developed the detailed operating procedures and wrote the manuals for normal and emergency conditions.

All procedures were worked out in detail in advance, and were controlled with the same discipline and formality as was the hardware. Crew procedures, mission rules, and the like were under tight configuration control and could only be changed through formal mechanisms.

The single most important training device was the simulator. Simulators were used to help develop procedures and to train and evaluate all operators--flight and ground crews alike. Simulators have an important advantage over actual hardware: they can easily be operated outside the normal envelope. All sorts of off-nominal conditions can be tested.

Simulation is a game of "what if." What if a thruster sticks open? What if a battery fails to take a charge? We put some or our best people to work as simulator operators to try to stump the astronauts and the controllers. Only a fraction of the time was spent simulating a normal mission. Then failure after failure and emergency after emergency were thrown at the operators. They concentrated not on the potentially major disasters, but on the small problems that could lead to such disasters. They learned that, more often than not, it would be a strange combination of events that could lead to a sudden catastrophe. By the time they were done, they had faced almost every conceivable problem and had learned how to handle it.

Perhaps the best example of the value of simulation was Apollo 13. A sudden explosion wrecked multiple spacecraft systems when the flight was 200,000 miles from Earth. The flight controllers took over, and pieced together a rescue effort that allowed the crew to return to Earth safely. When it was all over, it was clear that the controllers' detailed understanding of the systems, and their prior simulation of every element of the return (though never exactly the sequence of events which occurred), prevented what could easily have been a disaster.

Organization was especially important for the operational units. Lines of command and control were clearly established well in advance. Every individual knew his responsibilities and his authority. And these were not changed during an emergency. I might mention that the key individual in all manned flights was the flight director, generally a young man in his early thirties, who had complete authority to act under all conditions. Nobody second-guessed him.

The flight director was also a good leader of men. He developed an espirit de corps in his team that I have seldom seen equaled. He made what could have been a dull job (imagine sitting behind a console at 4:00 a.m. during the 84-day skylab mission) an exciting assignment. It can be done with good people, with proper motivation, and with a promising career as a reward.

A key ingredient in allowing a tightly-knit organization to function was a free and open flow of information. While *command and control* followed clearly established lines, *information* was available to everybody, not only within NASA, but to the general public as well. This, I believe, was also an important factor in maintaining credibility when the chips were down.

I should mention that we had planned, in advance, how best to inform the public in the event of a failure or an accident. Quick and complete reporting of the known facts was the key; speculation beyond the facts was avoided. The flow of information through designated spokesmen was continuous, but those involved in the operation--those who had to solve the problem--were called upon to brief the public generally only after the end of their shift.

CONCLUDING REMARKS

Since preparing this paper I have read the report of the President's Commission on the accident at Three Mile Island.

I was struck by the many areas of overlap between my remarks and the commission's report. Lessons we had learned in Apollo were obviously unknown to the people involved in the design, operation, and management of the Three Mile Island plant. This is not surprising, since the space program and the nuclear industry grew up independently of each other.

Yet, there are lessons from Apollo (and other space programs) that obviously could be of considerable benefit to the nuclear power industry. These lessons cover a wide variety of fields and disciplines: systems design, control room design, instrumentation, information display, testing, failure reporting, selection and training, simulations, and many more. (I would suggest that the space program also has much to learn from the nuclear industry--after all, most of what has been done to bring nuclear energy to its currrent state of development has been right, and not wrong.)

I believe it is essential for our economy (and hence for our very survival) that the nuclear power industry get back on its feet, and quickly. Not only must we continue to operate the existing power plants, but we must also complete those under construction and build more.

To do this with acceptable risks, the lessons of Apollo (and those of Three Mile Island, of course) should be considered, and used where they apply. In my view, the best way to do this is to involve people who are experienced in design, operation, and management of space programs in responsible line positions in the nuclear industry.

There is no other way to transfer knowledge.

Nuclear Power Reliability and Safety in Comparison to Other Major Technological Systems: Commercial Aircraft Experience

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WILLIS M. HAWKINS*

There was a certain amount of hazard that what George Low and I would talk about would be almost identical. But fortunately, George and I seem to have approached the subject of system safety each in a different way.

First, when we try to compare what has been done in the aviation industry, particularly in the air transport part of that industry, with what has developed in the nuclear industry, there are many parallels. But I don't propose to present myself as an expert in what the nuclear industry has, or should have, done. I plan to talk only about the air transport industry itself, something I should know about, and hope that you can draw your own conclusions as to what of this experience might be applicable elsewhere. If I can see a parallel, I will, of course, suggest its further consideration.

One of the first things that I would like to say--and we talked about this earlier this morning--is that our industry was permitted to develop in an entirely different environment than the nuclear industry. When we first began to fly and first began to try air transports, the mood of the country and the mood of the people was that a risk was worth taking if one could see some kind of benefit in the future. The total definition of the benefits now, for all of the things that we are doing technologically, is difficult to come by, and some of the "benefits" are almost as controversial as the technology itself. And so, the suggestion that the engineers lay their hearts in front of the public concerning risk also suggests that the engineers ought to have the privilege of telling people what the benefits are as well.

That is, many times, out of our control, but nevertheless it is a responsibility that the technical community will have to pick up if it is necessary to publicly discuss all risks. In any case, with the environment today, it is just possible that we would never have flown at all, and I am grateful, and everyone should be grateful, that the environment then was one of encouragement.

There are many things that are different in an airplane compared to a nuclear power plant, but while being different, they still address similar problems. An airplane, once it is airborne, can't stop. So an airplane emergency has to be handled in a different way than an emergency in something that is on the ground. An airplane has to fail "safe," but in doing so it has to remain operational. We call this "fail operational."

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In considering nuclear systems, one finds a mixture of both fail-safe and fail-operational--some elements can be shut down and some can't. In other words, part of a reactor has to keep flying, too. And so, the fail-safe and the fail-operational concepts, which involve different technical approaches, are required in both industries.

I propose today to summarize some history and tell you about the continually advancing state of the art in safety for air transport. I am going to do this with pieces of the airplane. I will discuss the structure of an airplane, the power that keeps it aloft, all of the systems that make it work, and then, lastly, I will talk about our experiences in the user-certification-design process.

Let's start first with the structure. I am pleased when I look back at the history of aviation that the technologists--and in those days, they were mechanics--had an early appreciation for the safety of flight, mostly because they were flying their own airplanes. If you will look at some of the old biplanes that are still flying today, you will find that they all carried what were called multiple flying wires. These are the wires that carry the lift load of the wings, but there were two of them, either one of which would sustain the load. If one of them parted, one could get back on the ground and fix it. This is a "multiple path" structure, in today's lingo. It failed safe and operational.

When we examine present structures, they are complex and the multipath principle isn't obvious. Double structure exists throughout all of our modern airplanes, either actually or through excessive design margins. In some cases double layers of metal are used to carry the loads. Incidentally, I don't know how well a fuselage would fulfill a boiler code, but our bookshelf on pressurized structure is about 42 inches long, too. A pressure vessel that contains the passengers, of course, is a boiler-code type of structure. If you pursue this in detail, you will find that there are multiple ways in which we go about ensuring that this pressure is maintained or a failure will not be catastrophic.

You may not know it when you look at the scenery, but you are looking through three layers of transparent material; one of two will carry the pressure of the cabin. Each window is mounted in a separate frame so that a frame failure won't take out both of them. And there is a third one inside, so that casual kids or people with diamond rings won't scratch the glass with potential subsequent failure. This kind of structural philosophy is applied throughout the entire design of the airplane, trying to be sure that future failures are only incidents.

So much for the structure. Let's now consider the power that drives the airplane. When we started out, we had only one power plant, and it was obvious reasonably soon that we weren't going to get that power plant to operate reliably enough to make our airplanes into practical, safe flight vehicles. It wasn't too long before we introduced two power plants on an airplane designed to transport people. Actually, in those days, reliability was still pretty grim, and so aircraft with three engines soon showed up. That turned out to be fearfully inconvenient, because the propeller on the south end of the airplane or on the north end of a very large fuselage wasn't very good. And so, quite soon most transports wound up with four engines.

Then the jet came into being, and these turbine engines would run between 4 and 10 times the hours between failures that a good reciprocating engine would run. This suggested that we could work our way backwards, and we did. The three engines came back into the picture, because it was much more convenient to put three on an airplane with a jet engine and in many cases we went back to two. There is a lesson that isn't obvious in this history. One shouldn't make laws too soon. I am old enough to know that back in the early days of the four-engined airplane there were some serious discussions about a law that all transport aircraft should have four engines. I would like to suggest that such a law would have been critically limiting to the advances that our technology provided for the public. In dealing with public safety we must be careful about how soon we make laws lest we stifle benefits.

Let's now talk about the systems in aircraft. There has been a very quiet revolution going on in this technology. The insides of an airplane are mighty complicated, and many of the things that have been done in our industry are directly applicable to almost any interactive mechanism, including nuclear systems. I share George Low's suggestion that somehow the two of us--the two industry groups--should work together to see what we can learn from one another. The concepts of total flight control must certainly be parallel in many respects to total reactor control. I have talked about failing safe and operational, and that is what one has to do in nuclear systems. There are lots of subtleties in these systems that may not be apparent.

We have multiple sources of powering systems as well as the airplane itself. We have multiple sources of distributing that power to where it is needed. We have multiple mechanisms to move surfaces on the airplanes (and there are multiple control surfaces), so that element failures can occur and we can still operate safely. There are some booby traps in these systems, too. If an airplane is operating beautifully on only half of the equipment that is aboard, the pilot had better know it. Because with a hidden failure, the next take off may be the equivalent of a single-engine airplane instead of a multi-engine airplane. Thus, the signal system that tells about a failure when the airplane doesn't act like there is a failure is just as essential as the the prime system.

Of course, when failures occur in an airplane, enroute, there has to be assurance that a further failure can also be handled. This may impose detailed knowledge of obscure backups, and constant training may still not assure one of complete crew familiarity. Thus the industry has developed a very interesting system that could be used elsewhere. We started out calling it the "EE and panic panel." The EE and panic panel gave a warning signal in front of the pilot so that he could not miss it. In addition to warning him, it told him where to look. Elsewhere in the cockpit, or at the engineer's panel, was a much more complete systems diagram with the failure element noted. There are other systems, both installed and in development, in which the flight engineer can call up from the on-board library a diagram of the system as it should be. Thus the engineer can see the difference in a "right" and a "wrong" system and can receive instructions on what he should do about it. The instructions, of course, can be automatic, with indication of the failure or corrective action specifically called up.

The complexities of such systems bring in the computer, as George Low has pointed out in the control for space missions. The computer helps not only in emergency situations, but also in many normal operating modes. The same computer function is the basis for the simulators that are universally used today. In the aircraft industry, we have come to use an augmented simulator. We call it "the Iron Bird." It is more than a simulator. It has in it everything that is in an airplane. All of the control systems are there; all of the control pistons are there; all of the power sources are there; all of the electrical lines; all of the hydraulic lines. And the essential support structures are all there. It is an airplane on the ground; it is hooked up to a cockpit that looks just like the cockpit of the airplane; and it, too, works just like the cockpit of the airplane. Everybody involved in the development process can get at that simulator. It is in use day in and day out. One can load it in such a way that improbable accidents can overload the system. Purposely, the system is "flown" for years to find failures before they happen in flight. I think the proper use of the Iron Bird is one of the real contributions that has been made to the safety of flight.

Finally, I believe it is pertinent to emphasize helpful elements of the user-certifier-creator relationship. The test programs I have talked about--the loading of test wings, as if operating, until they break; trying to explore the geriatrics of an airplane; the Iron Bird exercises--are all shared by the creator, certifier, and user. The airline pilots and the certifiers are in the cockpits telling the creator where he has done it wrong. The airplane maintenance people are all over the Iron Bird and the mock-ups, looking at whether or not they can get at everything for inspection and repair. User and certifier are at the production line--their own inspectors are at the flight line. Thus we have the maintenance and the inspection experts, the user, and the certifier all involved in the complete development of the airplane. It starts the day the designer lays down the general arrangement drawing and a license is requested.

The developer-user-certifier all participate in essential system evaluation. They look together at the instrumentation on the airplane. It, too, has to have the same kind of backup systems, and together some interesting rules have been worked out, some as the result of accidents that have bit us and taught us things. For instance, we accept no signal by implication on an airplane. If there is an actuator somewhere that pushes a push rod that turns a belt crank that pushes another push rod and locks a lock, one doesn't put the switch that says that lock is locked at the motor that drives all this mechanism. The signal switch is put at the lock where the hook goes around a pinion it is supposed to be locked to. When the switch says it is locked, it is locked, no matter what has happened to the rest of the mechanism.

Accepting signals of events by implication is a dangerous booby trap. It is just like the booby trap of multiple structures, where one can't inspect both structures, and an airplane may fly for years and be lost with just one more failure. The design review process that goes on amongst the creator, the certifier, and the user is a definitive, scheduled operation. It starts at the beginning, and the creator has to respond to suggestions of potential failure as time goes on. And, finally, the development system has to respond to what has happened in flight, even after the airplane has been certificated.

There is one characteristic about the certifier in the aircraft industry that I would like to emphasize, because I think it is unique and valuable. The certifier in the case of an aircraft, the Federal Aviation Administration (FAA), has a responsibility, by charter, to promote civilian flight. The certifier wants to see that airplanes fly. It is the part of the FAA responsibility to keep the airplanes flying safely. The FAA-aircraft developer-user is not an adversary relationship. This has developed some useful functional management mechanisms, where the certifier reaches into the company and picks an engineer, trains him properly, and endows him with a second hat; this engineer is not only working for the company to design the airplane, but he is also working for the certifier. He can blow the whistle. He is authorized to blow the whistle when he sees something going on that he thinks is detrimental from a safety standpoint. He is called upon from time to time to do design reviews on what other engineers are doing.

The designer has something that no outside certifier could really get. He has knowledge of the airplane and its systems. This seems to me to be of overwhelming importance. In addition to engineers, we have certified inspectors, certified manufacutirng people, certified manufacturing process people, and certified testing specialists. All of these represent the FAA, and they are an important part of the team that certifies the airplane. They are authorized--in fact, directed--to run design reviews. They are, of course, monitored and constantly covered by fulltime FAA personnel who come directly from the certifying agency. This is a good system. It is a healthy system. It puts more real knowledge into the certifier's actions and decisions than he could ever get any other way.

The licensing of the people who operate the airplanes is done almost the same way. There are certified pilots who can certify other pilots: the people who are flying every day, instead of every other week. That too is important and is the proper way to fulfill an essential function. Permit me again to emphasize the promotion aspect of the certifying agency. This is good and is certainly not criminal, as has been suggested by some FAA critics.

We have had some other history in our business that the nuclear industry is experiencing now--they are right in the middle of how to deal with advancing requirements for certification with operating systems developed under different rules.

When you look at some of the old airplanes that are certified and flying today, one has to ask, "How can that airplane possibly be certified with what we know today?" You can still buy a ticket on a DC-3. It is a fine, fine airplane. And the reason that it is still flying and still certified is that it has proven that whatever the new rules, however it was certified and whatever is in it compared to the modern airplane, it works, it works reliably, and it has proven that it can maintain its standards in the face of the advanced world.

As we look at the earlier things that have been done, let us be sure that we don't turn them all off without solid reasons. The older systems are providing the benefits that they were designed for and these benefits should not be lost without factually based solid reasoning.

What have I said? I hope I have said that aircraft may have been tougher than nuclear power to develop in the early days, but we had a different kind of an environment. We were privileged to take risks without justifying each and every one we took. As a matter of fact, risk wasn't a dirty word in those days. Maybe what we have learned in the process can be of some help.

I hope I have emphasized enough the close relationship among the certifier, the user, and the creator all through the concept of the design. I have tried to emphasize that the development and the testing were carried on with the user, the certifier, and the designer all working together, and the system was simulated up to and including the last nuts and bolts before the airplane was first flown.

We need to solve the energy problem that is facing us, just like I think we need to keep flying. I hope that nuclear power will get the long-delayed rational support it needs, and I hope that we won't be shamed into progress by some other more progressive nation. If we pool all of our knowledge, I am convinced that we can have all of the nuclear power we need and safely. I am available to help, if I can, and I would love to listen to what the nuclear industry has already done because it might help the airplanes get better.

The Electric Industry's Response to Current Events

JOHN D. SELBY*

I am pleased to be here today at the invitation of the Annual Meeting Committee and look forward to participating in what should surely be a lively discussion on the outlook for nuclear power in the wake of the March 28 incident at Three Mile Island.

I have been asked specifically to outline the industry's response to Three Mile Island and the reaction of the utilities that are engaged in nuclear power production, or are planning to engage in it. At this time, with the Kemeny Commission report hitting the news, intense interest in the subject is not only expected but most welcome.

In my remarks today, I will list only the highlights of a whole series of actions taken by the electric and nuclear industries beginning immediately following Three Mile Island. Keep in mind that the complete text of the Kemeny report, and the detailed analysis that might be entailed by it, are not the focus of these remarks today.

Rather, we are concerned with bringing you up to date on industry activity from March 28 onward. My remarks will cover briefly a number of continuing efforts, all of which would bear more lengthy discussion, if the time allowed.

Further, I should like to make it clear that the reaction of the industry was twofold:

> One, the cause of the accident and the events surrounding it should be openly examined throughout the industry on the basis of factual information and without bias.
>
> Two, lessons to be learned as a result of the incident should be promptly identified and given the widest possible publication.

It was increasingly apparent from the early hours of the Three Mile Island excursion that we in commercial nuclear power were being confronted with perhaps the most unusual event of its kind in the history of our industry. And we faced the reality that in related terms--in terms of public interest and concern--the shock of this accident will be felt for a long, long time.

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I believe the sense of urgency that gripped us increasingly in the days surrounding Three Mile Island served to unify the entire industry in its determination to spare neither the manpower nor the expense that would be necessary to solve whatever technical and operational problems had been presented by the accident.

It was immediately obvious that the nuclear option was on trial, probably for its life. Those of us who recognize the option as a major solution to world energy problems, to say nothing of domestic energy problems, were aware that not to react in a positive and responsible manner to that event would only further perplex a great many Americans who already had their confidence in this technology severely shaken.

Now I will take the four or five major subsequent developments within the industry in the days since Three Mile Island roughly in sequence, although, in fact, almost all of our coordinated activities occurred more or less simultaneously, once we had formed the Oversight Committee.

This committee was formed in April on the initiative of the Edison Electric Institute. Its full name is the Three Mile Island Ad Hoc Nuclear Oversight Committee. It consists of eight senior utility executives and provides direction to and coordination of the utility industry's response to Three Mile Island. Its chairman is Mr. Floyd Lewis, chairman and chief executive officer of Middle South Utilities, inc.

The Oversight Committee receives input from all sectors of the nuclear industry, including utilities, suppliers, and trade associations.

To this it adds the input of electric utilities in the nuclear field. Esentially every utility with nuclear power programs has initiated an internal review effort for self-evaluation of its activities. Internal changes are being made to assure that technical and managerial structures are arranged to provide the proper balance between safety, reliability, and costs. These individual internal utility efforts are expected to continue, in addition to the industrywide activities, with the knowledge gained individually shared with all other interests under the Oversight Committee's leadership.

Also, the Oversight Committee asked and authorized the Electric Power Research Institute to set up a Nuclear Safety Analysis Center to determine independently not only what happened at Three Mile Island, but why. The Nuclear Safety Analysis Center (commonly referred to as N-SAC) is to make recommendations for corrective action and is to act as the coordinator for the industry with regard to the technical responses. It also will help guide the implementation of programs rising out of the lessons learned in its Three Mile Island investigation. Mr. Edwin L. Zebroski, of the Electric Power Research Institute, is director of N-SAC.

A third key activity is under way. This grew out of the early realization that Three Mile Island raised questions as to whether or not the industry programs for selection, training, and evaluation of plant operators and nuclear operations were adequate. So, simultaneously with the Oversight Committee and N-SAC, the Policy Committee on Follow-up to the Three Mile Island Accident was formed, under the aegis of the Atomic Industrial Forum (AIF). As you perhaps know, the forum is an association of public and private organizations devoted to the utilization of the atom for peaceful purposes, with an emphasis on the word "peaceful." Mr. Byron Lee, of Commonwealth Edison Company, Chicago, is its chairman.

The Policy-Follow-up Committee early reconized the operation questions raised by Three Mile Island and recommended that an Institute of Nuclear Power Operations be established by the electric utility industry to provide a long-term solution to the problems of plant operations. The Institute of Nuclear Power Operations, commonly called INPO, is guided by a steering committee appointed by the Three Mile Island Oversight Committee. This steering committee is chaired jointly by W. S. Lee, of Duke Power Company, and A. J. Pfister, of Salt River Project, to guide the development of INPO.

In addition, the AIF Policy Committee further addressed such issues as emergency response planning, postaccident recovery, control room design considerations, unresolved generic safety issues, and related matters.

Other industry efforts are under way concerning the matter of insurance, a result of the financial consequences of Three Mile Island to the owners, and the matter of public information. Neither subject is a new one, but the implications of Three Mile Island in the financial sense, and the problems arising as a result of much public confusion during and after the accident, both require increased attention and detailed involvement toward solutions on the part of everyone in the industry.

This introduction to the major developments in the industry since Three Mile Island does not include areas of great concern to the various committees mentioned, including the areas being covered by a number of investigations into Three Mile Island on the part of others. For example, the President's investigation under Dr. John Kemeny precedes, apparently, a continued congressional investigation. And the Nuclear Regulatory Commission itself has been conducting a thorough, detailed inquiry, not only into Three Mile Island events, but also into related events that have taken place, or might conceivably occur, elsewhere in the industry.

But I think it is safe to say in the context of my assignment for today that I have highlighted the industry's response fairly and accurately.

I would like to bring you up to date, in the few minutes remaining, more specifically on the activities of the Nuclear Safety Analysis Center (N-SAC), the Institute of Nuclear Power Operations (INPO), and finish by highlighting certain activities of the Atomic Industrial Forum's Policy Committee.

For example, N-SAC put together an initial draft report analyzing the events at Three Mile Island by the end of June. It differs from the other sequence-of-events reports in that it contains extensive appendixes that analyze in detail what happened physically. The report makes no reliance on people's recollection. The instrument charts and the computer records were the main sources of data, together with a datalogger something like a flight recorder, which provides a more complete record of what was happening than the operators had.

An initial report of 380 pages and 17 appendixes was published at the end of July and is being supplemented.

N-SAC reported that there are roughly two dozen different contributing factors that can be identified. If almost any one of these factors had been a little different, there would have been no damage. The physical capability of the system to operate without damage is clear. However, the idea that the whole problem implied by Three Mile Island can be cured by treating just one of those factors is not plausible, considering classes of accidents like this. On the other hand, changing all two dozen factors may not be productive, even though there is some tendency to require this by regulation. Some remedies can preempt or conflict with others, and even useful ones may have widely different benefits and priorities. Somewhere in between these extremes there are a few very important remedies that can apply to most plants--and a few more that may apply selectively to some plant designs but not to others. Many other proposed remedies may range from convenience to cosmetic or even can be counterproductive or in conflict with existing systems. It is vital that a *small* number of the most meaningful remedies be implemented effectively without the dilution or diversion by a large number of less meaningful "do something" remedies.

The industry involvement of N-SAC has been to act as a clearinghouse at a technical level for the various owners' groups, industry committees, and technical working groups. This includes technical support to all seven of the AIF committees on Three Mile Island response, six utilities owners' groups, and the EPRI technical task forces. Utilities in turn have designated "N-SAC Coordinators" from 60 companies. Generally, these are the people who are in charge of the Three Mile Island response within each company. Fifteen additional utility people were designated for their interest in the health effects studies.

N-SAC has since then run or cosponsored a series of technical workshops. These include a group of people in the United States, and some overseas, who, along with N-SAC, have attempted to do the thermal-hydraulic analysis of the Three Mile Island accident. They met for several days to review status of these calculations and methods. A "Disturbance Analysis System" workshop was held to cover possible information aids for reactor operation. A workshop was held at Three Mile Island on the plant status and recovery plans and included a visit to the Three Mile Island plant. A valve-function monitoring workshop covered the use of acoustic monitors.

The N-SAC report is available to those who might want it, and meanwhile N-SAC continues exhaustive activities in many related areas. To take just one example, N-SAC and EPRI have established large and readily accessible archives of Three Mile Island-related data and information. Many utilities use material developed by N-SAC in their studies and in submittals to local and federal agencies. The archives are stored on microfilm with computer searchable indexing, which can be accessed by any utility. There is also a monthly newsletter printing 5,500 copies that covers current work, key developments, and general information related to the progress to the Three Mile Island accident.

N-SAC has started operation of the "NOTEPAD" Information System. This is a report medium providing daily update capability, but which doesn't add to the stack of papers on the desk. The terminal provides easy selectivity of just that information relevent to the user. It is available nationwide and provides an added vehicle for timely alerting of statistics to significant events.

In the matter of the Institute of Nuclear Power Operations (INPO), the institute is charged with ensuring a high quality of operation in nuclear power plants. Its purposes in brief are to establish industrywide benchmarks for excellence in nuclear operation and to conduct independent evaluations to assist utilities in meeting the benchmarks. It will determine educational and training requirements for operating personnel and will accredit training organizations.

The philosophy of the institute is to:

1. Promote an improved level of professionalism in nuclear power operation.
2. Involve plant operating staffs in the development of benchmarks in training systems for the conduct of the operation evaluations.
3. Use the best-available techniques and methods to develop operating and training practices and the human factors aspect of design in operation.
4. Utilize the best-available independent professional advice and counsel towards accomplishing the institute's objectives.
5. Support and improve existing practices and training systems wherever possible rather than supplanting them.
6. Help the utilities to help themselves rather than preempt their management responsibilities.
7. Encourage excellence.

The institute's Advisory Council is composed of distinguished persons in areas related to the institute's objectives, including prominent educators, scientists, engineers, industrialists, and health specialists. The day-to-day affairs of the institute will be managed by a president, and it is estimated that the functions of the institute will require a staff of about 200. It is anticipated that the president of the institute will be selected before the end of the year and that the institute will be fully operational in 1980.

As I indicated earlier, the industry is investigating a plan for improving nuclear insurance protection, and it is anticipated that participation in the Institute of Nuclear Power Operations will be a condition of obtaining such insurance. Thus, although participation in the institute will be voluntary, it is anticipated that there will be sufficient incentive to assure that the goals of the institute are achieved industrywide.

Meanwhile, as the work of N-SAC and INPO accelerate, the Policy Committee has assigned a number of subcommittees to specific critical issues, including Emergency Response Planning, Operations, Systems and Equipment, Post-Accident Recovery, Safety Analysis Considerations, Control Room Considerations, and Unresolved Generic Safety Issues. These subcommittee issues and the subtopics being addressed in each resulted from an early, intensive review of a massive list of Three Mile Island-evoked concerns that were culled for priority consideration. In addition, the utilities have formed reactor owners' groups to work with their respective vendors in order to expedite timely response to regulatory-generated requirements.

A primary purpose of this Policy Committee is to provide a broad coverage of the lessons learned at Three Mile Island. Under this approach, specific tasks are assigned to subcommittees, and a wide involvement of both people and organizations has been encouraged.

This facilitates the exchange of information among utilities, architect-engineers and constructors, and nuclear steam supply manufacturers. It also permits a general position to develop in a reasonably short time. The positions developed through the subcommittees are meant to provide a common basis for individual utility action and permit sufficient flexibility for satisfying specific company or site-related needs.

Using the preliminary input of these subcommittees, the Policy Committee as a whole developed an August 2, 1979, letter of comment on the first phase of the Nuclear Regulatory Commission's "lessons learned" task force report. With few exceptions, the committee found the Nuclear Regulatory Commission staff recommendations generally acceptable.

All of the activities under the Policy Committee embrace a central posture--the intent to learn as much as possible from the Three Mile Island accident and to modify practices to incorporate important lessons. This openness to change will supplement but not erase the reliance and confidence that will continue to be placed on the framework for design, construction, and operation established over the last 20 years. We want to give careful scrutiny to the entire process, making improvements where needed.

The recommendations of each of these subcommittees are now being reviewed for final approval by the Policy Committee. A serious effort has been made to keep both the industry and the NRC informed of our activities. Our final work product will receive wide distribution.

The sum of these activities is a general attitude toward constructive improvements derived from the lessons of Three Mile Island. While the regulatory process indeed has a specific role in assuring reactor safety, it is, in our opinion, subordinate in its effect on real safety to the efforts of the individual utilities and the industry that supports them. The industry efforts I have outlined, I would hope, should be a sign of encouragement to you and the public that nuclear safety can and will be improved.

I think I can commend to you the thought that the industry's response to Three Mile Island was positive and immediate. I think, or at least I hope, that your impression of this industry and its ability to stand to the issue and handle it straightforwardly encourages your support of the people to whom you've entrusted the nation's commercial reactor program. It is an ever-changing, viable program, and I believe you can agree with me that so long as we are alert, open, and responsive the leadership of this industry merits your continued trust and encouragement.

Nuclear Waste Management

EARNEST F. GLOYNA*

Problems involving the management of any type of waste frequently involves broad-scale public participation and occasionally encompasses a degree of technical complexity that does not lend itself to simple solutions. However, aggressive actions and intelligent choices in the available waste management options have consistently improved public health and have resulted in the betterment of man's total well-being.

The current problems of radioactive waste management are akin to many of the historical public health issues.[1] Every major public health issue concerning the treatment of water supplies, wastewaters, exhausted air, and solid waste have usually involved exhaustive debates. However, no previous set of technical solutions have met with such formidable resistance and have been attacked through the use of such pervasive uncertainties as that which surround commercial nuclear power and the associated radioactive waste.

This paper addresses relevant issues concerning radioactive waste management as follows: (a) general background discussion of present and future waste generation rates, (b) radioactive waste management issues, (c) research requirements, (d) conclusions, and (e) policy recommendations for managing high-level radioactive waste.

GENERAL BACKGROUND AND BASIS

The radioactive wastes of concern are produced by the defense-oriented nuclear programs, the nuclear power utilities, research efforts, and medical activities. This discussion emphasizes high-level waste management.

About 70 commercial nuclear power plants are generating electricity in the United States (99 under construction). Worldwide, there are about 210 commercial nuclear power plants in operation.[2]

In 1977, 12% of all electricity in the United States was generated by nuclear power, and at times the Northeast and Midwest relied on

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nuclear power for as much as 50% of their electric power needs. The existing nuclear power plants are reducing the electric utility industry's need for fuel oil by about 1.5 million barrels per day.

The present-day installed U.S. capacity is 50 gigawatts electric (GWe). It is generally assumed that 400 GWe could be available by the year 2000, after which it is anticipated that the capacity will level out or decline slowly depending on the availability of the necessary fuel. If no new reactors are placed into operation after 2000, the capacity would decline to zero by the year 2040.[3]

The waste derived from commercial nuclear power operations, whether low- or high-level, may be gaseous, liquid, or solid. Wastes that receive most attention today are those categorized as high-level, transuranic contaminated, and reactor spent fuel. Generally used definitions follow:

1. *High-Level Wastes (HLW)* are the portion of wastes generated in the reprocessing of spent fuel that contain virtually all of the fission products and most of the actinides not separated out during reprocessing. If a final decision is made not to reprocess spent fuel, this would be categorized as HLW. The waste is characterized by high levels of penetrating radiation, high heat-generation rates, and long radioactive half-life.

Presently, about 270,000 m^3 of high-level waste, mostly resulting from military operations, are stored in steel tanks and bins. To date, only about 2,300 m^3 of high-level waste have been generated as a result of commercial reprocessing activities.[4] Since April 1977, no commercial reactor fuel has been reprocessed in the United States, but other countries are reprocessing such fuel.

2. *Transuranic (TRU) Wastes* result predominantly from spent fuel reprocessing, the fabrication of plutonium to produce nuclear weapons, and plutonium fuel fabrication for recycle to nuclear reactors. TRU wastes are currently defined as material containing more than 10 nanocuries of transuranic activity per gram of material. Transuranic contaminated waste is usually generated by plutonium fuel fabrication-reprocessing facilities and laboratories using transuranic elements. It is estimated that 370,000 m^3 of these wastes have been buried or stored retrievable at five shallow-land-burial sites of the U.S. Department of Defense (DOE).[5] There could be as much as 200,000 m^3 of commercial transuranic contaminated waste accumulated by the year 2000. Potential limits for shallow earth burial of transuranic elements have been fully examined by models of individual pathways to man.[6]

3. *Low-Level Radioactive Wastes (LLRW)* contain less than 10 nanocuries of transuranic activity per gram of material, or they may be free of transuranic contaminants, require little or no shielding, and have low but potentially hazardous concentration of quantities of radionuclides.

Present production of solid, low-level radioactive wastes (LLRW), or that suspected of being radioactive, in the United States is about 113,200 m^3 or about 0.45 kg per person per year.[7] This amount of solid waste is about the same as that produced by a city with a population of 100,000. The U.S. Department of Energy produces about 50% of the LLRW.[8]

4. *Uranium Mine and Mill Tailings* are the residues from uranium

mining and milling operations that contain low concentrations of naturally occurring radioactive materials.

Uranium mill tailings, by volume, constitute the largest amount of all radioactive wastes. About 140 million tons of uranium mill tailings exist today.[4] These wastes contain the natural radioactive decay products of uranium in about the same concentration as the original ore. To control the movement of tailing particulates and gaseous radon-222, it is necessary to stabilize the tailing piles and localize the naturally occurring emissions.

5. *Gaseous Radioactive Effluents* are normally released to the atmosphere and thereby become diluted and dispersed to a nonhazardous level. These will not be discussed beyond this point.

6. *Decommissioning Wastes* are those wastes that occur as a result of dismantlement of reactor facilities. The volume and magnitude of this waste form is beyond the scope of this paper. One reference method of decommissioning is passive storage for 50 years before dismantlement. This time allows decay of most of the cobalt-60. Residual isotopes such as Ni-59 and Nb-94, 80,000-year and 20,000-year half-lives, respectively, require entombment consideration.

RADIOACTIVE WASTE MANAGEMENT ISSUES

The issues surrounding radioactive waste management embrace four basic considerations. These are: (a) U.S. policy as it relates to the spent fuel reprocessing question and fuel cycle evaluation, (b) waste management in terms of spent fuel handling and packaging and high-level waste solidification, (c) environmental impacts, and (d) sociopolitical considerations.

Policy

In the 25 years following the Atomic Energy Act of 1947, nuclear sciences and technology flourished. In the 1950's and 1960's, industry carried forward many developments that were begun in the laboratories. By 1975 federal policy was increasingly directed towards development of other energy resources. From 1977 forward, this policy has shown a preference for nonnuclear energy sources.

President Carter's nuclear policy statement of April 7, 1977, emphasized the nonnuclear policy. He announced indefinite deferral of commercial fuel reprocessing, redirected breeder R&D into alternative nonbreeding fuel cycles, proposed the cancellation of the breeder demonstration plant, and placed the breeder program on hold. In addition, the R&D program included two major studies--NASAP (Nonproliferation Alternative Systems Assessment Program) and INNFCE (International Nonproliferation Nuclear Fuel Cycle Evaluation)--in which the principal conclusions will not be available until early 1980.

Today, there is general worldwide agreement with the President's policy of reducing the spread of nuclear weapons and bringing all nuclear power activities under international safeguards. However, there is wide disagreement with the U.S. concept of self-denial of reprocessing of nuclear fuel and the timely development of the breeder. Obviously, waste management will be influenced by the nuclear fuel cycle that will be utilized. In the United States there exist three possible basic nuclear fuel cycle options: the once-through cycle, the uranium-only recycle case, and the uranium-plutonium recycle case. Figure 1 illustrates possible waste sources and the general case for light water reactors.

Two variations of the spent fuel cycle must be considered: deferred isolation of spent fuel in near-surface engineered facilities until disposal or reprocessing is permitted, and uranium reprocessing and recycling only with plutonium oxide stored at engineered surface facilities, or with plutonium remaining in solidified waste. It should be noted that about 40% less uranium ore is required and 30% less enrichment capability is needed if nuclear fuel is reprocessed. Also, the volume of reprocessed high-level solid waste, assuming no thermal constraints, could be as little as one-ninth that of the equivalent spent fuel.

Current U.S. regulations stipulate that commercial high-level wastes must be solidified within 5 years of its formation.[9]

Waste Management Considerations

Primary wastes from facilities generating fission products for both the once-through and plutonium-plus uranium recycle cases are presented in Table 1. In the once-through cycle, irradiated fuel assemblies are isolated and considered to be a waste only if reprocessing is ultimately

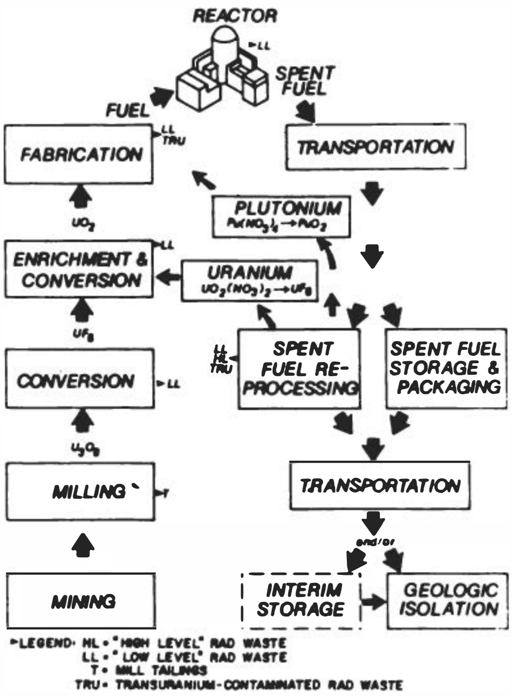

FIGURE 1 Commercial nuclear fuel cycle and types of waste generated.

TABLE 1 Primary Wastes from Facilities Generating TRU Wastes[10]

			Radionuclide Content, Ci/MTHM		
Facility and Waste Type	Fuel Cycle	Volume, m^3/MTHM	Fission Products	Actinides	Activation Products
Nuclear power plant	Once-through				
Spent fuel		0.4	3×10^{6}	1×10^{5}	2×10^{4}
FRP	Recycle				
Fuel residue		0.32	8×10^{2}	1×10^{2}	9×10^{3}
High-level liquid waste		0.6	1×10^{6}	2×10^{4}	--
Gaseous wastes		1.8×10^{6}	8×10^{3}	4×10^{-2}	6×10^{-1}
Combustible and compactable wastes		1.8	2×10^{1}	1×10^{2}	--
Miscellaneous liquid and particulate solid wastes		0.15	2×10^{2}	2×10^{2}	--
Failed equipment and noncombustible wastes		0.65	3	4×10^{1}	--

disallowed. Assuming reprocessing does occur, then the radionuclide content, as shown in Table 1, can be expected. The waste generated is shown as cubic meters per metric ton of heavy metal (m^3/MTHM) and the radionuclide content as curies per MTHM (Ci/MTHM). Table 1 is based on an assumed 1,200 MWe nuclear power plant, an independent spent fuel storage basin, and a 2,000 MTHM/yr fuel-reprocessing plant (FRP).[10]

For each waste type, the waste management system involves: waste generation, waste modification/solidification, packaging, onsite interim storage, possible transport to a central site and interim storage, transport to isolation site, and final isolation/disposal. Advanced high-level radioactive waste management programs may involve a wide variety of alternatives.

Presently, interim, near-surface retrievable storage and ultimate disposal in geologic formation presents a logical first generation solution for safe containment and disposal. Seabed disposal is certainly a potential alternative. Transmutation or disposal through extraterrestrial means continues to be of research interest. Man-made structures in geological formations such as salt, granite, shale, and basalt are of major interest.

Figure 2 illustrates the multiple barrier concept, which is foremost in the minds of many people involved in waste management. Herein solidified waste is contained in an environmentally acceptable mode through both engineered confinement and geological formations that serve as barriers. The fully engineered system would logically encompass consideration of the solid waste form, container, overpack, rock formation, and geographic isolation.

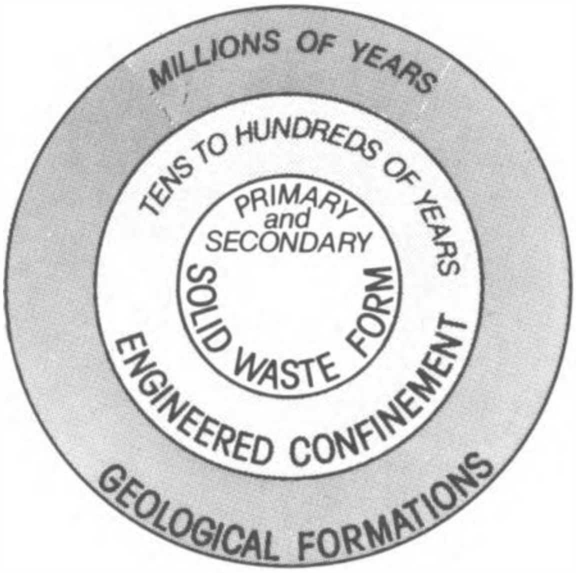

FIGURE 2 Multiple barriers.

The multiple barrier concept involves immobilization, surveillance, and isolation. It may be depicted by a tri-component management system as shown in Figure 3. Immobilization is increased by appropriate solidification. Emplacement of high-level solidified waste greatly increases the reliance on isolation and decreases the need for surveillance.

The solid waste form may consist of a primary phase, which contains the radionuclides at the atomic and molecular level, and a secondary phase, which binds the primary phase particles in a matrix of a secondary material. Within the overall system, which utilizes fuel element reprocessing, there exist a variety of options for producing solid waste forms: calcine, super sludge, ceramics, glass, metal matrix composites, and cement-concrete composites.

One aspect of the system approach to waste processing comes into focus clearly in the selection of a specific geological site. Four levels of studies are required for selecting a geologic site: a data search, regional overlook, site specific study on a regional basis, and a local site specific investigation. Details are shown in Figure 4.

Specific comments are warranted on the topics of spent fuel, spent fuel packages, high-level waste solidification, and the Swedish concept for high-level waste management.

Spent Fuel Two major strategies (INFCE Working Group 7) have been considered in development of environmental impact statements for spent fuel: strategy #1, LWR once-through fuel cycle; and strategy #2, LWR with full reutilization of plutonium as a fuel. The volume of wastes from strategy #2 is about twice that from strategy #1, but the aggregate fissile plutonium content in strategy #2 is reduced about 50-fold as compared to strategy #1. The heat generation rates per unit volume of heavy metal fed to the reactors differ substantially only after long times. This is of importance in regards to terminal storage or disposal.

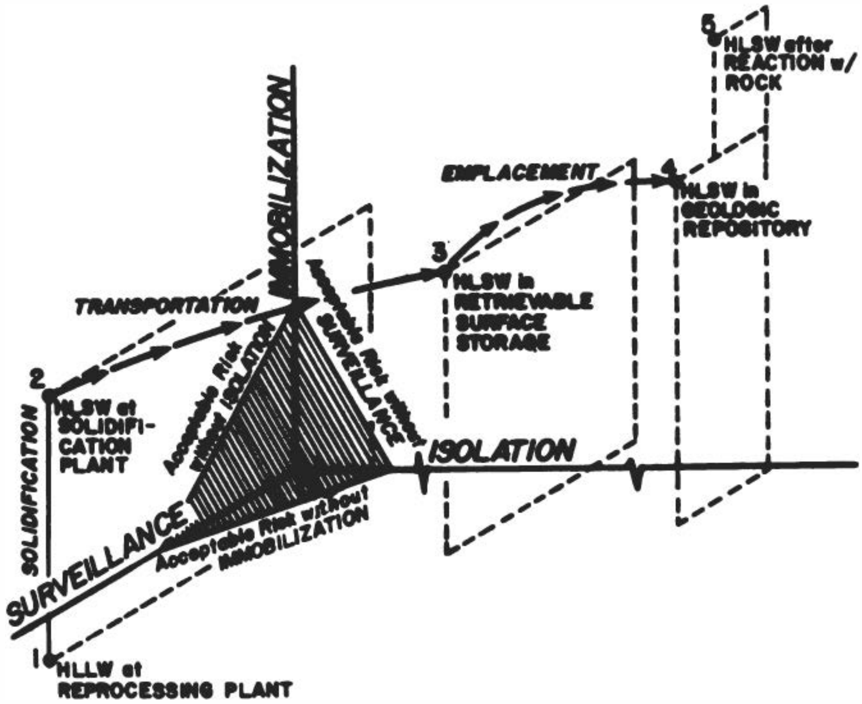

FIGURE 3 Tri-component management system.

Spent Fuel Packages In the United States there is a program for experimentally packaging and storing spent fuel using facilities previously associated with the nuclear rocket program in Nevada. Several options are being investigated for encapsulating the spent fuel. Some options include: utilization of a metal matrix fill, sandfill, glassy or ceramic materials, and multiple-barrier encapsulation of the spent fuel and canister at the time it is declared a waste.[11]

To date, the most comprehensive study on packaging of spent fuel has been conducted by the Swedish Project Kärn-Bränse-Säkerhet (KBS).[12] In this plan, the spent fuel would be stored on an interim basis in water for approximately 40 years. After this interim storage, groups of 500 fuel rods (1.5 MTHM) would be placed in a pure copper canister

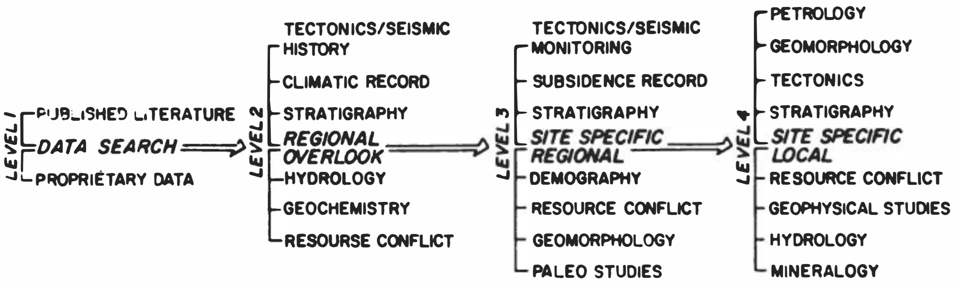

FIGURE 4 Geological studies.

0.77 m in diameter with 20-cm-thick walls. After the canister has been filled with lead and a copper cover welded on the top, the entire canister would weigh about 20 metric tons. For final disposition, the canisters would be placed in granite at a depth of about 500 m. For emplacement the canisters would be placed in holes, some 7.7 m deep and 1.5 m in diameter. Each hole would be lined with 40 cm of isostatically compressed bentonite.

High-Level Waste Solidification U.S. policy has redirected high-level waste vitrification towards defense/military wastes and those associated with proliferation-resistant fuel cycles.

One engineering unit, the Spray Calciner/In-Can Melter has operated at rates over 300 liters per hour (about 20 MTHM per day) for periods of 400 operating hours.[11] This unit has been flexible with regard to waste composition and has successfully treated fuels with a very high sodium content by adding silicate to the feedstream. While the technology is well developed, the disadvantages involve capacity limitation to about 500 liters per hour, a requirement for vibrators to prevent scale buildup, and the need for additives if high-sodium wastes are calcined. Otherwise, the system is simple, releases low amounts of radionuclides, is capable of variable capacity, and has a long life. The In-Can Melter has been demonstrated through the laboratory, pilot-, and plant-scale systems. Over 40 engineering-scale canisters have been produced with nonradioactive glass.

The Joule Heated Ceramic-Lined Melter is a new development in radioactive waste management and may replace the In-Can Melter system. This melter converts dry calcine and glass-forming frit to a molten glass. While the concept has been used by the glass industry for over 30 years, this system has not been operated in a remote hot cell.

The United States, as well as other countries, has selected borosilicate glasses as a contender for immobilization of high-level waste. Some question the stability of glass and containment, particularly in a salt environment. It is well known that time, temperature, and radiation affect the mechanical properties of the glasses. The rate of reaction increases with absolute temperature.

The temperature or solidification matrix need not be the dominant factor in a waste disposal system design. The system design must always consider the interplay between solidification, immobilization, and isolation as it relates to the multibarrier concept. Yet, there are those who would contend that the containment unit must be capable of withstanding all environmental attacks for at least 1,000 years. This solidification concept is difficult to justify.

Environmental Considerations

Environmental assessment generally follows the pathway of investigating potential effects associated with construction of waste management facilities, operation of the facilities, postulated accidents, transportation of wastes, and decommissioning of facilities and equipment. A generic environmental impact statement might include: accident analysis, atmospheric effect, resource requirements, radiological effects, health effects, ecological effects, and socioeconomic effects.

Risk of radioactive release and effects of waste, as shown in Table 2, are related. Important mileposts may be divided into three time periods: (a) repository operation, (b) first 100 to 200 years following decommissioning, and (c) thereafter. Figures 5 and 6, respectively, show the relative ingestion toxicity of fission products from a light water reactor and common materials.[13,14] After 1,000 years several metals exhibit a higher toxicity index than the fission products and unrecovered plutonium. The toxicity index is related to the cubic meters of dilution water needed to produce permissible drinking water levels. Figure 7 shows a comparison of ingestion toxicity in western coal ash and nuclear reactor discharges. During the first 500 years, Sr-90 exerts a strong influence, thereafter the toxicity is less than that of ash from coal containing 24 ppm of uranium.[15]

The subject of criticality always seems to be of real concern to the layman. Criticality events have occurred in nature and the results of recent studies are providing an insight into the movement of radionuclides. At Oklo, Republic of Gabon, loss of fissiogenic isotopes during reactor operation (500,000 to 2,000,000 years) was restricted to noble gases. Later, some Cd, Mo, Rb, Sr, Cs, and I loss developed. The rare-earth elements were retained (roughly 100%) until the present.[6,7]

TABLE 2 Classification of Issues

- Risk of Radioactivity Release
  - Effect of Radioactivity on the Biosphere
    - Methods of Possible Radioactivity Escape
      - Operational Period
        - Flooding
        - Vent to Air
        - Waste/Rock Interaction
          - Corrosion
          - Brine Behavior
- Post-Operational Period
  - Thermal Period
    - Thermally Induced Fracturing
    - Gas Generation Induced Fracturing
    - Groundwater Transport
    - Man-Caused Intrusion
    - Container Movement in the Formation
    - Water Intrusion
    - Criticality
  - Actinide Decay Period
    - Climatic Changes
    - Seismic Changes
    - Groundwater Transport
    - Man-Caused Intrusions
    - Water Intrusion (Boreholes)
    - Criticality
- Effects on the Geologic Formation
  - Thermal Effects
  - Waste/Rock Interaction
- Socioeconomic Impacts
  - New Community Effects
  - Psychological
  - Aesthetic
  - Civil Liberties
  - Costs
  - Distribution of Costs
  - Impaction on Nuclear Proliferation

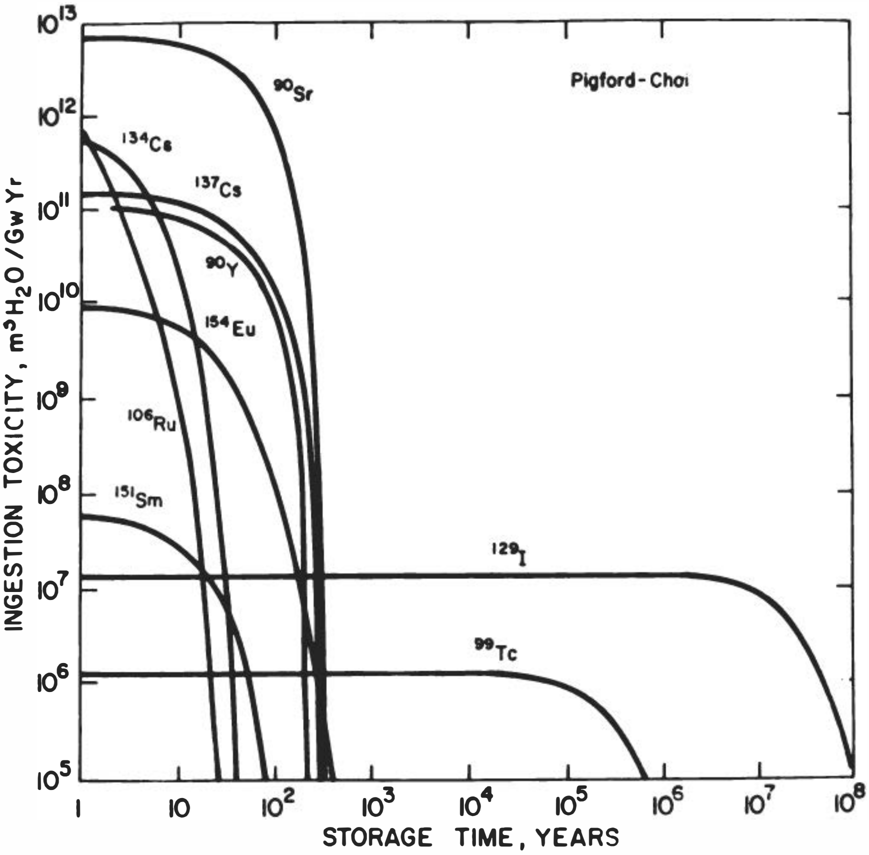

FIGURE 5 Ingestion toxicity of fission product from a light water reactor.[13]

Sociopolitical-Economic Considerations

There is no question that radioactive waste management has become a worldwide problem. Yet, there exist disparate public concepts as to the basis of disagreement surrounding the nuclear question. For example, to one segment of the populace nuclear power is an important part of the energy system that is expected to spur economic growth and create jobs.[18] To many, energy is the driving force for economic parity, and this significant fraction of the population is not ready to dump nuclear unless they are sure that the often-mentioned substitutes will keep this country going. Yet, in a country such as the United States, where public participation is only one essential element of a public acceptance program, governmental efforts primarily designed to resolve conflicts may in reality foster adversarial relationships. In the United States, in the system of widely disseminating alternative considerations,[4] it is not uncommon for those committed to eliminating nuclear power for their own objectives to use the waste issue in initiating adversarial propaganda.

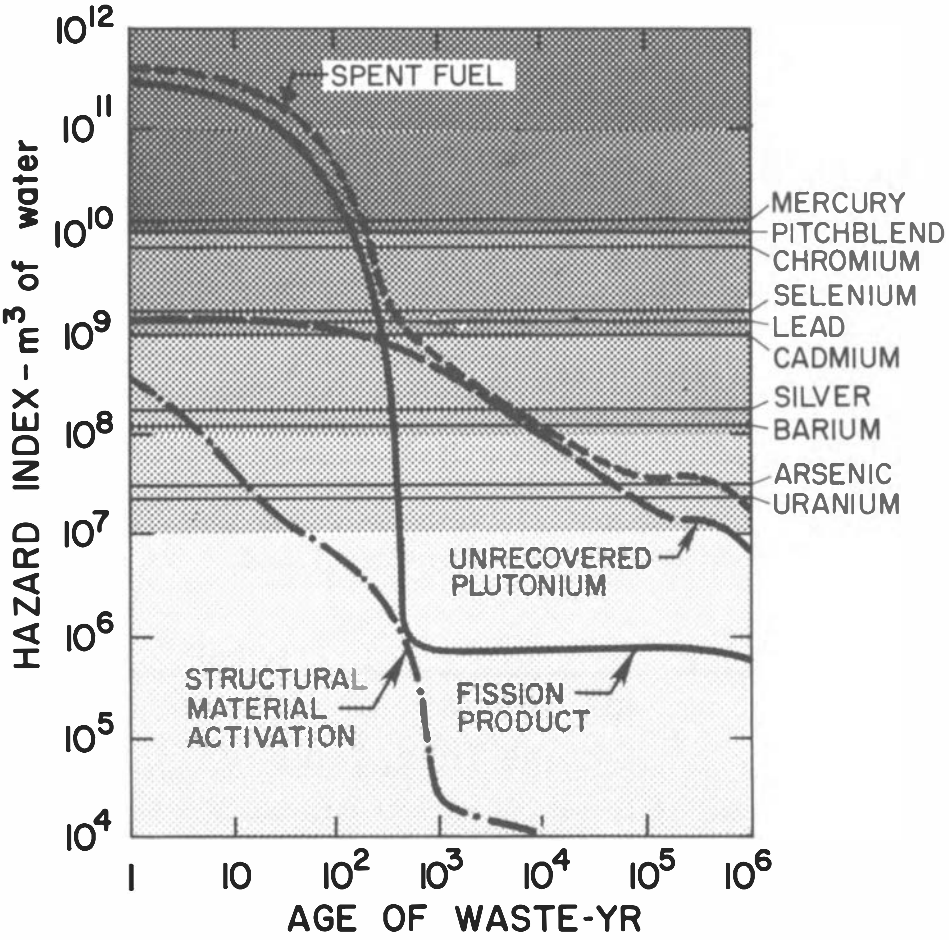

FIGURE 6 Toxicity index of spent fuel and high-level waste.[14]

The problem has become even more complex because there are those among us who choose to degrade the competence that exists in managing radioactive waste. The media calls it, "degrading the technical mystique." The erosion of confidence is brought about by a determined effort to retard the understanding of the social acceptance of commercial nuclear reactors and not permitting the development of waste management in a stepwise orderly manner.

If each issue can be separated from speculative commentary such as "almost available clean energy," "sociopolitical consequences," and a host of other equally vague statements that lead to further decline of public confidence in technology's ability to deal with the problem, progress may be reinstated.

It is recognized that there need not be a "crash" program to place the first repository into operation. However, it is a fact that the lack of federal waste management to proceed expeditiously is seen by some people as a demonstrated lack of capability for managing these wastes and therefore the nuclear option is not viable.

The placement of a moratorium or prohibition of deployment of the

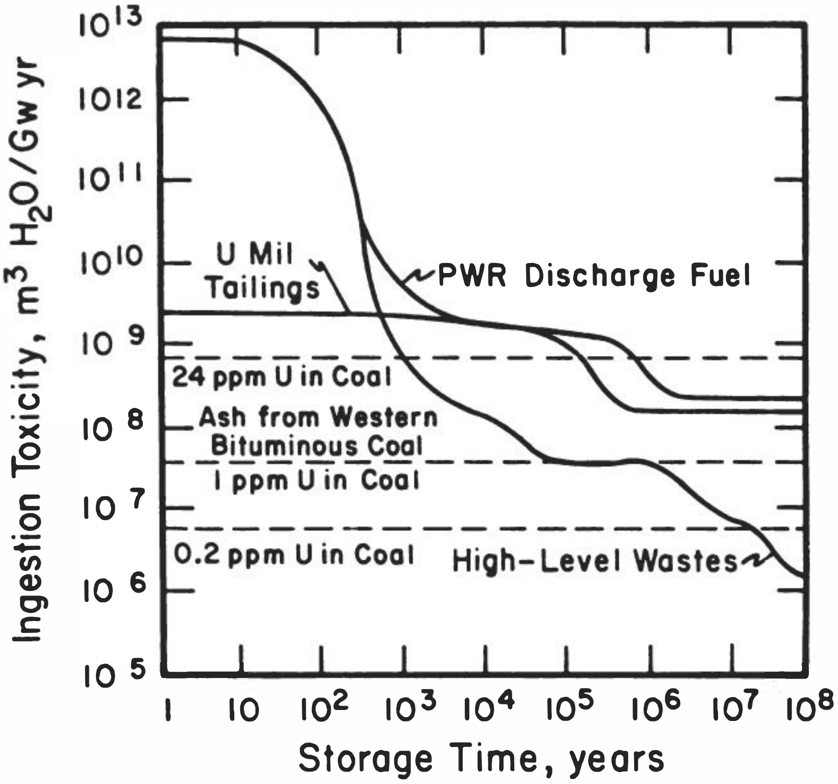

FIGURE 7 Comparison of ingestion toxicity in western coal ash, high-level wastes, discharge fuel, and mill tailings (uranium fuel 33.0 MWD/kg, cooled 0.41 yr before reprocessing.[15]

nuclear power option because of a perceived lack of technical competence for nuclear waste management is just not justified.

According to the Atomic Industrial Forum, in 1978 a nuclear kilowatt-hour of electricity cost about 1.5 cents to produce, or the same as in 1977. However, coal- and oil-generated kilowatt-hours cost, respectively, 2.3 and 4 cents in 1978 as compared to 2 and 3.9 in 1977. A National Economics Research Associates study estimates that the U.S. public will have to pay an extra $119 billion for electricity during the next 20 years if no nuclear power plants were allowed to start up. Further, the cost of waste management is not a significant deterrent for the decision to use nuclear-generated power. Estimates charged for having spent fuel, either on interim or ultimate disposal basis, have been about 0.15 to 1 mill per kilowatt-hour.

On the international scene, the United States has much to learn. Advanced programs exist in the United Kingdom, Belgium, France, and the Federal Republic of Germany. Similarly, the British incinerator design concept has been used in the United States. It appears that the transportation programs of Japan, the United Kingdom, France, and the Federal Republic of Germany are of interest to the United States because of the increasing technology for package design, testing, and risk accessment that is being developed by these countries.

The United States has four bilateral agreements relating to nuclear waste management. These are with Sweden, Canada, the Federal Republic of Germany, and the United Kingdom. Agreements with Belgium and Japan are pending.

RESEARCH REQUIREMENTS

Although technology is available to initiate one or more demonstration schemes for either surface or subsurface deployment, there is always room for continuing research. Continuing research and ongoing field demonstration go hand in hand. Research in the "System Development" of nuclear waste management, i.e., storage, transportation, and disposal, must warrant high national priority. This research will assist in defining the longer-term (5-10 year) nuclear waste management framework known as "System Deployment," i.e., development of strategic options, milestone definitions, and resolution of uncertainties.

Candidate research areas are: (a) improved separation of transuranics and isotopes such as strontium and cesium from reprocessed wastes, (b) development of solidification alternatives, (c) measuring containment vessel interaction with solidified masses, and (d) evaluating interaction of various engineered environments with alternative subsurface geologic media. All of this newfound information will be helpful in utilizing future site-specific data more efficiently.

The national research and development program can become more effective by:

(a) eliminating proliferation of research into every conceivable "what if" question and proceeding with all available resources along pathways that have the potential of success as measured against an integrated and logical systematic assessment;

(b) establishing realistic failure scenarios;

(c) proceeding to obtain that basic data that contributes to the major source of gaps in geologic repository knowledge, i.e., site-specific data: encompassing geologic, hydrologic, geophysical, geochemical, and other information;

(d) proceeding with in-situ tests to provide the information needed to develop systems designs that are conservative and workable;

(e) differentiating between containment, i.e., protection of water supplies, and isolation, i.e., protection against intrusion;

(f) delineating the first generation repository and waste forms so that engineered systems can be designed to mitigate risks, i.e., establish guidelines so that thermal inputs can be controlled and thereby meet temperature related criteria; and

(g) providing a workable and integrated assessment of "gaps and uncertainties" in scientific and technical knowledge related to geologic repository.

CONCLUSIONS

While it has not been possible in this brief discussion to develop the full logic to support any extensive conclusions in this important area, the author has taken the liberty to state the following conclusions, which, in his judgment, can be supported and are fundamental in recommending a national policy on high-level radioactive waste management. These are:

1. There is a well-developed technology that can be used to establish a geologic repository for pilot and demonstration purposes. There appears to be no technical obstacle to the selection of appropriate site and the design, construction, and operation of a subsurface repository.
2. There is a proven technology for the separation of radioactive waste from nuclear fuel; waste can be concentrated and solidified; residues can be incapsulated and transported; and these wastes can be stored either on the surface of the earth under interim-storage conditions or placed into a suitable geologic repository for demonstration, study, and ultimate disposal. Basically, these storage problems present no new difficulties, because throughout the history of the nuclear industry, it has been necessary to consider, evaluate, and utilitze the multiple barrier concept for radiation control.
3. The heat source term is subject to direct control by aging and/or dilution of the waste, waste package configuration, and repository emplaced spacing. Basic rock mechanics and heat transfer analysis are sufficiently advanced to enable conservative assessment and design of storage facilities.
4. There is an erosion of public confidence in technology to resolve the radioactive waste management problem. Much of this erosion has originated from those who use radioactive waste management, as almost any other waste management problem, to attack a primary target. It is time for the political leadership to recognize that nuclear power is a vital part of this country's well-being and that technology is available to safely store and demonstrate disposal.

RECOMMENDED HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT POLICY

There is an urgent need for a clear policy statement by the federal government to proceed with a comprehensive plan for the management of commerically generated high-level radioactive wastes. The following elements should be included in such a policy statement:

1. The federal government must make it clear that it has sole responsibility for the management and final disposal of all commercially generated high-level radioactive waste in a manner that is safe both for the present and future generations and with minimum impact on the environment. In support of this responsibility the federal government should establish the necessary regulations and procedures to cover:

- processing of waste for acceptance by the government,

- designation of time of acceptance,
- designation of place of delivery (including away from reactor [AFR] fuel storage,
- acceptance of all future liability,
- fixing compensation for residual value of spent fuel,
- fixing cost of storage of disposal.

2. The federal government should proceed immediately to develop a waste disposal demonstration program based on the use of deep geologic repositories. The demonstration program shall provide continued research and development in both waste management technologies and the geophysical considerations of a geologic repository. Further consideration of other alternatives to geologic disposal, with the exception of deepsea bed disposal, shall not be required for NEPA, licensing, or program planning purposes.

3. Waste will be stored on an interim basis in engineered surface storage systems until such times when a final decision on waste reprocessing has been made. The waste may continue in surface storage until they have cooled to a level that will minimize the potential uncertainties caused by the thermal behavior after disposal in a deep geological repository.

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Future Nuclear Systems Technology

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The remarks that I have been asked to make pertain to future nuclear systems, and that is a rather large order. In the short time available, what I will try to do is to indicate where I think various directions of advance in nuclear systems are likely to go.

I guess I would have to say at the outset that this is all predicated on the assumption that there will be a nuclear industry, something that cannot be entirely taken for granted. I myself subscribe rather strongly to the view of the future that Wolf Häfele presented so eloquently this morning, but there is real doubt as to whether this will survive in the present political debate.

It seems to me that one can identify five directions of evolution of nuclear systems, possibly a sixth. These are, first, and perhaps most important, toward a means of extending fissile resources through improvement of the efficiency of their use; second, improvements in nuclear safety; third, reduction in the environmental impacts of nuclear electric power generation, particularly water requirements; fourth, improvements in proliferation resistance of the nuclear fuel cycle; and, fifth, improvements in economics. And I would add as a sixth, and somewhat more speculative direction, the use of nuclear power for purposes other than the direct generation of electricity.

The first and most immediate area of interest is that of the extension of resources. The present light water reactor with a once-through fuel cycle, at least in the present configuration of the reactor, utilizes about 0.6% of the energy potential in natural uranium, about 0.4% of that being due to fissions of U-235 and about 0.2% being due to fissions of plutonium.

One can identify a series of technologies for extending resources, which I think are familiar to all of you. They can be classified in the following way: first, ways of extending resources without reprocessing essentially through the once-through cycle; second, ways of extending resources with reprocessing; and finally, ways of extending resources through other than nuclear fission option, namely, the fusion option or possibly combinations of accelerators and reactors.

Let me say just a word about each of these. First, in regard to the extension of resources without the reprocessing option, this is something

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that has come into prominence, of course, with the Presidential decision to defer reprocessing and the breeder. One of the main focuses of the INFCE study is to look at ways of extending resources without reprocessing. The options are improvements in the design of light water reactors, including increased burnup, changes in enrichment, lower tails assay in enrichment, and tails stripping.

Second, under this same rubric, there is possible further extension of resource efficiency through the use of other kinds of reactor designs, specifically advanced converters still using only the once-through fuel cycle. I think one has to state at the outset that the virtue of this direction of evolution is very strongly dependent on what one projects about the future growth of electric power. If you think that the kind of scenario that Wolf Häfele described this morning is almost inevitable, then all of these options really only extend resources something like 2 to 10 years and can be regarded primarily as buying time to offset unforeseen delays in the development of other options.

If you assume, as many enthusiasts of conservation do, that, in fact, the demand for electric power--at least in the advanced industrial societies--will saturate and level off after the turn of the century, then the introduction of more advanced reactors, even restricted to no reprocessing, could extend resources for periods up to, perhaps, 50 years or more.

The figures and tables in this report illustrate this point in a particularly graphic way. They are taken not from the CONAES report (Committee on Nuclear and Alternative Energy Systems, National Research Council), but from the Ph.D. thesis of an MIT student of David Rose's, Richard Lester. Lester considered three different options (Table 1) for the extension of resources, sticking with the once-through fuel cycle: first, extending burnup; second, reducing tails assay from the present value of 0.25% to 0.05%, beginning in 1988; and, third, replacing the present generation of light water reactors with heavy water reactors,

TABLE 1 Alternative Uranium Conservation Strategies for the Once-Through Fuel Cycle

Reference case (0): All-PWR economy[a]
0.2% enrichment tails assay
Average discharge burnup = 30,100 MWD/MT
Capacity factor = 75%

Uranium Conservation Strategy	Reduce Tails Assay to 0.05% in 1988	Increase Discharge Burnup to 50,000 MWD/MT in 1990	100% Penetration of 1%-U Fueled HWR's by 2000	Capacity Factor (%)
A	Yes	No	No	75
B	Yes	Yes	No	75
C	Yes	Yes	Yes	75

[a] In the United States at present, PWR's outweigh BWR's by a ratio of about 2:1. Lifetime natural uranium requirements for the two reactor types differ at most by a few percent, however, and in light of the many other assumptions used here, the error introduced by assuming an all-PWR economy is relatively small.

fueled by 1.0% to 1.2% enriched uranium, with 100% penetration of the new reactor market after the year 2000.

Figure 1 shows the three cases from Table 1, including a base case, which is simply business as usual; that is to say, the present design of a reactor with no change and two different estimates of uranium resources, the lower one essentially that used by the uranium resource group of CONAES and the upper one being the somewhat more optimistic inferences that have been made from recent DOE publications.

But you see in all of these cases that if the lower value for the uranium resources is the right one, one begins to be in trouble around the year 2000. This table is based on projections of nuclear power that give you a capacity of the order of 350 GWe around the year 2000.

I think the problem is illustrated more graphically, however, in Figure 2, which shows things not in terms of the total resources, but rather based on estimates of the rates of production of uranium; again, taken from the work of the Uranium Resource Group of CONAES, which has

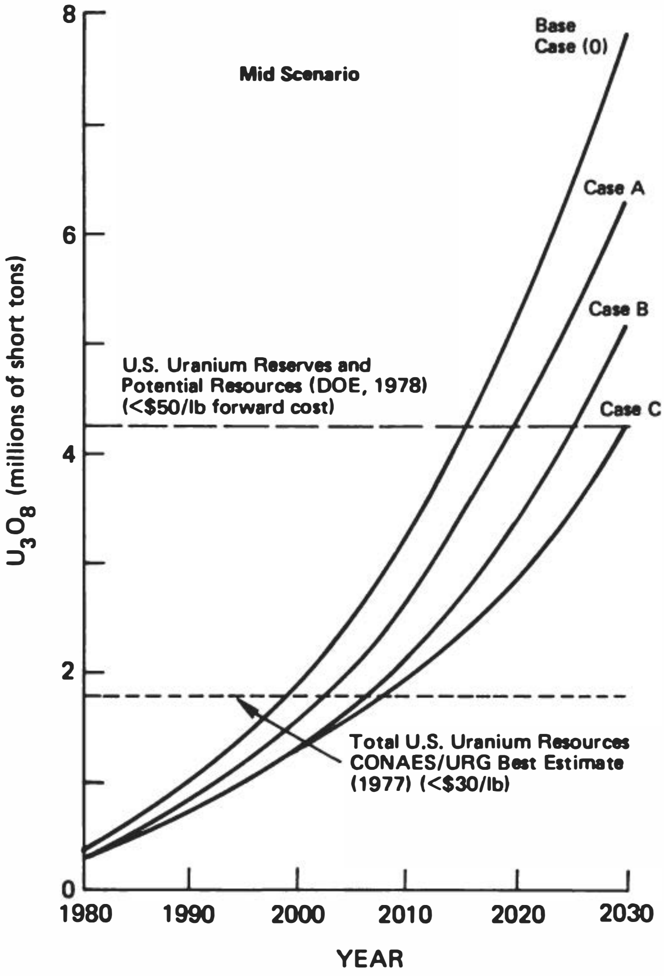

FIGURE 1 Cumulative U.S. uranium commitments: mid scenario.

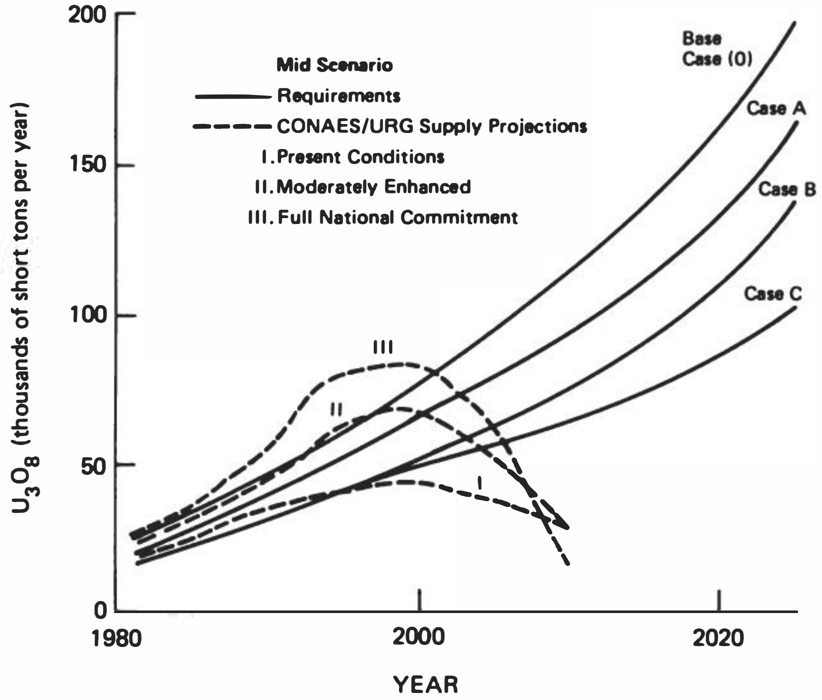

FIGURE 2 Annual U.S. uranium requirements: mid scenario.

been published. The three curves represent three scenarios of business as usual, moderately enhanced efforts at production, and the full national commitment to all-out uranium production.

The dotted curves are annual production curves, and the solid curves represent annual requirements. And I think you can see from this picture that, given the assumptions, only Case C really is compatible with the present projections of the producibility of uranium. The base case, zero, would be compatible with the full national commitment case of uranium production, but that is rather deceiving; because you see the uranium supply rather abruptly disappears soon after the year 2000, because part of that national commitment to uranium production is achieved at the cost of depleting reserves very rapidly.

Table 2 is an attempt to tie projections of needed nuclear power capacity to the actual scenarios that were used in the CONAES study, and I don't want to take the time to go into detail in these scenarios, except to say that they all represent cases of 3% assumed average economic growth between 1975 and 2010, and the Roman numerals represent a fourfold increase in real prices between 1975 and 2010, with very stringent mandatory conservation measures, in addition. Scenario II represents the same fourfold increase in prices, but with less use of regulation. Scenario III represents a doubling of prices, and Scenario IV essentially represents constant prices between now and 2010.

You can, for the moment, ignore the left-hand columns and look only at the right-hand columns, which give the capacity required in the year 2010 to meet the estimated electricity demand under these assumptions.

TABLE 2 Energy Used to Produce Electricity (in quads)

			2010		
			CONAES Scenario		
	1975	1977	II_3	III_3	IV_3
Nuclear	2	2.6	8(160)	18(360)	30(600)
Coal	9	10.1	23(460)	20(400)	29(380)
Other	9	9.0	8(160)	11(220)	9(180)
Total electricity	20	21.7	39(780)	49(980)	68(1,360)
Total primary energy use	71	75	115	140	188

NOTE: Figures in parentheses are installed generating capacity in gigawatts. An approximate conversion factor of 20 GWe per quad is used for 2010; this makes allowance for a reserve capacity of about 18%. The 1977 figures are from actual data.

And you can see, in the case of the stringent Conservation Scenario II_3, that you can by no means eliminate nuclear power, at least if you follow the assumption of 3% economic growth.

On the other hand, 120 GWe is less than would be projected on the basis of the plants now under construction; 210 GWe would be just a little bit more than the plants now under construction. With the lowest growth scenario, and optimistic assumptions about uranium supply, nuclear power might be extended well into the twenty-first century and then be gradually phased out in favor of alternative sources, but this could not be confidently anticipated today.

Some critics of the CONAES study believed the predictions of electricity growth were low, given the fact that electricity generation is capital-intensive, so that much of the cost is at the front end, and hence less sensitive to rapidly rising fuel costs on a percentage basis. To test the effect of alternate assumptions, I show in Table 3 two different cases of electricity growth. One arises from the CONAES models; the other, the high-electrification case, assumes that half the use of oil and gas in space heating in the base model was shifted to electricity. That is an arbitrary assumption, but it provides a simple way of getting a somewhat higher electricity growth to test its impact. It is assumed that all the extra electricity is produced by nuclear. You can see that the total nuclear capacity required in 2010 is nearly doubled in the low-growth cases.

You can also go all the way down to the case of constant prices, which, of course, I think all of us would agree now is a rather absurd assumption, but put in merely for exploratory purposes. You can get up to 820 GWe required in 2010, which, by the way, I am told by the Supply Delivery Panel people of CONAES, is still within the capacity of the nuclear industry.

I think the basic conclusion is that, as one looks at all of the

TABLE 3 The Sensitivity of Outcomes to Assumptions About Electrification

		QUADS		GWe	
		2010--Total	2010--Nuclear	2010--Total	2010--Nuclear
I_3	(base)	23	6	460	120
	(high-electricity)	27.5	10.5	550	210
II_3	(base)	39	8	780	160
	(high-electricity)	46	15	920	300
III_3	(base)	48	16	960	320
	(high-electricity)	56	24	1,120	480
IV_3	(base)	71	25	1,420	500
	(high-electricity)	87	41	1,740	820

possibilities of resource extension by use of various advanced reactor cycles without reprocessing, really important extension into the twenty-first century of the nuclear option is going to require reprocessing. And if electric power growth continues at any significant rate--by significant, I mean by more than 1% a year--after the year 2000, it appears that the breeder option is really the only one that is compatible with the resource estimates that I have indicated. Of course, many people regard the CONAES Uranium Resource Group's projections as unduly conservative, but the real issue is, what is a prudent base for planning. So the conclusion is that the breeder option dominates the widest variety of assumptions regarding future demands for electricity.

The other alternative is, of course, fusion. Almost everbody would agree with the conclusion that fusion is not an option that can be considered as a serious prospect within the time frame of 1980 to 2010, which we have been talking about. Fusion, if it is developed, is an option that comes well into the twenty-first century.

Let me now turn to the next topic, the question of prospects for improvements in the safety, health, and environmental effects of nuclear power. At the present time the LWR is the only reactor technology whose safety has been assessed in any detail, and consequently it is probably misleading to try to compare different reactor types. With the LWR the task ahead is the steady reduction of the uncertainties in the prediction of accident probabilities and consequences. Ideally we should be able to reduce the upper limit of conceivable hazard per reactor fast enough to offset the growth in the number of reactors. This will come about both from improvements in design and from reduction in the width of the uncertainty band. The greatest value of the fault tree methodology developed in the reactor safety study lies in its capacity to identify priorities for improvements in safety through pinpointing the most likely accident sequences and concentrating design improvements on them. We should avoid the trap of expending our energies on "proving" the safety of reactors rather than "improving" it.

While it is not possible to make careful assessments of other reactor types, there are some trends that can be mentioned. The inherent thermal inertia of the HTGR appears to be a safety advantage in principle; it will be hard to confirm this without both operating experience and detailed experience in the safety analysis of commercial designs. Somewhat the same considerations apply to the LMFBR, which has the important inherent advantage over LWR's that there is less potential for chemical and mechanical energy release in case of malfunction. The sodium coolant is not under pressure, and there is thus not the problem of flashing the coolant into vapor; furthermore, there is nothing analagous to the zirconium-water chemical reaction in case of a temperature excursion. On the other hand, the fast reactor is not in a minimum critical mass configuration, and hence the theoretical possibility of a recriticality accident could be higher than for LWR's.

For fusion the possibility of supercriticality excursions is eliminated, and it seems highly probable that the radioactive waste problem will be somewhat more managable. However, we cannot be confident until work has progressed to the point of firm engineering designs of prototype commercial systems. The radioactivity problem is highly dependent on choices of materials and detailed configurations.

On the next point, reduction of water requirements, important progress can be made. Probably the largest environmental problem associated with nuclear, and indeed all, electric generation is the large water requirement and the associated issues of thermal pollution. This is true of coal-generated electricity as well, but in that case is probably dominated by other environmental problems. Shifting to the LMFBR or the HTGR would make water requirements comparable to those for other power plants. Helium-cooled reactors, however, are attractive because of the hope that they could ultimately be operated with dry cooling. The HTGR or the gas-cooled fast reactor could be operated with gas turbines and thus bypass large water requirements. Although we probably have enough access to water supplies for electric power growth based on wet cooling for the rest of the twentieth century, dry cooling technology will become increasingly important for the twenty-first century if we are to continue to rely on dispersed electric power generation.

With respect to proliferation-resistant fuel cycles, the main issue is that of reprocessing. The breeder--and most advanced converters--depend on recycling fuel to realize their resource-conserving potential. There is a great deal of disagreement--including that within CONAES--as to how important reprocessing really is in relation to the international proliferation problem. Certainly there are cheaper and easier routes to nuclear weapons than through diversion of fissionable material from civilian nuclear power. On the other hand, civilian power is a very good "cover" for clandestine weapons activities; a political leader with a nuclear power industry, including fuel recycling, could retain the option of developing nuclear weapons without committing himself in advance to dedicated production facilities--at least that is the argument.

The big question is whether there is a "technical fix" for the proliferation problem. One of the principal arguments for going the advanced converter route in preference to fast breeders is the possibility of using a denatured thorium cycle. No consensus has crystalized on this, and there is a real question as to whether the extra costs of more elaborate fuel cycles can be justified by the real additional insurance they might provide against proliferation. Unfortunately, this is probably not primarily a technical question, because the key parts of the issue involve beliefs about plausible political scenarios. Nevertheless, I suspect that the development of proliferation-resistant fuel cycles will continue to receive some attention, although I do not believe they will prove to be determining in the choice of reactor systems.

On the questions of nuclear economics, the fundamental issue seems to be whether resource considerations or economic considerations will be determining. None of the advanced reactor types now being discussed--even the slightly enriched CANDU with a once-through fuel cycle--are economically competitive at current uranium prices. Much hinges on how fast uranium prices will rise, and whether it is necessary to develop and deploy uneconomic but resource-efficient reactor and fuel cycle systems in anticipation of future fuel scarcities. One argument would be that the lead time for reactor development is so much greater than the lead time for finding and mining uranium that we can afford to let uranium economics dominate the choice of reactor designs. This is in turn bound up with the distribution of uranium ore grades. If there is a continuing increase of total contained uranium with declining ore grade, as some think, then the economic approach seems reasonable. But if there are big gaps in distribution, with small resources in ores of intermediate grade--as the CONAES Uranium Resource Group thinks--then there is a case for developing more resource efficient systems well in advance of their economic competitivesness.

On the final issue, that of the use of nuclear energy for nonelectric purposes, I will not say much. However, I do agree with Wolf Häfele that this is being neglected in much current discussion. Future advances in reactor design that lead to greater resource efficiency are going to put a higher and higher premium on using off-peak energy. Or to put it another way, as electricity generation becomes more capital-intensive, off-peak electricity or thermal energy derived from off-peak operation of genrating plants will tend to become more and more of a bargain. This should stimulate a search for effective ways of using this cheap source of energy, essentially by storing it for use at different times or in readily transportable form.