ORAU/IEA-84-6(M)
Research Memorandum

THE SECOND NUCLEAR ERA

Alvin M. Weinberg
Irving Spiewak
Jack N. Barkenbus
Robert S. Livingston
Doan L. Phung

March 1984

Institute for Energy Analysis
Oak Ridge Associated Universities
Oak Ridge, Tennessee 37831-0117

This document is
PUBLICLY RELEASABLE
Barry Steele
Authorizing Official
Date: 10/25/06

Research memorandums document substantive work in progress and receive internal review.

This report was prepared under contract number DE-AC05-76OR00033 between the U.S. Department of Energy and Oak Ridge Associated Universities with funds provided by The Andrew W. Mellon Foundation.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

eb

DISCLAIMER

CONTENTS

Page

CONTENTS (Continued)

CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Institute for Energy Analysis with support from The Andrew W. Mellon Foundation has studied the decline of the present nuclear era in the United States and the characteristics of a Second Nuclear Era which might be instrumental in restoring nuclear power to an appropriate place in the energy options of our country. The study has determined that reactors operating today are much safer than they were at the time of the TMI accident. A number of concepts for a supersafe reactor were reviewed and at least two were found that show considerable promise, the PIUS, a Swedish pressurized water design, and a gas-cooled modular design of German and U.S. origin. Although new, safer, incrementally improved, conventional reactors are under study by the nuclear industry, the complete lack of new orders in the United States will slow their introduction and they are likely to be more expensive than present designs. The study recommends that supersafe reactors be taken seriously and that federal and private funds both be used to design and, if feasible, to build a prototype reactor of substantial size.

EXECUTIVE SUMMARY

The accident at Three Mile Island has all but ended the first nuclear era in the United States. No new reactor has been ordered since 1978, and some 58 reactors either ordered or under construction have been canceled. Nevertheless, the incentives to preserve the nuclear option remain very strong. Power delivered from nuclear plants continues to be cheaper than power from fossil plants. Nuclear power in many ways poses a lesser threat to the environment than does coal-fired power.

The Institute for Energy Analysis obtained support from The Andrew W. Mellon Foundation to investigate whether a Second Nuclear Era might be possible based on power reactors that are inherently more forgiving than current light water reactors. In order to gain a perspective on the potential of inherently safe reactors, it was necessary to assess also the current trends in safety of commercial reactors, and the economics of nuclear plants were evaluated since no technology can be deployed if it is not economical.

If we measure the safety of reactors by the median probability of a core melt as revealed by probabilistic risk assessment, then we must conclude that every one of the commercially available reactors--pressurized water reactor, boiling water reactor, heavy water reactor, and high-temperature gas-cooled reactor--is sufficiently safe; that is, its median core-melt probability is not higher than the proposed NRC safety goal, 10^{-4} per reactor-year. We found that the core-melt probability for LWRs is on average about three- to sixfold lower today than it was before Three Mile Island (TMI) because of voluntary and Nuclear Regulatory Commission-mandated changes carried out after TMI. In addition, estimates of the fission product release from most accidents have been reduced considerably from pre-TMI predictions.

Although present reactors are very safe, their safety depends on the proper response of active safety systems and plant operators during emergencies. The Process Inherent Ultimately Safe reactor proposed by ASEA-ATOM appears to be inherently safe--i.e., no sequence has been identified that would lead to a core melt. Moreover, PIUS seems to be highly resistant to acts of sabotage or war and to be particularly forgiving of inadvertency on the part of the operator. If PIUS could be built as cheaply as an LWR, and if it could be operated conveniently and reliably, then it could be a means for restoring confidence, as well as increasing utility interest, in nuclear power.

While PIUS is a unique concept, we expect that it is not the only possibility for an inherently safe reactor. Small, modular gas-cooled reactors have fail-safe characteristics and may be of interest in a Second Nuclear Era.

There will be no Second Nuclear Era unless the costs of nuclear power are kept under control. The cost of nuclear power from the plants currently in operation is low, provided average or better plant availability is achieved. By current standards, the initial investment in these plants was a bargain, and even if something like $150 per kW has been spent on each unit for backfitting, the plants are still very competitive with fossil plants.

The plants currently under construction have expected costs varying from about $1100 per kW to $3500 per kW or more (in 1983 $). At the low end of the scale, nuclear power is competitive with coal; at the high end of the scale, nuclear power is unattractive.

Based on the above findings, our study has come to two main conclusions and recommendations:

1. Incrementally-improved, post-TMI light water reactors pose very low risks to the public even in a world with several times as many reactors as are now operating. However, investor risk and high, uncertain capital cost may limit their market.

2. The development of a Process Inherent Ultimately Safe (PIUS) reactor or other inherently safe concepts should be undertaken to provide a technological alternative with intrinsic safety as an option for widespread deployment in the future. If preliminary development of the system continues to show promise, a prototype of such a reactor should be built to better determine its operability and economics and to prove its safety characteristics.

The development of even safer conventional reactors is already taking place with the commercial development of advanced pressurized and boiling water reactors. If the incrementally improved LWR is to be the only option available for a Second Nuclear Era, there may be little that government or the nuclear enterprise need do beyond what is now being done.

We are unconvinced that such a laissez-faire approach provides an adequate range of options or is an optimal course for extensive deployment of reactors in a world where there is much concern about the safety of nuclear plants.

We urge development of PIUS or an equivalent inherently safe concept to a stage where its practicality can be determined. This would require a prototype of about 100 MWe and would cost on the order of $500 million. Such an undertaking might be international, and we can envisage private sources providing some of the funds.

We are not unmindful that this recommendation could be interpreted to imply that we do not believe current reactors are safe enough. On the contrary, we are convinced that existing, post-TMI reactors pose low risks to the public. We believe, too, that evolutionary changes to LWRs could make them safer still. However, the evolutionary changes to LWRs have tended to improve safety at the expense of greater complexity and cost. We believe that a reactor that derives safety from simple features that are inherent in the system could profoundly increase the acceptability of nuclear energy.

CHAPTER I. INTRODUCTION

The first nuclear era ended in the United States with the accident at Three Mile Island on March 28, 1979. Actually no new reactor had been ordered since 1978*; and between 1978 and 1983, 58 reactors[1] that had been ordered or were under construction were canceled. Other countries, notably Sweden, the Netherlands, and Austria have also turned away from nuclear energy, at least for the time being.

Nevertheless, the incentives to preserve the nuclear option remain very strong. Though the world today is experiencing an oil glut, this is surely a temporary phenomenon. Every economical alternative to oil ought therefore to be maintained; nuclear power is one of the most important of these alternatives. Power delivered from nuclear plants continues to be cheaper than power from fossil plants. Nuclear power in many ways poses a smaller threat to the environment than does coal-fired power. This became very evident in 1983 with the increased concern over acid rain. In the long run, with the accumulation of carbon dioxide and the depletion of fossil fuel, nuclear power will afford an economical alternative that would eliminate these concerns.

Today, 13 percent of the electricity[2] used in the United States is generated with light water reactors. When reactors under construction are completed, nuclear fission will provide about 20 percent of the total electricity[3] that will be used in 1990. The fleet of reactors will represent an investment of $150 billion (1983 $)--an extraordinary achievement for a technology that was totally unknown 50 years ago.

Few in the energy business would therefore dispute that preservation of the nuclear option is an extremely important element of national energy policy. This was a finding of the Institute for Energy Analysis 1976 study, "Economic and Environmental Implications of a U.S. Nuclear Moratorium 1985-2010."[4] In this study the Institute for Energy Analysis

---

*In 1975, the peak year, a total of 236 reactors were operating, under construction, on order, or announced in the United States. Since this time 92 of these reactors have been canceled or discontinued. Of the remaining 144 reactors on the books, ten do not have current scheduled completion dates, and it is possible that some of these may be abandoned.

(IEA) concluded that the United States could undergo a period of 25 years with no new nuclear reactors and not suffer intolerable environmental and economic consequences; however, the pressure on coal would become very great, and we therefore recommended that all necessary measures be taken to maintain the viability of nuclear energy.

These sentiments echo those of David Lilienthal, the chairman of the Tennessee Valley Authority during World War II and the first chairman of the Atomic Energy Commission. In his book, Atomic Energy, A New Start,[5] written in 1980, Lilienthal argued that nuclear energy must not be allowed to die and that a key element in its resurrection was development of reactor systems that would be regarded by the public as patently and transparently safe. Thus Lilienthal anticipated a rebirth of nuclear energy: a Second Nuclear Era based on better reactors and better institutions.

Lilienthal discussed his ideas with the staff of the Institute for Energy Analysis shortly before his death; we were pleased that many of his ideas were consistent with ideas for improving nuclear energy that the Institute had promulgated in the wake of its nuclear moratorium study. These ideas had been discussed at two Gatlinburg, Tennessee, workshops on "An Acceptable Future Nuclear Energy System"--the first held in 1976;[6] the second in 1979[7] after the TMI-2 incident--and at a third workshop on "Acceptable Nuclear Futures" at Oak Ridge in 1980.[8] Though the Gatlinburg workshops were concerned primarily with institutional improvements, the possibilities of better technology were never far from the minds of the participants. The 1980 workshop, attended by a dozen of the old-timers who had set the technological paths for the current nuclear era, recommended serious study of power reactors that were inherently more forgiving than current light water reactors. In 1981, IEA therefore requested support from The Andrew W. Mellon Foundation to investigate primarily technological approaches to the development of nuclear reactors that would fulfill the requirements set down by David Lilienthal--first and foremost, reactors that were sufficiently safe to restore the confidence in nuclear power which had been shattered by the TMI-2 accident. The Mellon Foundation has supported our project with two grants--one for $400,000 to investigate technological alternatives and a second of $53,000 to examine regulatory barriers to a rational nuclear energy system. In addition, the Institute has used a previous Mellon grant to support three senior fellows who spent several months at IEA working on our project. We are very grateful to the Mellon Foundation for this generous support.

Our study was conducted over a two-year period from October 1981 to September 1983 by staff of the Institute for Energy Analysis. Thirteen papers, by staff members and by outside organizations or consultants, were prepared. Two additional related papers were undertaken by IEA staff members for the Office of Technology Assessment. These supporting papers are referenced in this report as appropriate and several are being published as research memoranda. Workshops were held on reactor costs and on the safety of the Process Inherent Ultimately Safe (PIUS) reactor concept. We were helped very much by our Advisory Committee: Hans Bethe, David Freeman, John C. Franklin, Joseph Hendrie, and Herbert G. MacPherson. Our conclusions however, are not necessarily endorsed by the Advisory Committee. We therefore have invited each member of the Advisory Committee to comment on our findings. These comments are included at the end of the report.

In conducting our study, we invited the views of many of the Western world's reactor community. Our study therefore had the benefit of advice and consultation from Combustion Engineering, Commonwealth Edison, Electric Power Research Institute, General Atomic, General Electric, Institute of Nuclear Power Operations, Nuclear Regulatory Commission, Oak Ridge National Laboratory, Tennessee Valley Authority, and Westinghouse in the United States; the United Kingdom Central Electric Generating Board; Interatom and KWU in Germany; ASEA-ATOM in Sweden; and Hitachi in Japan. We are grateful to all of these organizations for their cooperation and help.

THE WANING OF THE FIRST NUCLEAR ERA

Nuclear power grew out of the military uses of fission--first as a by-product of the atom bomb and then as a spin-off from the pressurized water reactor developed originally to power the American nuclear navy. Of the world's 277 reactors[9] operating in 1983*, 212, representing 77 percent of all nuclear power, are light water reactors (LWRs)--129 are pressurized water reactors (PWRs) and 83 are boiling water reactors (BWRs). In the United States the light water reactor is used in all but three power-producing installations.

The light water reactor, a direct descendant of the submarine reactor, shares with the latter its inherent advantages and deficiencies. First of all, the LWR is simple in concept: light water--as moderator, coolant, and working fluid--has long been familiar to the utilities. Beyond this, the LWR is the most compact of the thermal neutron reactors. A large PWR operates at a volumetric power density of 100 kW per liter,[11] and its specific power averages about 40 watts per gram of fuel.[12] These two characteristics--inherent simplicity and compactness--were decisive in the original decision to base submarine propulsion on the light water reactor.

Because the LWR is so compact, its thermal inertia is small; perturbations of the system are reflected quickly in changes of temperature and pressure. If cooling were interrupted in a 1000 MWe PWR, the temperature of the water would increase at the rate of about 30°C per minute even after a scram. The temperature rise would be accompanied by a rapid increase in primary system pressure. Thus a primary design criterion for all PWRs requires that the core be cooled adequately after a loss of coolant accident during the short time available before an uncooled core would suffer serious damage.

---

*Worldwide there were 518 power reactors[10] operating or under construction in 1983. Of these, 277 are operating. Also, 415, or 80 percent of the reactors, are LWRs.

This requirement, which in good measure derives from the inherent compactness of the LWR, compromises the inherent simplicity of the system. A modern LWR is festooned with safety systems, all of them geared to keep the core cool even after the primary cooling has failed; most of these auxiliary systems must spring into action in a matter of minutes. The original simplicity of the LWR--one of the features that recommended it for naval propulsion--has given way in the LWR's central station embodiment to a complicated array of controls, auxiliary cooling systems, redundant power supplies, and complex instrumentation.

This has contributed to the rising capital cost of LWRs. Actually, it has not been so much the intrinsic cost of the individual safety systems that has raised the price of the LWR as it is the changing nature of the regulations requiring redesigns and rework. Because the measures to ensure the safety of the LWR are themselves complex, questions regarding their adequacy are more easily raised than answered. For example, the arduous hearings on the emergency core cooling system (ECCS) of 1972 stretched over 23 months and filled 22,000 pages of testimony.[13] The emergency core cooling systems designed at the time have since been proven to be more than adequate; nevertheless, the hearings led the regulatory branch of the Atomic Energy Commission (AEC) to mandate operating limits on LWRs that have added to the operating costs of the reactors.

One can give many other examples of how uncertainty as to the integrity of the core under very unlikely, but extreme, accident conditions has resulted in the mandating of new backup systems or the reworking of existing systems. Perhaps the most prominent are the measures now required to earthquake-proof plants. The guarantee that an LWR can ride out an earthquake-induced acceleration of 0.25 g has required the addition, on average, of about $150 million worth of snubbers, pipe supports, and engineering.[14] The snubbers are unreliable and subject to frequent failure; the piping consequently may become overstressed during thermal cycling. The resulting pipe work is now very rigid, but by like token, access to equipment for inspection or repair is less convenient. Whether the attempts to improve resistance to earthquakes have improved safety remains arguable.

With growing operating experience, other difficulties with LWRs have revealed themselves--notably, pipe cracking in BWRs, steam generator failures in PWRs, and embrittlement of some of the early pressure vessels. Some of these deficiencies are traceable to the properties of the light water coolant, rather than to the low thermal inertia of the LWR. Though for each of these deficiencies fixes seem to be available, their presence tends to reduce the attractiveness of nuclear power based on light water reactors.

Reactors coming on-line during the 1980s will cost between $1100 and $3500 or more per kilowatt (1983 $),[15] compared to about $587 per kilowatt (1983 $) on the average for the 57 reactors[16] completed before 1981. Though some of the escalation is directly attributable to the added safety devices, most of the escalation comes from a combination of poor labor productivity, high interest rates, and stretched-out construction schedules--the latter resulting either because demand has not risen as fast as had been anticipated or because of poor management. If nuclear plants were less complicated, their construction would place fewer demands on their designers and builders. Insofar as safety is responsible for these complications and resulting management inadequacies, one can, at least indirectly, attribute to safety concern a large share of the cost overruns experienced by some unfortunate nuclear projects.

Public attitudes toward nuclear power, reflected in an ambivalent Congress and sometimes hostile state and local governments, reflect the impact of Three Mile Island and cost overruns. Polls show that less than half the public favors expansion of nuclear power.[17] The concerns most often cited are about reactor safety, cost, and nuclear waste disposal.

Nuclear reactors now being built often appear to their owners to be very expensive, complex and demanding, and beset with uncertainty. Based on a survey made by the NRC in 1981,[18] it appears that the extensive changes mandated by the NRC following TMI were, in the eyes of the utilities, thrust upon the utilities with little or no planning and frequently required use of resources in an inefficient manner. The laudable goal of increase in plant safety and reliability was frequently lost in the demand of meeting unrealistic schedules with arbitrary priorities. A recent Electric Power Research Institute (EPRI) survey[19] of 11 utilities that operate light water reactors disclosed that the 57 utility management, operating, and maintenance personnel who were interviewed believed their reactors were safe but had reservations about a number of vital points closely related to safety and operability. These points are as follows:

- NRC-mandated additions of progressively more safety-related equipment too often reduce operability, maintainability, and availability; the rather uncoordinated superposition of so many systems may often reduce rather than increase safety.
- 1200-1300 MWe plants are too large.
- Containment buildings should be larger to provide more space for maintenance.
- Present plants respond too rapidly to transients.
- Nuclear plants should be less sensitive to events in secondary systems.
- The auxiliary feedwater systems need simplification and improvement.

The complexity of these plants creates risks to the investors. The risks are compounded by lack of public support. And with electricity demand currently growing at just over 2 percent per year[20] in the United States, instead of at the historical rate of 7 percent per year, the outlook for more nuclear power plants is doubtful.

We have gone full circle. One need only read the literature of the early 1950s to realize that at that time no one knew whether nuclear power would be cheap enough to compete with coal (then selling for $4 per ton), let alone natural gas at less than 10¢ per million Btu. In the 1962 AEC Report to the President on Civilian Nuclear Power,[21] nuclear power was regarded as on the threshold of being competitive with conventional power only in the highest fuel cost areas. This period of doubt as to the economics of nuclear power was dispelled with the construction of the Oyster Creek 560 MWe boiling water reactor at a fixed price of about $348 per kWe and the H.B. Robinson pressurized water reactor at $265 per kWe (1983 $).[22] A tide of orders for reactors ensued, and by 1978, 202 reactors* were either in operation, under construction, or on order.[23]

As the cost of nuclear reactors rose and demand for electricity fell below expectations, orders for new reactors diminished. Finally we reached the present moratorium characterized by no new orders and many cancellations.

It is all too easy to dwell on the deficiencies of light water reactors revealed during the First Nuclear Era. But the accomplishments as an economical source of power must be set against these deficiencies. As we stated earlier, 13 percent of the electricity in the United States is generated with light water reactors. In 1982, nuclear power was on the average 11 percent less costly than power from coal[24] in the United States. The economic advantages of nuclear power are even greater in Europe and Japan. LWRs have produced and are producing substantial amounts of electricity reliably, with essentially no environmental impact--assuming that the waste disposal problem is eventually solved--and with no known fatalities caused by radiation.

During the past decade, demand for primary energy in the United States has fluctuated between 79 quads and 71 quads per year.[25] The average demand for the decade was 75 quads. These fluctuations are shown in Figure 1. At the same time, the fraction of energy used in the form of electricity has increased as a percent of energy demand. In 1973 the fraction was 26.6 percent, and by 1982 it had increased to 34.1 percent. Also at the same time, the absolute generation of electricity increased from 1.86 trillion kWh to 2.24 tkWh, an average annual increase of just over 2 per-cent.[26] This trend toward electrification has been scrutinized at IEA; we

---

*In the peak year 1975, 236 reactors were operating, under construction, on order, or announced in the United States.

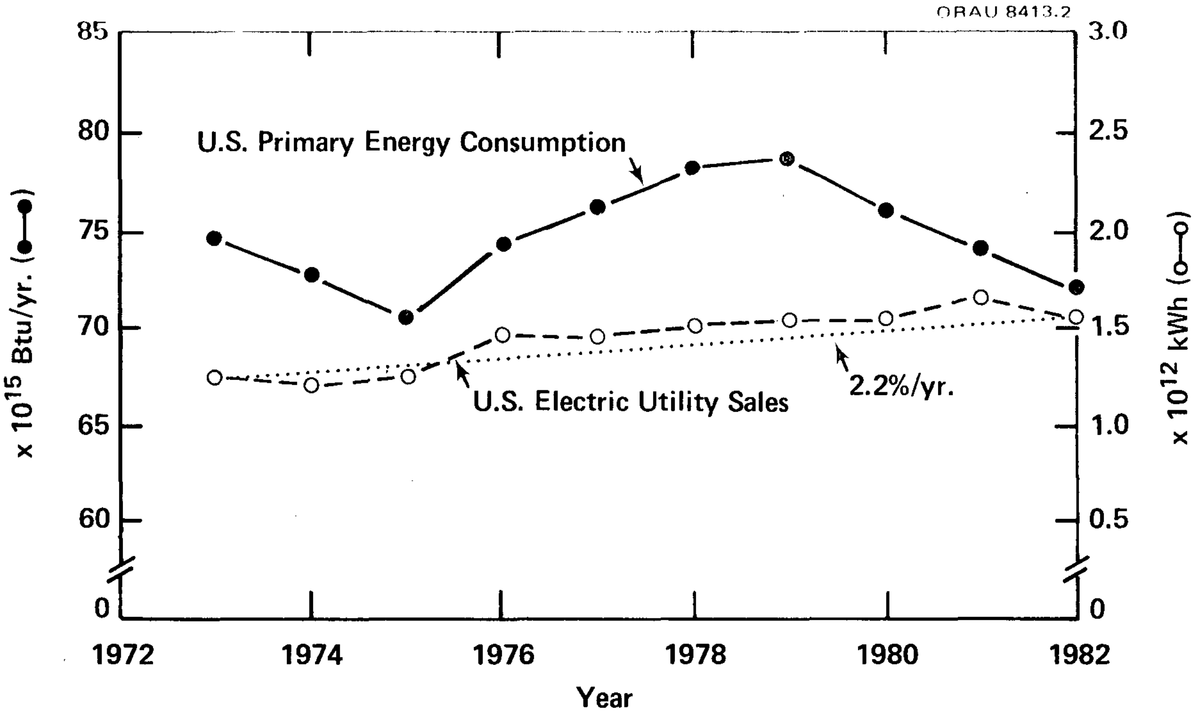


FIGURE 1. TRENDS IN ENERGY USAGE

Source: Energy Information Administration, Monthly Energy Review, DOE/EIA-0035 (83/06), June 1983, p. 80.

believe that it is likely to continue mainly because electricity is so important a factor in economic productivity. Basing the future growth of electricity production entirely on fossil fuels could introduce serious supply and environmental problems. Thus to deny a future in which nuclear energy provides an important fraction of the growing demand for electricity seems to us to be extremely imprudent. In short, as we concluded at the three workshops on nuclear power, let's fix nuclear energy, not bury it.

THE CRITERIA FOR A SECOND NUCLEAR ERA

As judged by the cancellation of many nuclear plants and the lack of new orders, utility investors and executives must regard further expansion of nuclear capacity as undesirable. Though some consider nuclear reactors to be too expensive, the main concern is about the uncertainties that surround nuclear projects: Will the Nuclear Regulatory Commission require additional backfits? How long will construction last? Will the utility be able to attract and retain the necessary specialized talent? Given the very long lead time and the uncertain projections of growth in demand, will a nuclear plant become a white elephant? Will public utility commissions honor cost overruns associated with nuclear plants? How large is the risk and how large the price of a repetition of TMI-2, even though TMI-2 caused no physical harm? What risks are introduced through potential public opposition to a nuclear project?

A Second Nuclear Era in the United States has as a prerequisite a recognition of need for additional generating capacity. No utility executive is likely to enter into new commitments for large blocks of capacity without strong increasing electrical demand and support from state agencies. One early signal of such an increase in demand would be a need for reactivation of some of the suspended nuclear projects, currently numbering ten.[27]

For nuclear energy to play its full role in the future, both a skeptical utility industry and a skeptical public must regain confidence in nuclear power. Some actions, such as demonstration of secure disposal of wastes, all agree must be taken. Fortunately, the passage of the Nuclear Waste Policy Act of 1982[28] at long last has set the stage for resolution of the waste issue. This Act levies a tax of 1 mill per kWh on all users of nuclear electricity, the tax to be used for waste disposal. By 1990 this should bring in close to $600 million per year.[29] Though one cannot expect that wastes will be handled in a fully acceptable way by then, one can at least say that the matter is now receiving considerable support and attention.

The unfavorable trends in nuclear plant costs must be reversed for nuclear power to regain favor in the marketplace. What magic did we possess in the late 1960s and early 1970s that allowed us to build plants that were cheap and are still regarded as adequately safe? Why does the industry not consistently run plants at a 65 percent or a 70 percent capacity factor instead of 55 percent? Still, one must realize that many of the reactors soon to go into operation are good economic bets. The alleged poor economics of nuclear plants is not based on the performance of the most successful plants but on the performance of the poorest. But for the utility executive who must decide whether to build or not, this gives little comfort: How does he know that his new plant will be among the best, not the worst?

Some of the uncertainty would be removed if the regulation of nuclear power were both more flexible and more reasoned. For example, when a deficiency is discovered in a particular plant, all existing plants are usually required to retrofit to remedy the deficiency. In some cases, as in the requirement for an unequivocal measurement of the water level in a PWR, such retrofitting seems entirely reasonable. On the other hand, where a retrofit simply assures conformance with an existing regulation, which is itself quite arbitrary, such action can be regarded as overly rigid. For example, was the NRC justified in requiring extensive reinforcement of vessel supports to prevent vessel motion in response to a highly improbable large pipe break at a particular location? Or when TMI-1 was ordered to remain closed for years when other reactors of the TMI-2 type were allowed to operate, was this action motivated by a clear notion of what was thereby accomplished, or was it a rather capricious action prompted by the public and political upheaval caused by TMI-2? One would hope that a reborn nuclear energy industry could enjoy a regulatory system that is less subject to arbitrary decisions.

The central questions addressed by the Second Nuclear Era study are If future reactors are intrinsically safer than today's LWRs, would the nuclear industry be better off? And do plausible concepts exist for such forgiving reactors, either based on improved LWRs or on totally different combinations of coolant and moderator? In focusing on these questions, we make an underlying assumption: The frustrations over regulation, the mounting costs of reactors, and the public's disaffection with nuclear power are, in final analysis, traceable to concern over the 15 billion curies of radioactivity contained in a 1000 megawatt LWR. The radioactivity can never be avoided. But if one could design a device that would make a TMI-2-like incident essentially impossible, would not much of the current regulatory system be superfluous; would not the public's aversion to nuclear energy be reduced; and insofar as such concerns ultimately are reflected in high cost and risk, would not utilities once more regain their interest in nuclear power?

When IEA undertook this study, we realized that incremental improvements in LWRs afforded a path to safer reactors, and so much of our study has been devoted to assessing how safe LWRs have become because of post-TMI retrofits. The improvements in LWRs have been impressive--so impressive, we believe that nuclear power, as compared with other risks, is very safe. We realize that such a judgment, made by a group who has long been tied to the nuclear enterprise, might appear biased. Moreover, we must also concede we adopted the stance that certain threats--acts of war, earthquakes beyond a certain size, sabotage, acts of terrorism--are too farfetched to be considered in design standards. Yet, unlikely though they may be, one cannot give a totally compelling reason for ruling such events to be irrelevant: a Second Nuclear Era might last for a long time; events that on a short time scale may be regarded as too unlikely to occur, on a scale of hundreds of years, might be worthy of attention.

In the long run, it would make sense to have a totally forgiving reactor that is resistant to these very unlikely threats. Not all operators of nuclear power plants are equally competent. Utilities in countries with weaker technological traditions could not be expected to bring resources to their nuclear operations as strong as those of utilities in countries that have a strong technological tradition. Thus reactors that make fewer demands on the competence of their operators, constructors, and regulators would make nuclear power available in many more settings than is now practicable.

Fossil-fueled power plants are used in every country and by every utility; nuclear power plants are largely confined to those countries and to those utilities that have reached a high level of technological sophistication. That the technologically weaker countries may be prone to political instability strengthens the case for a reactor so forgiving that it could survive essentially any level of violence short of an attack with nuclear bombs.

We therefore have focused part of our study on a search for reactors that are intrinsically more forgiving than is the LWR--that is, reactors that depend for their safety, not on the intervention of safety devices, but rather on physical principles. We studied several such concepts, notably the ASEA-ATOM Process Inherent Ultimately Safe reactor (PIUS)[30] and the small, modular, high-temperature gas reactor.[31,32] We also reviewed, very briefly, a few other ideas, some of them very old, for inherently safe reactors. In all instances, inherent safety is achieved by providing the reactors both with much more thermal capacity than LWRs possess and/or a means for rendering a gross loss of core cooling impossible.

In addition, we examined other types of commercial reactors--notably the high-temperature gas reactor (HTGR) and the Canadian deuterium-uranium reactor (CANDU). We are grateful both to GA Technologies for its paper on HTGR safety,[33] and to Atomic Energy of Canada Limited and Ernest Siddall for a paper on *CANDU* safety.[34]

Can a reactor be both intrinsically safe and affordable? Unless a forgiving reactor is affordable, no one will buy it. Of course, the balance between safe as possible and cheap as possible cannot be drawn once and for all, and for every country. Sweden, which has mandated a phase-out of nuclear power by 2010 and which has no indigenous fossil fuel, might be prepared to pay more for a very safe reactor than would the United States with its abundant coal. Nevertheless, we recognize the cost of a potentially forgiving reactor as being primary. We would contribute little to resolving the nuclear dilemma were we to recommend reactors that are too expensive, no matter how safe they are. Economic criteria must be met in the Second Nuclear Era just as they had to be met in the First Nuclear Era. Unfortunately, the ultrasafe reactors we have examined are mostly concepts, not realities. Whether they would be competitive, therefore, will remain uncertain until more work has gone into their design.

Another requirement for a Second Nuclear Era is more consistent and understandable regulation. Nevertheless, we are unconvinced that regulatory inadequacy per se is the central difficulty. In a democracy, a technology that is viewed as dangerous by half the public simply cannot be regulated in a way that all participants will consider fair and responsible. This situation will change only if the technology, as perceived by the public, is regarded as no longer threatening. We cannot say how much the technology must improve to accomplish this change in public attitude; safe and reliable operation during the next decade should be crucial. Improvements in the technology--either incremental (including standardization) or drastic--ought to convince all but the most doctrinaire that nuclear energy can be an acceptable source of energy.

Such technological improvements will avail us little in the Second Nuclear Era if the regulatory agency takes no heed of them. Intrinsically safe reactors would not require the regulatory scrutiny nor the prescriptive style that is now the rule. But whether the existing regulatory apparatus will accommodate itself to such technological improvements remains to be seen.

Other institutional reforms have been subjects of study at IEA during our Acceptable Nuclear Future project;[35,36] they remain relevant for the Second Nuclear Era. For example, we continue to find merit in a concentrated siting policy with most new reactors being added to existing sites: the ultimate configuration might then resemble that of Canadian, French, Soviet, or Japanese design with as many as 8 reactors on each of 100 sites, most being expansions of existing sites. Consolidation of utilities and companies engaged in operating and constructing nuclear reactors appears to us to be inevitable. Eventually in the United States one might contemplate twenty such companies rather than the 60-odd utilities now so engaged. Measures such as this are ultimately aimed at increasing the flow of information within the nuclear community so that never again need a TMI-2 happen without the operators knowing that very similar precursors had occurred at Oconee, Rancho Seco, and Davis Besse. But we do not pretend in this study to have done justice to all these institutional issues, nor have we examined in full detail waste disposal and fuel assurance, issues that will surely require resolution in a Second Nuclear Era. Our task was to examine possible technologies for a rebirth of nuclear energy based on forgiving reactors.

THE PLAN OF THIS REPORT

This report of the Second Nuclear Era study is divided into four chapters. Chapter I has summarized what went wrong with the First Nuclear Era and given the criteria for a Second Nuclear Era. Chapter II is a discussion of the technical and economic issues, including a summary of the available reactor technologies, a review of reactor safety, a summary of reactor economics, and a discussion of the nuclear fuel cycle. Chapter III is a discussion of the institutional issues. Finally, Chapter IV is a summary of the results of the study, presenting the conclusions and recommendations. There is an addendum giving comments by members of the Advisory Committee.

The main body of the report is augmented by a series of supporting papers presenting the studies on which many of our findings are based. Readers who wish to go more deeply into the technical justifications for our conclusions would do well to study these papers, lengthy though they may be. The following is a list of the supporting papers:

Technology of Reactors

K. Hannerz. 1983. *Toward Intrinsically Safe Light Water Reactors*, Research Memorandum, ORAU/IEA-83-2(M)-Rev. Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 105 pp.

C. Fisher, P. Fortescue, **A.J. Goodjohn**, B.E. Olsen, and F.A. Silady. 1984. *The HTGR--An Assessment of Safety and Investment Risk*, GA-C16928, prepared by GA Technologies, 1983, to be published as a Research Memorandum. Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 101 pp.

E. Siddall. 1984. *The CANDU-PHW Reactor in Relation to a Second Nuclear Era*, Research Memorandum, ORAU/IEA-83-11(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 21 pp.

A.P. Fraas. 1984. "Survey and Assessment of the Technological Options Available to the Nuclear Industry in the 1980 to 2000 Period," prepared for the Office of Technology Assessment, 1982, to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 40 pp.

Economics, Safety, and Other Technical Issues

D.L. Phung. 1984. *Review of Light Water Reactor Safety Through the Three Mile Island Accident*, Research Memorandum, ORAU/IEA-84-2(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 114 pp.

D.L. Phung. 1984. *Assessment of Light Water Reactor Safety Since the Three Mile Island Accident*, Research Memorandum, ORAU/IEA-84-3(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 193 pp.

A. Weinberg. 1984. "Waste Management in the Second Nuclear Era," to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 12 pp.

D. Phung. 1983. Economics of Nuclear Power: Past Record, Present Trends, and Future Prospects, Research Memorandum, ORAU/IEA-83-13(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 36 pp.

I. Spiewak. 1984. An Investigation of the Nuclear Source Term, to be published as a Research Memorandum, ORAU/IEA-84-5(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 23 pp.

I. Spiewak. 1984. Option for the Assurance of Nuclear Fuel Supply, to be published as a Research Memorandum, ORAU/IEA-84-4(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 16 pp.

Institutional Issues

J. Barkenbus. 1983. Prospects and Opportunities for Nuclear Power Regulatory Reform, Research Memorandum, ORAU/IEA-83-5(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 75 pp.

J. Barkenbus. 1984. "An Assessment of Institutional Alternatives for Nuclear Power," prepared for the Office of Technology Assessment, 1983, to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 49 pp.

I. Tiren. 1983. Safety Considerations for Light Water Reactor Nuclear Power Plants: A Swedish Perspective, Research Memorandum, ORAU/IEA-83-7(M). Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 42 pp.

E. Siddall. 1984. "The Future of the Nuclear Energy Industry (Thoughts on Alvin Weinberg's 'Second Nuclear Era')," to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 11 pp.

E. Epler. 1984. "Optimization of Prevention vs. Mitigation for Minimum Risk," to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 35 pp.

CHAPTER II: TECHNICAL AND ECONOMIC ISSUES

TECHNICAL PATHS TO A SECOND NUCLEAR ERA

Present-day light water reactors, evolutionary improvements to those reactors, high-temperature gas-cooled reactors and heavy water reactors, as well as inherently safe reactors are all possibilities for use in the Second Nuclear Era. This section describes the technical characteristics of these devices.

As we have indicated in Chapter I, the most important criteria for choice of reactors in a Second Nuclear Era are safety and low cost. Other criteria are commercial availability, ease of licensing, and operability, though the latter is extremely difficult to assess.

Pressurized Water Reactors (PWRs)

A large number of pressurized water reactor designs have been built or proposed. Large "conventional" PWRs are currently offered by Westinghouse and Combustion Engineering in the United States, by Framatome in France, by Kraftwerk Union in Germany, by Mitsubishi in Japan, and by the Soviet Union. We cannot cover all of these designs and shall limit our discussion to a few that illustrate trends. These are the Westinghouse Sizewell B design, the Combustion Engineering System 80, the Kraftwerke Union PWR, the Westinghouse Advanced PWR, the Westinghouse Two-Loop Plant, and the Consolidated Nuclear Steam Supply of Babcock and Wilcox.

The Sizewell B Reactor

In the early 1970s, Westinghouse, together with a group of U.S. utilities and Bechtel, evolved a standard PWR design, SNUPPS.* SNUPPS is a conventional Westinghouse four-loop reactor with vertical U-tube steam generators and is typical of today's U.S. plants (Figure 2).[37] The first

---

*SNUPPS: Standardized Nuclear Unit Power Plant System

ORAU 8413.4

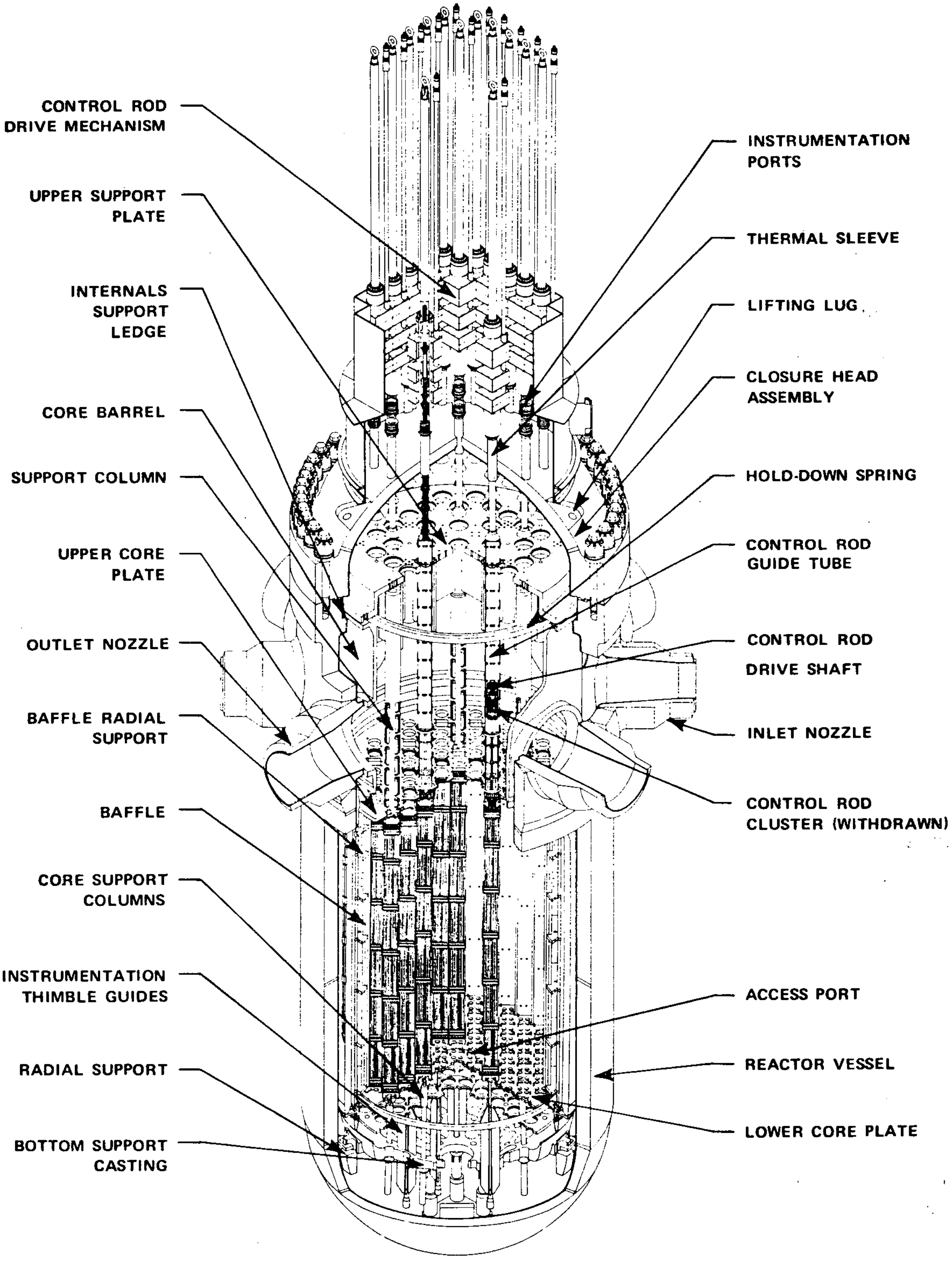


FIGURE 2. REACTOR VESSEL INTERNALS OF LARGE PWR PLANT

Source: Westinghouse Electric Corporation, Systems Summary of a Westinghouse Pressurized Water Reactor Nuclear Power Plant, (Pittsburgh, Pennslyvania, 1971), p. 40 (reproduced with permission).

plant of this series is Callaway, scheduled for operation in 1984. Unfortunately, the other SNUPPS plants have been canceled.

SNUPPS incorporates two independent reactor shutdown systems with a backup emergency boration system, two high-pressure and two intermediate-pressure emergency core cooling pumps, and three diverse auxiliary feedwater supply systems to help remove residual heat from the steam generators. Most of these features are present in other Westinghouse LWRs, and SNUPPS may be regarded as being typical of modern Westinghouse PWRs. The core-melt probability of these plants as calculated by probabilistic risk assessment (PRA) is usually in the range 10^{-4} to 10^{-5} per reactor year.[38]

An improved version of the SNUPPS design, and one in which the greatest attention has been given to safety, was prepared by the Central Electricity Generating Board (CEGB) in the United Kingdom for a plant designated Sizewell B. To meet the stringent requirements posed by the high population density in the vicinity of the site, the CEGB made an intensive five-year study[39,40] of the reactor safety problems and the measures that might be taken to minimize the probability of an accident. This study was exceptionally thorough and included the exploration of a wide range of possibilities and much new design work.

The Sizewell B design[41] has increased safety above that of the SNUPPS (Callaway) design with the following additions:

1. Four high-pressure safety injection (HPSI) pumps dedicated to safety, each with heads lower than 2000 psi and with higher flow volumes than Callaway's. The actuation of the HPSI pumps will automatically shut down the higher head charging pumps, thus preventing overpressurization in overcooling transients.

2. Four accumulators, any two of which are sufficient for core cooling at the 600 psi pressure range (instead of the required three at Callaway).

3. Four low-pressure pumps to recirculate water for core cooling at low pressures and for the containment sprays. These pumps are dedicated to residual heat removal. In addition, the high-pressure HPSI suction is automatically switched to the containment sump when the refueling water storage tank is low. In older Westinghouse reactors, including SNUPPS, such switching to this backup source of water must be done manually.

4. An additional steam-driven auxiliary feed pump, in addition to the two electric pumps already in SNUPPS. All the pumps are farther apart than at Callaway and are therefore less subject to common-mode failure.

5. Four diesel generators (instead of two) to provide emergency power in the case of loss of offsite power.

6. A microprocessor-based reactor protection system backed up by a secondary protection system based on solid-state switches.

7. An emergency boration system as a backup reactor trip system to cope with anticipated transients without scram.

8. An extra diesel-driven emergency charging pump to make up for pump seal leakage during station blackout.

9. An additional isolation valve between the high-pressure reactor cooling system and the low-pressure residual heat removal system to minimize the chance of the containment bypass accident sequence (the so-called V sequence).

10. Connections to provide water from fire pumps to containment safety features.

11. construction of ring forgings with no major welds in the beltline region of the reactor pressure vessel to minimize the chance of vessel brittle failure due to irradiation and overcooling transients.

12. A secondary containment vessel to further reduce the probability of an escape of radioactive material to the environment.

The probabilistic risk assessment for the Sizewell B reactor gives a mean core-melt probability of 1.1×10^{-6} per reactor year,[42] about two orders of magnitude below that of a typical U.S. reactor. The probability of a large release of radioactivity is estimated to be 3×10^{-8} per reactor year.[43] The cumulative impact of the measures designed to improve safety beyond that of the standard SNUPPS design has been estimated to increase the power plant capital cost about 20 percent.

The Combustion Engineering System 80 PWR

Combustion Engineering supplies a standard reactor with vertical U-tube steam generators, functionally equivalent to the standard Westinghouse system.[44] Their design uses four pumps and two steam generators. The first System 80 plants expected to become operational are the Palo Verde reactors. The System 80 protective instrumentation includes computers that monitor safety-related parameters in four parallel channels to prevent spurious trips and to retain high plant availability. The control rod design provides a large amount of control to maintain subcriticality at low temperatures without the presence of soluble boron. The System 80 primary system pressure is maintained without using pilot-operated relief valves, which have been a source of operational problems at some PWR plants (including Three Mile Island 2).

The Kraftwerk Union PWR

Kraftwerk Union (KWU) in Germany has followed design practices somewhat different from those in the United States in developing their line of PWRs. These differences stem in part from the greater population density in Germany producing an even greater desire for engineered safety features. KWU employs both a lower power density and a lower heat flux in the reactor core than in U.S. PWRs[45] (93 kW per liter versus 102 kW per liter and 48 W per cm^2 versus 68 W per cm^2, respectively). The KWU containment is backed by a secondary containment, and the containment vessels are larger, making it possible to separate equipment and hence reduce the chance of common-mode failure. The reactor pressure vessels are made larger to reduce the fast neutron dose to the steel (by a factor of about 3 to 5), and the vessels are made of forged rings to eliminate axial welds at the reactor beltline region where radiation fluence is high. In addition, there is more separation of functions in the auxiliary systems and more capacity of the components. There are four independent primary reactor cooling circuits, for example, each with its own circulating pump and steam generator and each equipped with sufficient capacity in the pumps and tanks of its emergency feedwater system to remove at least half of the afterheat under emergency conditions. This equipment, together with a dedicated set of diesel generators to provide emergency power, is housed in a special shielded building. Both this building and the main reactor containment structure are designed to withstand the impact of an aircraft crash directly on the buildings. These buildings are also designed to withstand both severe earthquakes and attempted sabotage.

Throughout the plant there is extensive use of both redundancy and diversity in the instrumentation, controls, and auxiliaries. These measures are coupled with much physical separation to minimize further the possibilities and/or effects of common-mode failures. (German regulations require greater protection against common-mode failures than do those in the United States.) These features, coupled with the measures outlined above, have led to a core-melt probability, as estimated by PRA, of 10^{-5} per reactor year[46] for accidents that might cause serious core damage.

Studies at Karlsruhe and KWU[47] indicate that the probability of activity release from the containment system in the event of severe core damage is very low--of the order of 10^{-4}. Their analyses indicate that at least five days would be required for the pressure in the containment vessel to build up to the point where cracks would develop and leakage could start. Further, in the event of such a release, the amount of activity that would escape would be attenuated by factors of as much as 10^6[48] because iodine and cesium would remain dissolved in water and aerosols would largely settle or plate out.

The Westinghouse Advanced PWR

The Advanced PWR (APWR)[49] is a joint effort of Westinghouse and Mitsubishi Heavy Industries, intended initially for the Japanese market. It represents a further evolution of the Westinghouse four-loop design toward rather ambitious objectives: 90 percent plant availability, 20 percent savings in fuel cost, resistance to an 0.7 g earthquake, reduced public and occupational risk, load following capability, and capital cost at conventional levels.

Fuel utilization in APWR is improved by means of movable zirconia rods that displace water moderator and thereby adjust the neutron spectrum.

The safety system includes four high-pressure pumps, four accumulators (actuated at 600 psi), four core reflood tanks, four low-pressure pumps, four heat removal exchangers, two emergency letdown heat exchangers, two refueling water storage tanks, two spray additive tanks, and one emergency water storage tank. Safety systems are separated more widely than in earlier Westinghouse designs. The secondary side of the steam generators can be equipped with four dedicated, passive, condensers and water storage tanks which enable the plant both to withstand a complete load rejection without actuating the primary relief valve, and to provide decay heat removal through the steam generators. The APWR containment is dry but has sumps normally filled with water to increase the heat absorption capacity and to ensure supply of water to the emergency pumps. The core-melt probability of the APWR is about 10^{-6} per reactor-year.[50]

The Westinghouse Two-Loop Reactor

Westinghouse offers a two-loop, 640 MWe PWR based on the design of a reactor[51] being built in the Philippines. The scope of supply is broader than the nuclear steam supply system and includes key safety-related items usually considered "balance of plant." The two-loop plants have operated much more reliably worldwide than the larger plants and are claimed by the vendor to be as economical as the larger plants.[52] They may appeal to utilities experiencing slow load growth or those that believe 1200-1300 MWe plants are too large, as stated in the EPRI utility survey.[53]

The Consolidated Nuclear Steam Supply

The Consolidated Nuclear Steam Supply (CNSS) is a conceptual design for a 400 MWe PWR[54] developed by the Babcock & Wilcox Company and United Engineers & Constructors, Inc. The study was undertaken because of the anticipated advantages provided by a small, modular, standardized nuclear system: shorter lead time, greater certainty of capital costs, lower financial risk, maximum amount of shop fabrication, and simple safety features. The CNSS is an integral PWR with steam generators within the reactor vessel and pumps located vertically in the vessel head. The designers consider this type of design to be particularly economical for a period of low and uncertain electrical load growth.

Boiling Water Reactors (BWRs)

The two main suppliers of BWRs worldwide are the General Electric Company (GE) and ASEA-ATOM of Sweden. Hitachi and Toshiba supply BWRs in Japan, and KWU, in Germany. Boiling water reactors are supplied competitively with pressurized water reactors over roughly the same size range. They are illustrated by the BWR/6 and the Advanced BWR.

The BWR/6 Design

The BWR/6 is the current GE reactor system (Figure 3).[55] It is a direct cycle boiling water reactor with a reference Mark III pressure suppression containment. Steam is generated in the core and conveyed directly to the turbine.

A principal design feature of BWRs is the existence of a natural circulation flow path within the reactor vessel so that there is adequate coolant flow capacity for removing the afterheat from the core by natural thermal convection as long as the water inventory in the reactor vessel is maintained at the proper level. Further, the BWR primary system can be

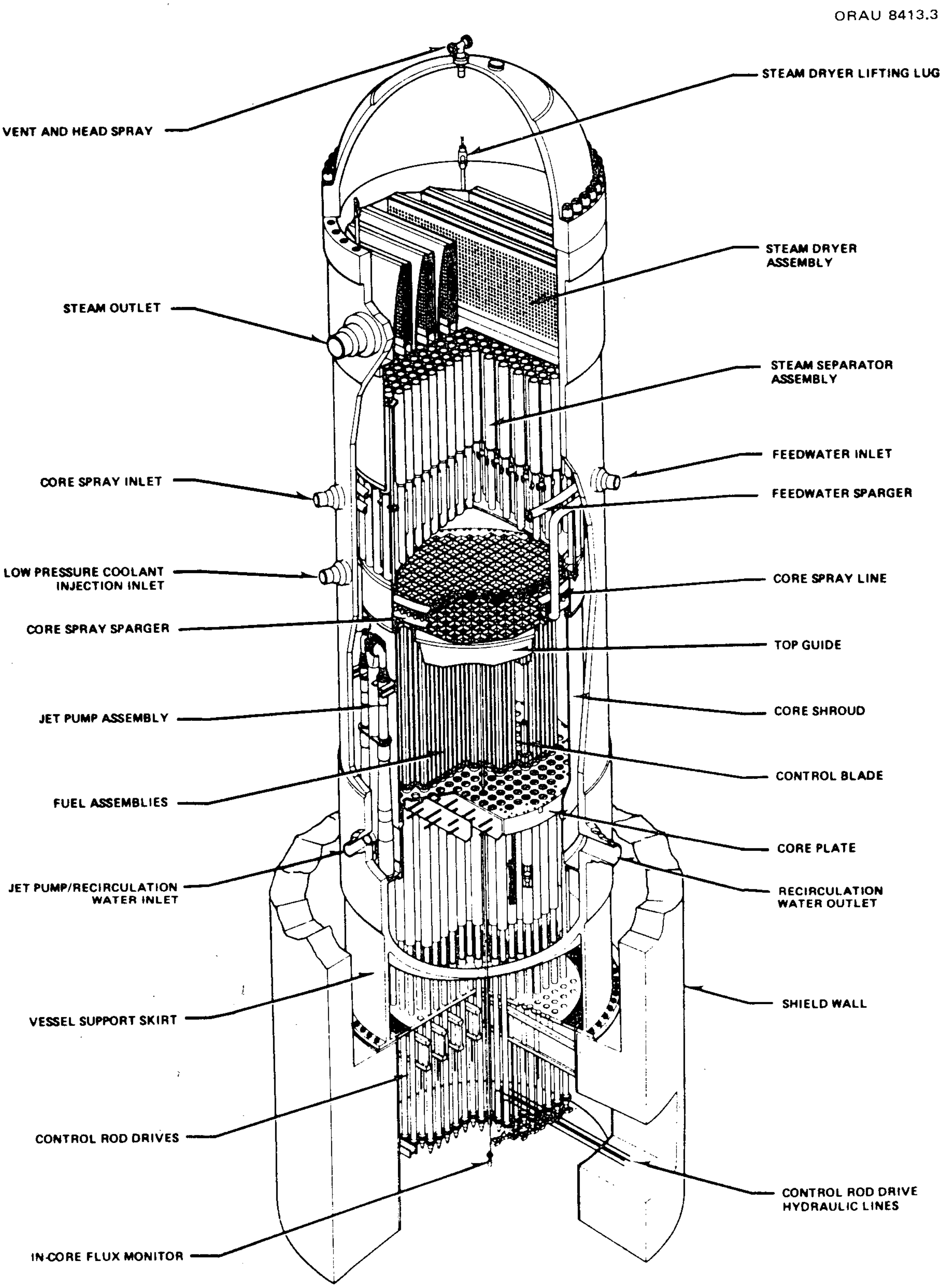


FIGURE 3. BWR-6 REACTOR ASSEMBLY

Source: General Electric Company, <u>BWR/6 General Description of a Boiling Water Reactor (Rev.)</u> (San Jose, California, 1980), p. 2.2 (reproduced with permission).

depressurized rapidly; low-pressure as well as high-pressure pumps can therefore be employed to maintain the proper water level in the reactor vessel. There are a total of 13 pumps in the BWR/6, 11 of which can individually handle nonbreak transients.

Other improvements include increased redundancy and separation of functions. These changes have resulted in a marked reduction in the probability of core melt for an accident that could result in severe damage to the core.

The Mark III containment is the latest version of the pressure suppression containments used on all but the very earliest BWRs. Pressure suppression containment systems employ a large pool of water (the suppression pool) and a system of vents leading from the reactor cavity to the suppression pool. Following a postulated reactor primary system rupture, steam and fission products released from the reactor will be channeled to the suppression pool. Experiments show that the bubbling of these materials through the pool should remove over 99 percent of the iodine and particulate fission products from the vented gases. Thus the vast majority of the radioactive fission products that might escape from the core in the event that severe core damage did occur would be retained within the primary containment system. The Mark III containment building has been enlarged and strengthened relative to earlier designs, and potential bypassing of the suppression pool has been eliminated.

From all this, it follows that not only is the probability of an accident that would cause severe damage to the core very low (about 5×10^{-6} per reactor year claimed by General Electric for the BWR/6[56] versus about 3×10^{-5} for the Peach Bottom 2 plant, an earlier BWR), but if such an accident were to occur, the probability of the escape of substantial quantities of fission products to the atmosphere would be exceedingly low.

The Advanced BWR

The Advanced BWR (ABWR)[57] is being developed for use in Japan by GE in partnership with Hitachi and Toshiba. The key feature of the ABWR is the use of in-vessel pumps for recirculation flow, a design that has been used successfully by ASEA-ATOM and KWU. The troublesome external recirculating piping can be eliminated, considerably reducing the size of the maximum pipe rupture which can occur. Another feature is the use of redundant electric and hydraulic fine motion control rod drives. Steam bypass capacity has been increased from 35 percent in the BWR/6 to 100 percent, thereby improving the ability of the BWR to respond to turbine trips. The design emphasizes increased redundancy, diversity and physical separation of systems, and multiplexing of the instrumentation.

The ABWR is expected to be more operable and safer than the already very safe BWR/6. Reduced exposure for the plant operators during maintenance is also expected.

Heavy Water Reactors--The CANDU-Pressurized Heavy Water Reactor

The CANDU reactor has been operated successfully by Ontario Hydro since 1968, when the 206 MWe Douglas Point reactor started. The four-unit Pickering station (515 MWe per unit) that started up in 1971[58] has been at or close to the top of the list of the world's reactors when ranked according to plant availability. A total of 16 CANDU-type reactors are in commercial operation in four countries.[59]

The CANDU reactor is a heavy water moderated, pressurized heavy water cooled reactor.[60] The core consists of an array of horizontal pressure tubes surrounded by a low-pressure calandria containing the relatively cool moderator (Figure 4). Natural uranium zircaloy-clad fuel bundles are loaded and removed from the pressure tubes during operation by fueling machines operating at the two faces of the core. Heat is transferred from the heavy water primary system to a light water secondary system in vertical U-tube steam generators.

ORAU 8413.6

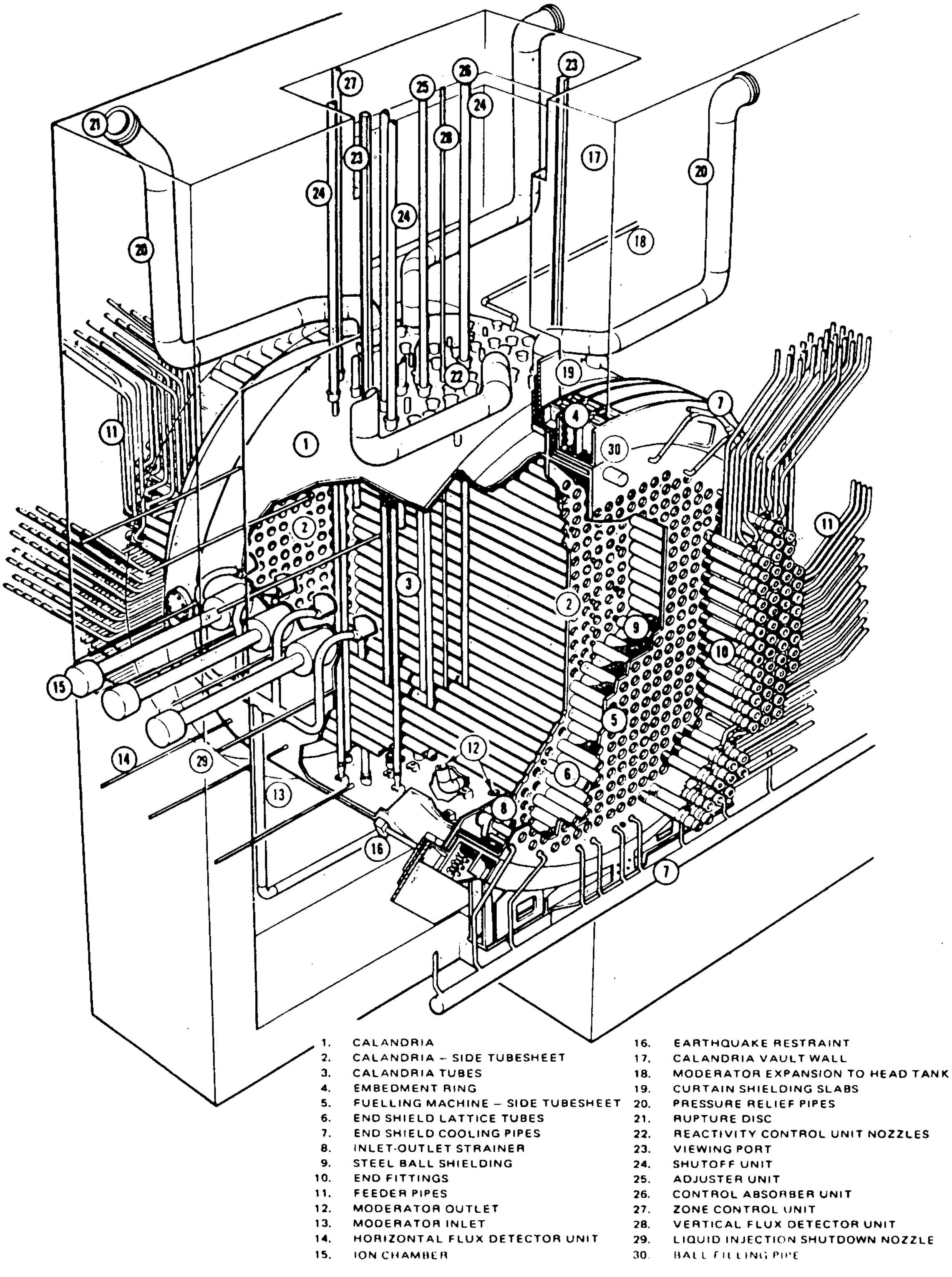


FIGURE 4. CANDU REACTOR ASSEMBLY

Source: E. Siddall, The CANDU-PHW Reactor in Relation to a Second Nuclear Era, Research Memorandum, ORAU/IEA-83-11(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984), p. 80.

Control of the CANDU reactor is maintained primarily through on-stream refueling. Computers control the routine plant operation.

The CANDU reactor is subject to many of the same potential accident initiators as a PWR. However, transients would generally occur more slowly because of the large thermal inertia of the moderator and pressure tubes. No PRA of a CANDU reactor has yet been reported, but it would be expected to be in the same range as that of a PWR.

The capital cost of a CANDU plant has been estimated to be about one-third higher than that of a light water reactor,[61] the main difference being the cost of the heavy water. The range of light water reactor capital cost is sufficiently broad, however, that comparisons are uncertain.[62] The overall economics of light and heavy water reactors are about the same in view of the high availability and low fuel cost of the CANDU.

Recent studies[63,64] of "U.S. CANDU's" have been conducted by DOE and by EPRI. These studies indicate that CANDU reactors could be built and licensed for operation in the United States but some design and licensing decisions could prove difficult. The pressure tubes, which contain full primary system pressure, do not currently conform to the American Society of Mechanical Engineers Pressure Vessel Code. If the tubes were required to have thicker walls, then slightly enriched fuel would be preferred to natural uranium. (The longer burnup achievable with enriched fuel gives it an economic advantage over natural uranium fuel in any case.) Other features which would be novel to the NRC include the seismic analysis of the core, the use of on-stream refueling and security problems related to continuous fuel handling, and computer control of the reactor.

The High-Temperature Gas-Cooled Reactor (HTGR)

The experience gained in the operation of the Dragon Reactor in England, the Peach Bottom I Reactor of Philadelphia Electric, the Arbeitsgemeinschaft Versuchs-Reaktor (AVR) in Jülich, Germany (all three were experimental reactors), and the Fort St. Vrain prototype reactor near

Denver provide a good basis for assessing the operability, maintainability, safety, and costs of high-temperature gas-cooled reactors. The reference reactor design for commercial supply is a 2240 MWt (858 MWe) HTGR being developed by General Atomic under DOE contract.[65]

The HTGR is a helium-cooled, graphite-moderated reactor assembled in a prestressed concrete pressure vessel (Figure 5). The primary system pumps and steam generators are located in cavities in the vessel. Fuel is in the form of graphite-coated uranium oxide or carbide particles in graphite blocks dispersed in a large stack of graphite moderator blocks. The superior high-temperature characteristics of the fuel and moderator allow the HTGR to generate steam at temperature and pressure conditions approximating those of modern fossil-fueled boilers.

The HTGR has some inherent safety advantages.[66] Probably most important is the relatively low power density of HTGRs--between 5 and 10 percent of that of a conventional PWR. Further, inasmuch as the fuel is dispersed throughout the moderator, the heat capacity closely associated with the fuel is over 100 times that for an LWR. Thus, in the event of an accident that interrupts the flow of coolant to the core, the elapsed time between the cessation of coolant flow and severe damage to the core (if no automatic or operator action is taken) is of the order of ten hours in an HTGR, rather than tens of minutes for a PWR--a difference of more than an order of magnitude. One factor contributing to this is that lateral heat conduction through the graphite blocks in the HTGR core is sufficient to remove a substantial fraction of the afterheat from the core and carry it out through the reflector, from which the heat is radiated to the water-cooled steel liner of the reinforced concrete pressure vessel.

The HTGR's prestressed concrete pressure vessel has redundant load-carrying steel tendons which are readily inspectable and replaceable. The tendons keep the concrete and the vessel liner in compression. The vessel is designed to withstand 2400 psi, over twice its operating pressure. Should a crack form during a pressure transient, the resulting small gas leak would tend to be sealed when the gas pressure is reduced. Thus,

ORAU 8413.5

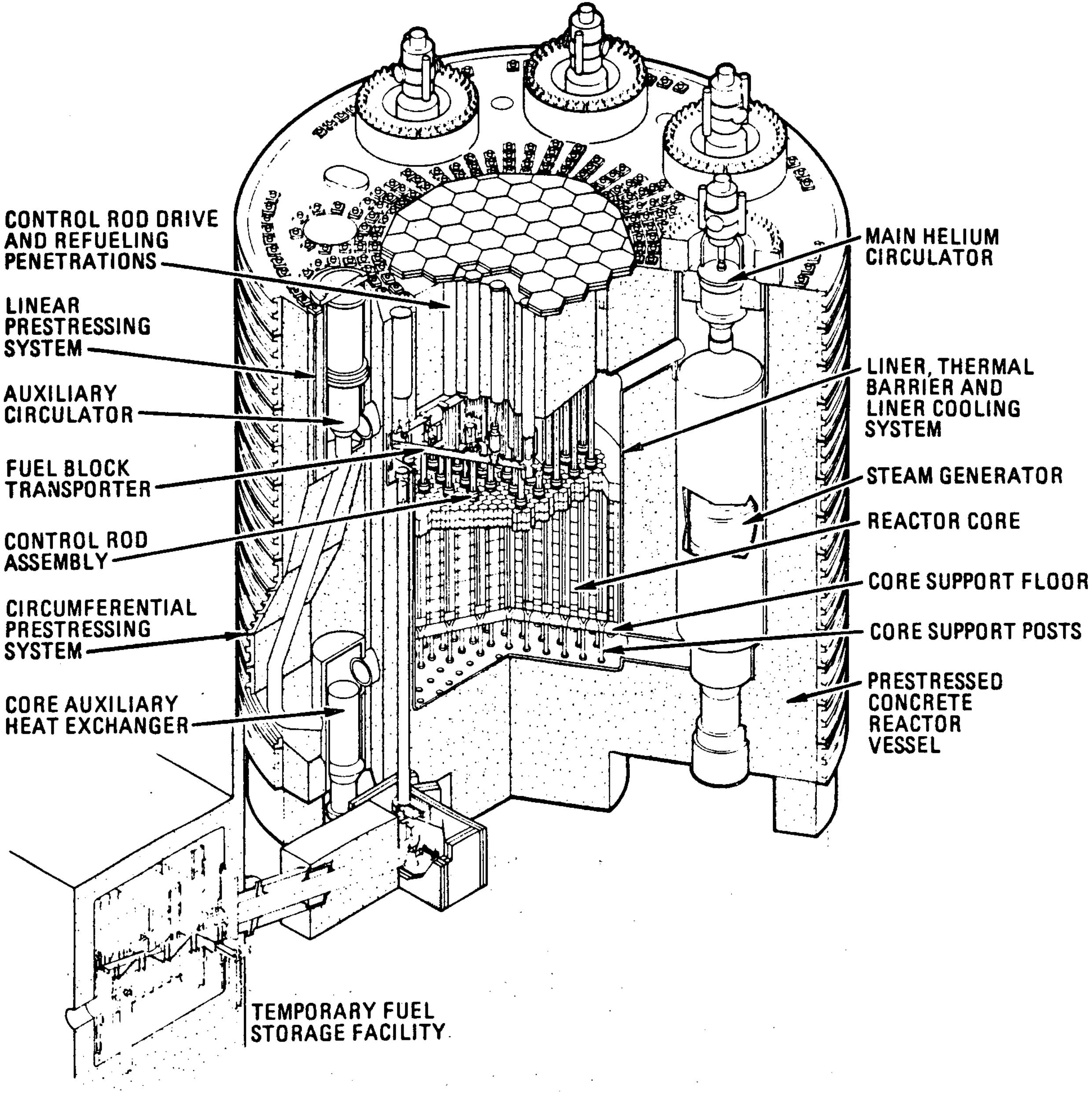


FIGURE 5. 2240 MWt HTGR NUCLEAR STEAM SUPPLY SYSTEM

Source: C. Fisher et al., The HTGR--An Assessment of Safety and Investment Risk, GA-C16928, prepared by GA Technologies, 1983, to be published as a Research Memorandum (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

catastrophic failure of the vessel is not possible under loads possibly imposed by the HTGR.

The HTGR has gravity-operated shutdown rods as well as an independent gravity-operated shutdown system. There is a dedicated emergency core cooling system for decay heat removal following a possible depressurization accident; this contains three redundant and diverse loops each capable of carrying the cooling load. Should the dedicated cooling system fail to operate, the liner cooling system (designed to keep concrete temperatures below code allowables during normal operation) is the ultimate protection for the reactor structure against a core heat-up accident.

The PRA of the reference HTGR indicates a fuel damage probability of 4×10^{-5} per reactor year,[67] comparable to those of PWRs. It should be recognized that the character of the fuel damage in an HTGR would be less severe than that in an LWR. The fuel and graphite structure remains basically as before, except some of the more volatile fission products escape the coated fuel particles into the gas stream. Severe accident analysis of HTGRs indicates that there would be damage to the heat transport systems in the event the dedicated core cooling systems fail and that there would be damage to the vessel should the liner cooling system be lost. However, most of the nonrare gas fission products are retained within the reactor vessel even in the worst accident scenario that has so far been envisioned.

Economic evaluations of the HTGR have tended to estimate its costs to be slightly higher than those of LWRs.[68] There are large uncertainties in these comparative estimates since the costs of LWRs have been increasing in response to regulatory changes while the impact of new regulations on the HTGR are often not apparent. Should the HTGR be exempt from certain regulations which are tailored to the needs of LWRs, its relative economics might be substantially improved.

The licensing of the reference HTGR could probably be readily accomplished since the NRC has licensed the Fort St. Vrain reactor and maintains an active HTGR evaluation program.

Inherently Safe Reactors

Although the previous sections indicate that by skillful design and the liberal use of redundant components and systems it is possible to evolve a system design giving a probability for a severe core-damage accident of the order of 10^{-5} per reactor year or less, the resulting systems would be very complex and the uncertainties that surround the PRA methodology are such that the absolute value of the risk is subject to debate. An alternate approach is to design a reactor that is inherently and transparently safe. The search for inherently safe reactors has been one of the main thrusts of the Second Nuclear Era study. Most of the effort has been devoted to a concept proposed by ASEA-ATOM of Sweden, the Process Inherent Ultimately Safe (PIUS) reactor. Another system which has received considerable effort is the modular HTGR. Several other concepts have been proposed but are not reviewed here in detail for lack of information.

The PIUS Reactor

In view of the Swedish moratorium on nuclear power, ASEA-ATOM decided in 1979 to go back to basic principles and design a light water reactor that would be incontestably safe to operate. Their criteria included not only safety from the standpoint of any conceivable accidents caused by equipment or operator failures but also safety from external events such as earthquakes and from sabotage or terrorist attack. This protection was to be had without calling into action any active safety equipment and without any human actions. The intrinsic protection should last a week or more to provide time for further actions to be taken. It was also desired that the plant could be operated after such an outage. Many experts have examined this new concept critically and have been unable to find any series of events, including sabotage and terrorist actions, that appear to have an appreciable probability of causing severe damage to the reactor core. Thus the system is perhaps unique and deserves special attention.

Description. The PIUS system is shown schematically in Figure 6. A large, prestressed, concrete reactor pressure vessel (PCRV) with a cavity diameter of 13 m and a cavity height of about 35 m encloses the entire primary circuit of a PWR. The containment vessel is filled nearly to the top with borated water so that virtually all of the primary circuit is immersed in a pool. The essential point of PIUS is a clever passive means of flooding the reactor with borated water if the core is in danger of losing coolant and of keeping the borated water out of the reactor during normal operation. This principle is also used in the district heating SECURE reactor, which is proposed for construction in Helsinki, Finland.

Both the primary circuit and the pool are maintained at a pressure of approximately 90 atm by the pressurizer of the primary circuit which is located in a steam region at the top of the cavity in the containment vessel. Inasmuch as the pressure drop in the primary circuit is just a few atmospheres, the envelope of the primary circuit separating it from the pool is required to carry only a small pressure differential. However, the hot primary circuit (which runs at ~270°C) must be covered with a layer of thermal insulation to reduce the heat losses to the pool water (which runs at ~50°C).

As can be seen in Figure 6, the system provides natural thermal convection since the reactor core is at the base of a hot water column about 30 m high. The density difference between the hot water in the riser above the core and the cold water in the pool is sufficient to give a pressure differential of about half an atmosphere. A large opening is provided between the primary system and the pool water at both the top and the bottom of the core-riser column. Honeycombs are provided in these open regions to inhibit convection currents, while the difference in density between the hot and cold water serves to maintain a stable position for the hot-cold liquid interface in each honeycomb under normal operating conditions.

Control. The system is designed for a constant water flow rate through the primary circuit and a constant reactor outlet temperature over

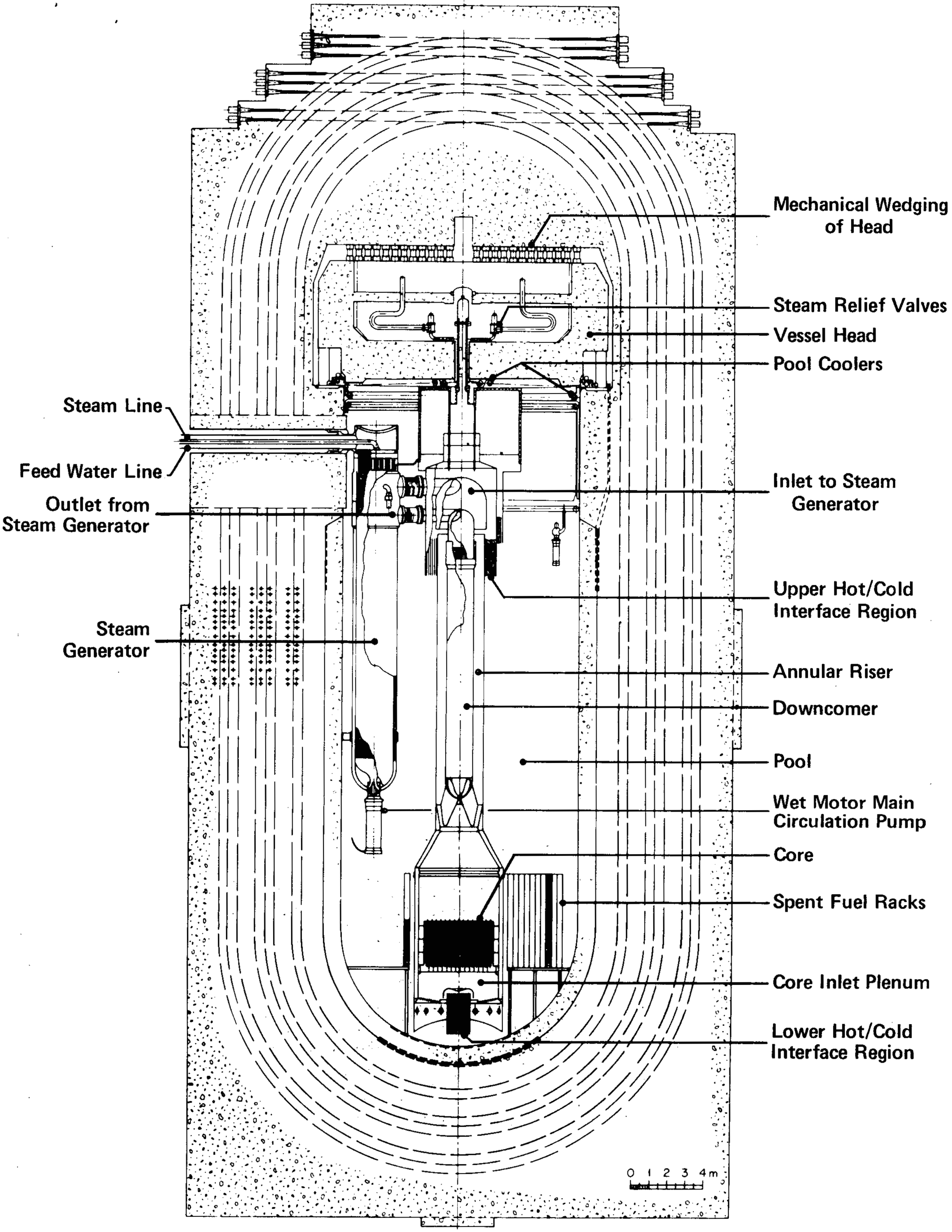


FIGURE 6. PIUS CONCRETE VESSEL AND PRIMARY REACTOR SYSTEM

Source: ASEA-ATOM, Vasteras, Sweden.

the normal range of power operation. The circulating pumps for the primary circuit provide sufficient head to overcome the pressure drop through the primary circuit including the core and riser portion. The pump speed is modulated so that the pressure head available for flow through the core and riser is exactly equal to the difference in static head between the hot liquid in the core-riser column and the cold liquid column in the pool. Maintaining a constant water flow and a constant reactor discharge temperature means that the reactor inlet temperature drops as the power increases. The static pressure differential between the pool and the core-riser column does not have to be exactly balanced because the height of the honeycomb region is approximately 1.5 m. This serves to accommodate small variations in the difference in head available from the circulating pumps and the static head in the pool. However, in the event of any pump stoppage caused by a loss of electric power or a bearing failure, the flow through the primary circuit pump and steam generator stops, but thermal convection through the core will begin immediately because of the differential head available for natural thermal convection up through the core and riser and back down through the pool. Of course, as soon as this heavily borated cold pool water enters the core, the nuclear reaction is quenched. Note that no instrumentation and control equipment, valves, or pumps must operate to cope with an emergency. Further, there is sufficient water in the pool so that if there were to be a concurrent failure in the circuit acting to cool the pool water, the pool water temperature could rise to the point where a pressure relief valve at the top of the containment vessel would begin to release steam, and the afterheat generated from that point on would be carried off by evaporation of pool water. The capacity of the containment vessel is sufficient to provide cooling water for a week after such an accident before the level of the water would drop to the point where the core would be uncovered. Make-up water could then be added to the pool from fire trucks.

Protection from Terrorist Attack. The reactor vessel would be covered by a huge shield plug that could be moved out of the way only with special tooling. With this shield plug in place over the reactor, the tooling would be disassembled and stored offsite so that no terrorist could employ it to remove the shield plug and sabotage the reactor. At least two days would be required to reassemble the tooling, and in that time it should be possible to cope with terrorists. An examination of this and other conceivable scenarios by several dozen experts has failed to yield any credible course of events that could lead to serious damage to the core and hence the potential for a substantial release of fission products. As a consequence, there appears to be no plausible sequence of events that could result in either serious damage to the core or a serious release of radioactivity to the atmosphere.

Crucial Problems. The principal concerns expressed by those who have reviewed the PIUS concept have been with respect to the stability and control of the interfaces between the cool pool water and the hot primary circuit (particularly under transient conditions), the capital cost of the large prestressed concrete pressure vessel, and the difficulties of maintenance through the deep water pool.

The basic design study in Sweden included the development of a digital computer model of the system and the investigation of a fairly wide variety of severe transients; the results indicated that the system was stable, and the interfaces, well behaved under every condition considered. However, the various factors affecting the position of the hot-cold interfaces are surprisingly complex for this otherwise simple system, so much so that the computer model is quite involved and its validity uncertain. The question of interface stability is being investigated experimentally by the Tennessee Valley Authority in the United States and by ASEA-ATOM in Sweden.

The problems of maintaining the primary circuit equipment inside the pressure vessel depicted in Figure 6 are certainly difficult. However, even in conventional PWRs, activity levels in the primary circuit are too high for contact maintenance; special remote handling equipment must be developed. If such equipment were developed during the detail design of the PIUS system, the overall costs of maintaining PIUS could be comparable to the costs of maintaining a PWR. The PIUS reactor would presumably avoid the continual testing and replacement of safety system components characteristic of a conventional LWR.

It is very difficult to estimate the cost of PIUS, which is still a concept and not even a design. The main new cost item in PIUS is the massive concrete pressure vessel. Although such vessels have been developed for water reactors in Sweden, the cost in a U.S. setting is uncertain. The amount of concrete and steel per kW of capacity in PIUS is expected to be in the same range as in some U.S. reactors.[69] The cost of the vessel tends to be offset by elimination of the safety systems and redundant equipment no longer required.

The commercial application of PIUS would require a staged development program to prove its feasibility and to demonstrate its licensability and operability. Since PIUS is a modified PWR, much technology already in commercial use could be applied. However, even under favorable circumstances it would take 8 to 9 years, according to ASEA-ATOM, to put a demonstration plant into operation. In view of the funding process for reactor development in the United States, we believe a realistic schedule for this country would be 12 years.

The Modular HTGR

Both Interatom in Germany and General Atomic in the United States have proposed modular designs[70,71] for a 250 MWt (100 MWe) unit that could be employed in groups, e.g., four would make up a 1000 MWt (400 MWe) plant. The small plants are similar to the large HTGR described earlier except that the primary system components can be housed in cylindrical steel vessels. The modular HTGR shares the attractive safety characteristics of the HTGR but does not require any active safety systems or human actions to protect the public in the event of an accident.

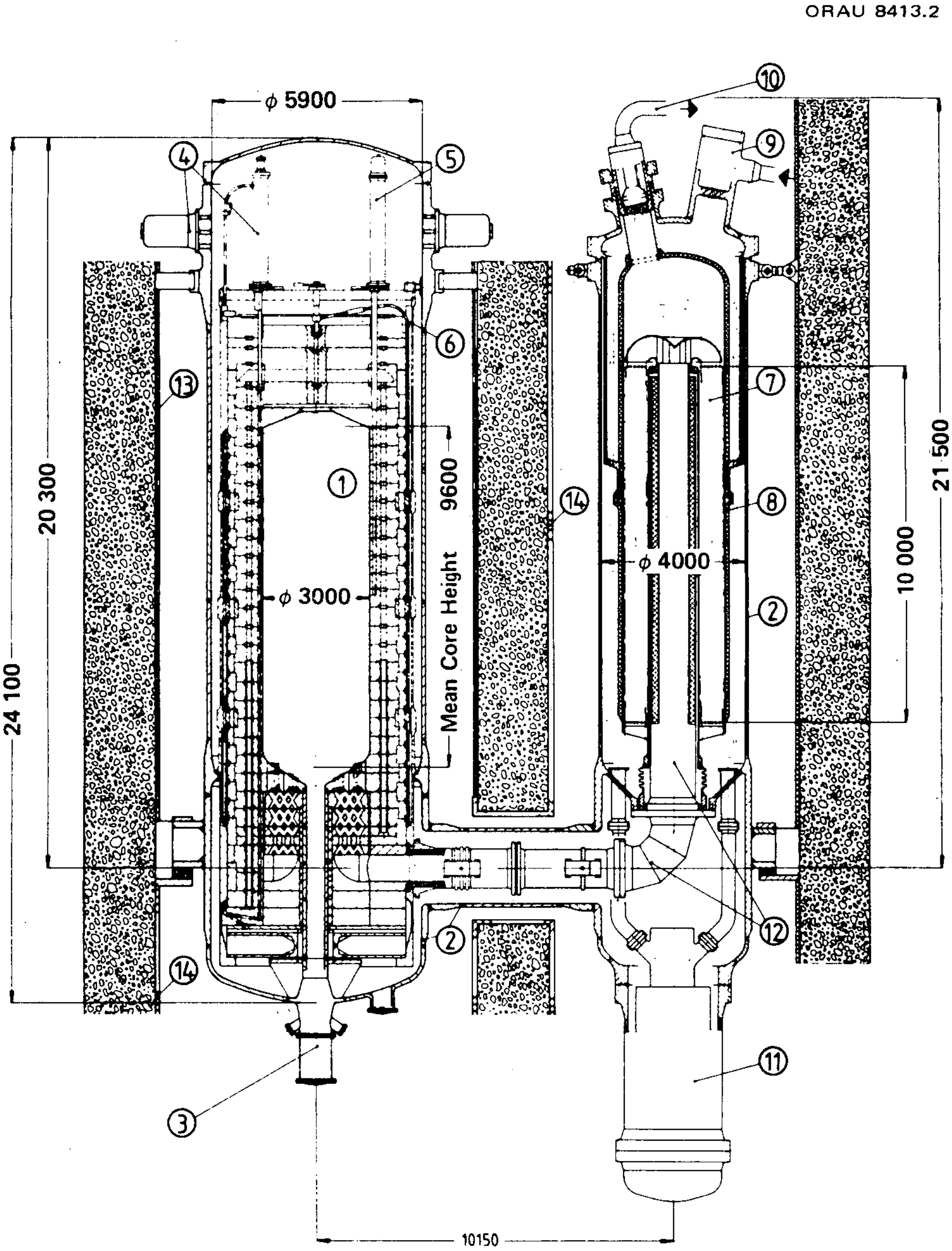
The power density in the modular HTGR is only 3 kW per liter, compared with a power density of 6 kW per liter in a standard HTGR, 60 kW per liter in a BWR, and 100 kW per liter in a PWR. Its extremely low power density confers on the modular HTGR a very high degree of safety. In the event of a loss of coolant accident, the fuel temperature will not reach a high enough level to cause any major release of fission products. This characteristic of the modular HTGR qualifies it as being inherently safe.

The German design uses the same type of pebble-bed core as has been operated successfully in the Arbeitsgemeinschaft Versuchs-Reaktor (AVR) at Jülich and is used in the Thorium High-Temperature Reactor (THTR) under construction at Hamm-Uentrop. The AVR, a 15 MWe reactor, achieved power operation in 1968 and recently operated at 950°C for extended periods. It has been subjected to a variety of transients proving the fail-safe principles claimed for the modular HTGR.

The core of the German modular reactor is placed in one vessel, while the blower and steam generator are placed in a second vessel (Figure 7). The core diameter for the modular design was limited to around 3 m so that it is possible to get adequate reactivity control with just control rods in the reflector, i.e., with none in the core. This avoids the possibility that a control rod might become ineffective because it would fail to penetrate an unfavorable fuel ball configuration in the pebble bed.

The U.S. design is similar to the German design except that the reactor core is prismatic (similar to Fort St. Vrain) and the primary system components are mounted in a single vessel.

One advantage of the small size of the modular design is that a unit could be shop-fabricated and shipped to the site. The 250 MWt (100 MWe) unit, for example, has the reactor and steam generator installed in a cylindrical pressure vessel 6.2 m in diameter and 35 m high. Shop fabrication should lead to major reductions in cost and construction time as well as yield a higher quality product. These advantages of the modular design from the cost and construction standpoints might be offset by the increase in the amount of instrumentation and control equipment needed because each of the modular units would require a full set of such equipment and some additional equipment would be needed to operate a multiplicity of units in parallel.



1. Pebble Bed
2. Pressure Vessel
3. Fuel Discharge
4. Boronated Spheres
5. Reflector Rod
6. Fuel Loading
7. Pipe Assembly
8. Outer Shroud
9. Feed Line
10. Live Steam Line
11. Blower
12. Hot Gas Duct
13. Surface Cooler
14. Insulation

FIGURE 7. CROSS SECTION OF A MODULAR UNIT FOR STEAM GENERATION

Source: R. Reutler and G.H. Lohnert, "The Modular High Temperature Reactor," Nuclear Technology, 62(July 1983):24 (reproduced with permission).

In view of the fail-safe nature of the modular plant, the German licensing authorities have ruled that the associated balance-of-plant equipment can be commercial grade as opposed to "reactor grade." This approach to licensing should improve the overall economics.

In the German design, the heat transfer systems and the reactor core are in separate vessels; this allows the plant to endure a temperature transient without serious damage to the heat transfer systems. This is not the case in the U.S. design, where all systems are in the same vessel; the more compact U.S. design should have a lower capital cost, however.

The critical uncertainties regarding the modular HTGR are the economics and commercial feasibility of the system, the scientific principles having been proven in the AVR. The U.S. Department of Energy and Gas-Cooled Reactor Associates in the United States and the German Government and KWU in West Germany are sponsoring development programs for the modular HTGR. However, the commercial potential cannot be established without the design, construction, and operation of a prototype in the 100 MWe-size range.

Aside from commercial considerations, there are some very unlikely severe accidents which may cause radioactivity releases from the modular HTGR. These would be initiated by external events (earthquakes, explosions, terrorist attacks) which would break the primary system and expose irradiated fuel to combustion in air.

Other Inherently Safe Concepts

We have less information on other inherently safe proposals. However, we list them here to illustrate the variety of approaches to the elimination of serious accidents in reactors. None have been developed sufficiently to allow a serious estimate of practicality.

The Horizontal BWR. The General Electric Company examined a concept for a large natural circulation boiling water reactor in 1959.[72] The fuel rods were to be mounted horizontally in an eleven-foot diameter cylinder.

The power rating was to be determined by the number of modular sections of core, each with its own control rods and fuel assemblies. The concept was expected to develop 45 kW per liter of core (versus 56 kW per liter for a forced-circulation BWR/6). It is claimed that the reactor can be shut down by gravity forces without the use of rods and that shutdown heat can be removed by air cooling.

While this concept appears to be simpler and require fewer safety systems than a conventional BWR, we do not have sufficient information to determine whether its safety requires no active systems or operator intervention.

The Deep-Well Reactor Concept. Westinghouse, in 1981, examined a concept for a natural circulation direct cycle reactor located 2100 feet below the surface.[73] The reactor is pressurized by the head of water above the core, and the core is cooled by liquid water which flashes on its way to the power conversion equipment (similar to a liquid geothermal cycle). In the event of a forced shutdown, safety rods go into the core and a large amount of pool water is available to remove decay heat through passive actions. Again, we do not have sufficient information to fully evaluate this system.

Inherently Safe LMFBRs. Edward Lantz, in a 1980 letter to Nuclear Safety,[74] proposed an "inherently safe" unpressurized pool-type, sodium-cooled reactor which would be controlled by the movement of bottom entry fuel assemblies. Free gaseous fission products would be removed continuously from the reactor to a naturally cooled, well-protected site. Decay heat would be transported to atmosphere by presumably passive systems that would preclude fuel melting.

The Large LMFBR Pool Plant being studied by Rockwell International and Argonne National Laboratory[75] attempts to incorporate fail-safe features. This would allow the intermediate heat transport system to be nonsafety grade, a significant cost savings.

The development of an inherently safe, economical Liquid Metal Fast Breeder Reactor (LMFBR) appears to be a sufficiently reasonable long-term goal so as to deserve serious consideration. Birkhofer[76] reports the PRA of the German SNR-300 to show a core-melt probability of 2×10^{-6} per reactor-year. The LMFBR was not given prime consideration in the Second Nuclear Era study because it is a plutonium-fueled reactor; this limits its widespread deployment early in the twenty-first century. However, the LMFBR could become the primary source of fission energy later in the Second Nuclear Era if it were to meet cost and safety criteria.

The Pool-Type Steam-Cooled Reactor. M. A. Schultz and M. C. Edlund[77] have proposed a unique variation of the PIUS reactor that contains a plutonium-uranium oxide core at the bottom of a pressurized pool. The core is cooled by a fog which maintains reactivity at a natural maximum. If the amount of water in the core either increases or decreases, the reactivity decreases. The reactor is shut down with water flooding the core, removing decay heat to the pool as in the PIUS concept.

The steam-cooled reactor may be promising as a breeder or near-breeder for the long term. Considerable analytic study and development would be required to confirm and optimize the reactor design.

Selection of a Reference Inherently Safe Concept

It appears there may be a number of avenues to reach the goal of a relatively simple reactor design whose safety depends on passive, rather than active features. Some of these might be economic, especially if "nonreactor grade" standards could be used for the bulk of the plant's systems.

The PIUS concept was chosen as the reference for this study for a number of reasons:

1. It is a pressurized water reactor and can therefore utilize much of the experience gained in the commercial nuclear industry.
2. Enough design and analysis has been carried out on PIUS to eliminate the obvious challenges to safety.

3. It has superior resistance to external events such as sabotage, terrorism, and acts of war.

4. There is a reasonable chance that a SECURE reactor, the low-pressure district heating version of PIUS, will be built in the next few years.

5. There is a plausible argument that PIUS costs would be reasonable.

The other inherently safe concept with a substantial engineering base, the modular HTGR, is also attractive. However, we have reservations about its resistance to some external events, such as terrorist attack, and we are uncertain that its costs can be made competitive with LWRs or with coal plants; regulatory relief would help to bring costs down. We hope that development of the modular HTGR can be carried far enough for a firm cost estimate and for a convincing demonstration of its inherent safety.

The other inherently safe concepts suggested were not selected as the reference concept either because insufficient information had been developed or because they are based on plutonium fuel.

TECHNICAL REVIEW OF THE SAFETY OF REACTORS

Safety Institutions and Philosophy

Most early civilian reactors were similar to military ones or were prototypes of designs conceived to prove the feasibility of the various combinations of fuels, moderators, and coolants. By the late 1950s, two main product lines emerged: the pressurized water reactor (PWR) and the boiling water reactor (BWR). The 60 MWe Shippingport PWR was commissioned in 1957, the 200 MWe Dresden 1 BWR was commissioned in 1960, and the 175 MWe Yankee Rowe PWR was commissioned in 1961.

The chief players in the development of civilian nuclear energy in the 30-year period since 1950 were the Joint Committee on Atomic Energy of the U.S. Congress, the Atomic Energy Commission (now the Nuclear

Regulatory Commission and the Department of Energy), and the nuclear industry. The Reactor Safeguards Committee, now the Advisory Committee on Reactor Safeguards (ACRS), played a key role as the Atomic Energy Commission's reactor safety arm. In 1953, Edward Teller, as head of the Reactor Safeguards Committee, stated that the ultimate responsibility for safe operation had to be placed on the shoulders of the owner-operators.[78] In 1956, Willard Libby, the then-acting chairman of the AEC, indicated to the Congress that the potential dangers of reactors to the public were large and that the ultimate safety of the public depended on three factors: (1) recognizing all possible accidents, (2) designing and operating the reactors in such a way that the probability of such accidents is reduced to an acceptable minimum, and (3) combining containment and isolation of radioactivity to protect the public should an accident occur.[79]

In the early 1960s, the ACRS took the position that nuclear reactors must be safer than other contemporary technologies. Although efforts were not or could not be made in the 1950s and 1960s to delineate all possible accidents and to determine their probability of occurrence, reactor safety was assured through defense in depth. Thus, the fuel is encased in cladding, the core is protected from reactivity excursions, the heat is removed from the core, the core is cooled by an emergency system under upset conditions, and a containment building is placed over the entire primary reactor system to contain any accidental releases. Reactors are generally sited in locations with low populations, although a few were sited near large cities during a period when reactor designers and regulators were very confident in their ability to prevent severe accidents.

Reactor design criteria, developed over the years, are published in the Code of Federal Regulations (CFR), Title 10, Part 50, Appendix A.[80] There are 64 criteria covering reactor design from the fuel to the containment to the radioactive waste system. Safety system design is based on the single-failure criterion, which stipulates that reactor safety must be maintained following a plant upset even if any one safety component fails to operate. The implementation of this criterion leads to several design concepts, including redundancy, diversity, and physical separation.

Although most other countries with nuclear reactors followed the United States' example, some, such as West Germany, Belgium, and Sweden, established additional criteria. For example, the N-2 criterion stipulates that reactor safety must be maintained following a plant upset even if one safety component fails and another is out of service for maintenance. The 30-minute criterion stipulates that no operator interference is required in the first 30 minutes of the upset.

Other important U.S. design criteria include: quality assurance (Appendix B of 10 CFR 50), reactor vessel material (Appendixes G and H), radioactive waste release during normal operation (Appendix I), emergency core cooling (Appendix K), and fire-resistant design (Appendix R).

The result is that reactors are designed to withstand large internal and external accidents without subjecting the public to undue risks. The Design Basis Accident (DBA)[81] was stipulated to be the result of the double-ended rupture of the largest pipe of the reactor coolant system. The DBA served for a long time as a basis for equipment qualification and for siting new reactors. The DBA, however, does not cover the full range of possible accident conditions. For example, there are no provisions for events such as reactor vessel failure, degradation of the core cooling system to a point that a core melt will take place, or anticipated transients without reactor scram.

Operational Problems and Fixes

The development and demonstration stages of civilian LWRs lasted well into the middle 1960s. Confidence in the safe and economic exploitation of nuclear energy was high. Despite this attitude, there were a dozen or so incidents, both in the United States and in other countries, which caused severe damage to reactor cores. The majority of these reactors were experimental. The 3 MWt SL-1 Army reactor actually experienced a reactivity excursion and a steam explosion; three operators were killed.[82] However, the public during this period was largely in favor of nuclear energy.

An indication of the high degree of confidence in reactor technology was the vendors' design of newer, larger, and more sophisticated reactors without the benefit of extensive operating experience with smaller reactors. For example, General Electric designed the 200-MWe Dresden 1 in the late 1950s with the steam drum outside the reactor vessel. By 1966 it had designed the 1060-MWe Browns Ferry reactors[83] with the steam separators and dryers all within the reactor vessel. Westinghouse designed the Yankee Rowe reactor in 1958 for 180 MWe. By 1968 it had a contract for the Trojan reactor[84] at 1100 MWe. Perhaps even more remarkable, Combustion Engineering and Babcock and Wilcox started their present product lines in the middle 1960s with reactors in the 800 MWe[85] range, then increased the size to the 1300 MWe range[86] by the early 1970s.

As earlier reactors accumulated service experience, some operational problems developed. This is not unexpected in a new technology; the difference in the case of nuclear reactors lay only in that many hundred thousand megawatts of capacity had been ordered before these problems became apparent. The 1970s saw vendors and utilities trying to correct operational problems and the regulatory bodies trying to prescribe regulations based on lessons learned from these operational problems.

Some of the most notable operational problems with reactors include pipe cracking in the out-of-vessel recirculation lines of BWRs, fuel-clad interaction which limited load following capability, containment weakness of the BWR Mark I and II under Loss of Cooling Accident (LOCA) dynamic loading (now largely resolved), steam generator tube failure in early Westinghouse designs, sensitivity to the coolant system conditions in Babcock and Wilcox once-through steam generators, and water-hammer caused by the sudden collapse of steam in auxiliary feedwater manifolds. Many of these problems have safety significance and caused extensive investigation, retrofits, and additional costs.

Other operational problems were not safety-related but also caused extensive reactor downtime and eroded the economics of nuclear electricity vis-à-vis coal-generated electricity. Problems with the steam turbine and electric generator caused as much as 20 percent of major forced outages. These frequent shutdowns represent undesirable challenges to the safety systems.

From the safety viewpoint, operational events that may lead to core damage accidents are important. A systematic screening of some 19,000 licensee event reports covering some 400 reactor years over the period 1969-1979 revealed 52 such events, or 1 in every 8 reactor years.[87] Most well known among these events are the Browns Ferry fire (3/22/75), the Rancho Seco overcooling incident (3/20/78), and the Three Mile Island accident (3/28/79). Since TMI, other events took place that are also significant: the small-break LOCA at Crystal River (2/21/80),[88] the partial failure to scram at Browns Ferry (6/18/80),[89] the steam generator tube rupture at Ginna (1/25/82),[90] and the failure of the automatic reactor protection system at Salem (2/22, 2/25/83).[91]

The responses to these operational events have been mandated NRC fixes. For example, Appendix R to 10 CFR 50[92] was a response to the Browns Ferry fire and required extensive modifications to reduce the vulnerability of the control systems to fire. Many changes have resulted from the TMI accident as will be discussed later. Thus, nearly every reactor in the country has evolved into a unique design. This is in contrast to the situation in France or the Soviet Union where there are many reactors that are essentially identical.

The Rasmussen Reactor Safety Study

Early government support of the fledgling nuclear industry was not only the funding of research, development, and demonstration, but also the protection of the industry from third-party liability. The Price-Anderson Act, enacted in 1957, provides $560 million in liability insurance to partially mitigate this threat. The Price-Anderson Act represents an early recognition of risks associated with nuclear plant operations.

A study conducted in 1958, WASH-740,[93] indicated that if a 500 MWt reactor melted and breached the containment, it could theoretically kill 3400 people, injure 43,000, and cause $7 billion in property damage. As reactors increased in number and size, the results of WASH-740 were revised upward in 1967 but were not made public. By the early 1970s, however, there was pressure from many quarters to make a thorough review of the consequences of reactor accidents. The Reactor Safety Study was commissioned in 1972 with a charter to study the probability, as well as the consequences, of reactor accidents.

The Reactor Safety Study, headed by Professor Norman C. Rasmussen of the Massachusetts Institute of Technology, was carried out by experts from many organizations. It took three years to complete, was reviewed by many organizations and individuals, and was published in 1975 as WASH-1400.[94] The study examined the 810 MWe Surry PWR and the 1100 MWe Peach Bottom BWR as typical power reactors. It used the event tree technique to delineate accident sequences, used the fault tree technique to determine unreliability frequencies of safety systems and functions, and used probabilistic techniques to analyze data. The results of the study indicated that the median core-melt frequency for commercial PWRs is approximately one every 15,000 reactor years (6×10^{-5} per reactor year) and is uncertain by a factor of five in either direction. The corresponding prediction for BWRs is approximately one every 30,000 reactor years (3×10^{-5} per reactor year). WASH-1400 goes on to predict that a large release of radiation (here assumed to be over 10 percent of the iodine plus other selected fission products) would occur about once in every three PWR core melts and even more frequently for BWR core melts. Should the wind direction be toward a nearby center of population, the offsite casualties from such releases could number several thousand and property damage could be many billions of dollars.

WASH-1400 also revealed several previously little-noticed aspects of reactor safety. It pointed to the more frequent plant upsets, such as small-break loss-of-coolant accidents, system transients, and operator errors as important contributors to risk. The industry at the time was assuming that if a reactor system could deal with a large pipe break accident, then it could also deal with smaller ones. The study also confirmed the value of the emergency core cooling system, redundant power supply, residual heat removal, and containment.

Critiques of WASH-1400 came from several quarters. Industry claimed that WASH-1400 results were too conservative[95] and that deterministic criteria used in the licensing process were even more conservative. The Union of Concerned Scientists[96] complained that the WASH-1400 results were too optimistic and misleading and that actual reactor core-melt frequencies and consequences were higher, perhaps by an order of magnitude or more. The American Physical Society and the Lewis Review Committee (an independent peer review group appointed by the Nuclear Regulatory Commission)[97] praised the study for being a benchmark in safety methodology, pointed out that the study methodology was especially good for comparative analyses, recommended improvement through the study of licensee event reports, and recommended using the study's methodology in the licensing process. However, the Lewis review assigned larger uncertainties to the probabilities of accidents than were estimated in WASH-1400.

The Reactor Safety Study remained on the shelf and controversial for several years until the accident at TMI. This accident brought about increased interest in this study and its methodology.

The Accident at TMI and Its Repercussions

The accident at TMI has been described by many others, and we mention it here only because of its profound impact on the subsequent operation and regulation of reactors. TMI 2 is an 880-MWe Babcock and Wilcox reactor owned by Metropolitan Edison of the General Public Utilities System, engineered by Burns and Roe, and constructed by United Engineers and Constructors. It started commercial operation in December 1978.

On March 28, 1979, main feedwater was lost (possibly caused by faulty in-service maintenance of the condensate polisher), and the safety rods shut down the fission reaction as designed. The primary system temperature and pressure increased because of the resulting inadequate heat removal from the steam generators. The pressure increase opened the pressurizer pilot-operated relief valve (PORV) as designed. When the primary system pressure dropped to 1700 psi, the high-pressure safety injection (HPSI) system was actuated as designed. However, the PORV did not reclose as designed and the operators did not realize until 140 minutes later that this was causing a loss of coolant. Meanwhile, the operators misread the high water level in the pressurizer as an indication that the primary system (including the reactor vessel) was excessively filled with water by the HPSI. They throttled, then shut down the HPSI and opened the coolant letdown line, thus causing the reactor core to be uncovered. The core was severely overheated during this time; decay heat and metal-water reactions caused the exposed part of the core to slump. The reactor core was finally immersed in borated water 16 hours after the accident began.

Early in the accident, the relief valve of the tank receiving water from the pressurizer PORV opened, and radioactive water spilled onto the containment floor. This water collected in the sump, and the sump pump automatically pumped water to the auxiliary building, thus violating containment isolation. The tank receiving this water overflowed, spilling radioactive water on the auxiliary building floor with off-gas vented to the atmosphere. The total radioactivity release was estimated later to be about 2.4×10^6 curies of noble gases and 13 to 17 curies of iodine. The average radiation dose received by each of the 2.2 million people in the surrounding area was below 1.5 millirems; no one offsite is known to have received more than 70 millirems. This is small compared to the annual exposure of about 150 millirems most individuals receive from natural and medical radiation.

The accident disabled the TMI-2 reactor, and in the aftermath the NRC denied the sister TMI-1 reactor permission to restart. This is costly to Metropolitan Edison, the General Public Utilities system, and to their customers.

There were many inquiries into the accident. The most important of these are the Presidentially-appointed Kemeny Commission[98] and the NRC-appointed Special Inquiry Group (Rogovin Inquiry).[99] Both inquiries concluded that "people problems" and "management problems" were the principal causes. They recommended that the NRC be restructured, that more efforts by the utilities and the NRC be put into training the reactor operators, that better equipment be available in the control rooms of reactors, and that emergency preparedness at the reactor sites be improved.

The NRC stopped licensing new reactors for a year as it devoted its attention and resources to the aftermath of TMI. It combined all recommendations into a plan called "TMI Action Plan." This comprises 347 detailed actions covering plant design, operation, and emergency preparedness. Implementation of the action plan has consumed the NRC's attention and resources since TMI. As of early 1983, the NRC has largely been successful in implementing its TMI Action Plan; ninety percent of the 198 priority items and 45 percent of the 149 other items had been implemented or were in the process of implementation. Thus overall about 70 percent of the action plan is now in effect.

The NRC has several other programs that appear to be more vigorously pursued since TMI. The Inspection and Enforcement program annually makes some 3500 inspections of reactors in operation or under construction and has resident inspectors at each site. The Systematic Assessment of Licensee Performance program evaluates the licensee's reactor operation, personnel training, and corporate management. The resulting performance evaluations indicate considerable variation of quality of operation. The Systematic Evaluation Program assesses the needs of older reactors to satisfy the TMI lessons as well as other new requirements.

The NRC has also broadened its safety research program to include degraded core phenomena, radiological source terms, pressurized thermal shock, containment behavior, human factors, probabilistic risk assessment (PRA), and other areas not given emphasis prior to TMI.

Before TMI, the U.S. nuclear industry was very fragmented, with some 140 reactors (about 70 in operation and 70 under construction) manufactured by 4 vendors, engineered by over a dozen architect-engineers, constructed by some 20 contractors, and operated by about 60 utilities. Communications between utilities, chiefly through the NRC, were minimal.

Since TMI, the utilities have pooled resources to form the Nuclear Safety Analysis Center, the Institute of Nuclear Power Operations, and Nuclear Electric Insurance, Limited (NEIL). In addition, they expanded the number of owners' groups. All parties now realize that the industry must improve its internal communication to enhance learning and to address common technical and institutional problems.

The Nuclear Safety Analysis Center (NSAC) serves as a think tank for the industry on technical safety problems and their solutions. NSAC has extensively analyzed TMI and other accidents, has done research on the pressurized thermal shock phenomena, investigated NRC designated unresolved safety issues, and has participated in the industry's degraded core analysis program (IDCOR).

The Institute of Nuclear Power Operations (INPO) is chartered to promote quality reactor operation.[100] As of 1983, it had completed two rounds of evaluation visits at all operating reactors and is now embarking on the third round. Each such visit is conducted by a team of about ten experienced people who spend two weeks at the site evaluating a list of operational areas, including corporate management of nuclear matters. The reports written by the team are discussed with operators and management for speedy resolution. INPO reports good cooperation in acceptance and response in the form of corrective actions. To enforce its recommendations, INPO uses the peer process: between evaluators and the evaluated, between the INPO president and the utilities' presidents, and between the INPO board of directors and the utilities' boards of directors. The last resort for resolving the remaining disagreement is referral of the case to the NRC and the insurance underwriters, a process INPO has not used thus far.

In addition to operations evaluation, INPO also evaluates reactors under construction, disseminates analyses of significant events, facilitates communication among utilities, promotes good operating practices, accredits utilities' training programs, and maintains data on safety events and nuclear plant equipment reliability.

TMI has demonstrated that the cost to the affected utility of an accident is very high even when no member of the public is hurt. The newly created NEIL[101] offers $415 million in excess property damage insurance (over the $450 million already available through other underwriters) and some $195 million towards the cost of replacement power. Each reactor now is covered by $560 million for liability and about $1.0 billion for property damage, at an annual premium of between $6 and $8 million, and promised contribution towards indemnification should a mutually insured reactor suffer an accident.

The industry's owners groups[102] bring together utilities that own similar equipment and the vendors who manufacture that equipment. Some owners groups are BWR Owners' Group, Westinghouse PWR Owners' Group, Westinghouse Steam Generator Owners' Group, Babcock and Wilcox Owners' Group, and Combustion Engineering Owners' Group.

The reactor vendors have also been hard at work since TMI to service their reactors. For most reactor vendors, the service business now dominates; reactor design has dropped to second place as backlogs have cleared and new orders have not arrived. Some notable equipment marketed by the vendors since TMI includes the core water level monitoring system, the hydrogen mitigation system, the safety-grade power supply for the pressurizers, and the radiation monitoring systems. Vendors have also developed new reactor systems described in the previous section.

In retrospect, TMI revealed flaws both in nuclear safety technology and in safety philosophy: reactor deployment had been expedited without extensive operational experience; design for safety was too narrowly focused; rules and regulations were developed after, rather than before commercial reactor deployment; the industry was fragmented and tended to rely on the Nuclear Regulatory Commission for safety guidance; information was not effectively shared; and not enough attention had been given to the human aspects of reactor operation and public reaction to the specter of a reactor accident. But the response to TMI by industry and government has been significant. There is little doubt that reactors today are safer than they were before TMI.

The Nuclear Source Term

The experience at TMI and at other reactor accidents, together with experiments that have been conducted recently, show that the nuclear source term* of WASH-1400 (0.3 billion curies of noble gases and 0.9 billion curies of non-noble gas fission products) greatly overstates the probable release of radioactivity.[103] The source term is currently under intense review by the NRC, and it is not possible to predict the outcome of the review. However, our analysis of the data indicates that the largest catastrophic release of WASH-1400 cannot be ruled out but that the frequency has been overestimated by a factor of 20; it should be 5×10^{-7} per reactor year instead of 10^{-5} per reactor year.[104] The most likely large release of non-noble gas fission products is reduced in magnitude by a factor of ten (to about 0.08 billion curies) and in frequency about a factor of 2 to 5×10^{-6} per reactor year.

The largest release which could occur at the Surry PWR, according to WASH-1400, would cause 350 to 6200 early fatalities, depending on the effectiveness of evacuation. There would also be 1400 latent cancer fatalities. As discussed in the preceding paragraph, the most likely large release in our analysis would have a factor of ten fewer non-noble gas fission products; this would limit early fatalities to 3-60 and latent cancer fatalities to 140.

---

*Nuclear source term is the radiological emission which is anticipated after a core damage accident in a nuclear reactor. The source term is of interest because it is the principal hazard to the public resulting from the operation of nuclear power plants.

The very large catastrophic release requires an early breach of containment either before or shortly after the core melt. There are very few mechanisms available for this early failure; they include a massive missile or earthquake or overpressure from steam and/or a hydrogen explosion. If containment failure can be delayed for an hour or more after the core melt, then the fission product aerosols within the containment settle and the source term is reduced. A relatively innocuous source term results if containment failure is averted for a day or more.

To summarize, we believe the data justify a significant reduction in the seriousness and probability of large releases from LWRs, though we cannot rule out the possibility of a very large release.

The Safety of Reactors Before and After TMI

Qualitatively, U.S. LWRs after TMI are much safer than they were before TMI because of TMI lessons learned, hardware retrofits, and better and more uniform operating procedures. To estimate quantitatively how much safer reactors are today than before TMI, we catalogued the core-melt frequencies resulting from the four most important event trees for BWRs and PWRs in three cases:[105] before TMI, WASH-1400, and after TMI. The four event trees include small-break LOCA, loss of offsite power (T_1), system transients other than T_1 that leave the power conversion system (PCS) inoperative, and system transients other than T_1 that leave the PCS operable. These event trees account for over two-thirds of the total accident probability.

System unreliability values for each safety function of the event trees were determined for the three cases: the before TMI case by using values from the Oak Ridge National Laboratory-Science Applications, Inc. (ORNL-SAI) precursor study[106] for the period 1969-1979; the WASH-1400 case by using values from WASH-1400; and the after TMI case by using values from the Indian Point PWR PRA[107] and Limerick BWR PRA.[108] Reconciliation of data was made where necessary by also consulting the INPO and SAI critiques of the ORNL-SAI study.

Our results indicate that the core-melt probability of reactors before TMI was perhaps twice the estimate in WASH-1400 but that improvements incorporated into reactors since TMI have reduced the probability to 1.5 to 3 times below the WASH-1400 estimate. This makes the core-melt probability of reactors after TMI 3 to 6 times lower than that before TMI. The actual computed ratio is 6 for PWRs and 3 for BWRs. The median core-melt probability for PWRs is higher than for BWRs in all three cases--before TMI, WASH-1400, and after TMI.

As for risk to the public, post-TMI LWRs have benefited from reduced core-melt probability (factor of ~5), reduced source term as the result of more accurate prediction (factor of ~20), and greater attention paid to emergency planning (factor of ~2). The risk to the public from a current post-TMI reactor is thus at least 10 times and possibly 100 times less than that presented in WASH-1400, which already predicted a low risk compared to other societal risks.

Though these estimates suggest that post-TMI reactors are quite safe, we must point out that estimates of core-melt probability are inherently uncertain and such uncertainty alone raises the estimated core-melt frequency for a given number of reactor years. For example, we find that if the probability of a core melt per year is log-normal with a median equal to 1.7×10^{-5} per reactor-year and an error factor of 10 (roughly, the median could be 10 times too high or too low), then the expectation of a core melt in 9000 reactor years would be 0.23; whereas if the error factor were 1, the expectation would be 0.14.[109] We find it reassuring that even very large uncertainties with the same median in the estimated core-melt probability would hardly double the estimated expectation value of a core melt over the next 20 years for a 500-reactor world, provided the assumption of log-normal probability distribution is justified.

Future Directions for Reactor Safety

The NRC, following TMI, has proposed a goal of 10^{-4} per reactor year for the core-melt probability as estimated by PRA. There is no doubt that the majority of LWRs today meet this criterion. These reactors can also satisfy the goal of adding not more than 0.1 of 1 percent to all other risks confronting society or individuals. Can we therefore conclude that today's reactors are safe enough?

In a 500-reactor world, one might expect a meltdown every 20 years in reactors satisfying the safety goal. As the number of reactors increases in a Second Nuclear Era, the likelihood of a meltdown would also increase. Though posing little risk to the public at large, a meltdown of any one nuclear plant could pose many risks to all investors in nuclear power. We propose, therefore, that as the number of reactors increases, the safety goals should be tightened for new reactors.

Reactors already being developed, such as the Sizewell B PWR, the APWR, and the ABWR appear to have a desirably low meltdown probability. However, safety is gained through increased redundancy and complexity as compared to present already complex designs. We are disappointed that there is no sponsor, in industry or in government, for development of a low-cost light water reactor that is simple to operate and maintain, and where safety is assured through a few fundamental and easily understood features.

Such features include the following:

1. reliable shutdown systems that eliminate the anticipated transient without scram (ATWS) problems
2. reliable primary water supply to keep the core covered, and reliable level measurement
3. reliable, dedicated, shutdown decay heat removal systems

It can be argued that if the above features are assured, then any other malfunction would not damage the fuel. Hence much of the rest of the nuclear plant can be built to conventional engineering standards at lower cost. Until the NRC accepts this argument and modifies the present prescriptive mode of regulation, the industry would have little incentive to support detailed design of such plants.

Our analysis of the source term indicates that public risk might be further reduced or virtually eliminated through improved containment design. The objective would be to eliminate those failure scenarios that lead to early rupture or bypass of the containment. German containment designs may already accomplish this goal.

We also favor judicious selection of reactor sites in low population areas, insofar as possible, as a means of reducing both public risk and public apprehension.

We believe the measures we advocate are needed to reduce risk and cost on the part of the investor and to contribute to improved confidence in nuclear power on the part of the public and elected officials.

THE ECONOMICS OF NUCLEAR POWER

The continuing cancellation of partially completed nuclear power plants provides eloquent testimony to the mismatch between the economic/financial characteristics of nuclear power plants and the utilities' present criteria for generating capacity. Yet, nuclear reactors generate the lowest cost power in many utility systems. This section of the report summarizes the economic record of operating reactors and of plants under construction and examines present and future trends.

It is obvious that the economic/financial characteristics of nuclear power plants must be made consistent with the perceived needs of utility investors for there to be a Second Nuclear Era.

Economics of Operating Nuclear Reactors

As of June 1983 there were 82 power reactors operating in the United States with a capacity of about 66,000 MWe and supplying about 13 percent of the nation's electricity. The national average costs of electricity generation by these reactors (including fixed charges, O&M, and fuel) have been consistently lower than those of coal-fired power plants (6 percent lower in 1976, 25 percent in 1977, 32 percent in 1978, 17 percent in 1979, 8 percent in 1980, 16 percent in 1981, and 11 percent in 1982, as shown in Figure 8).

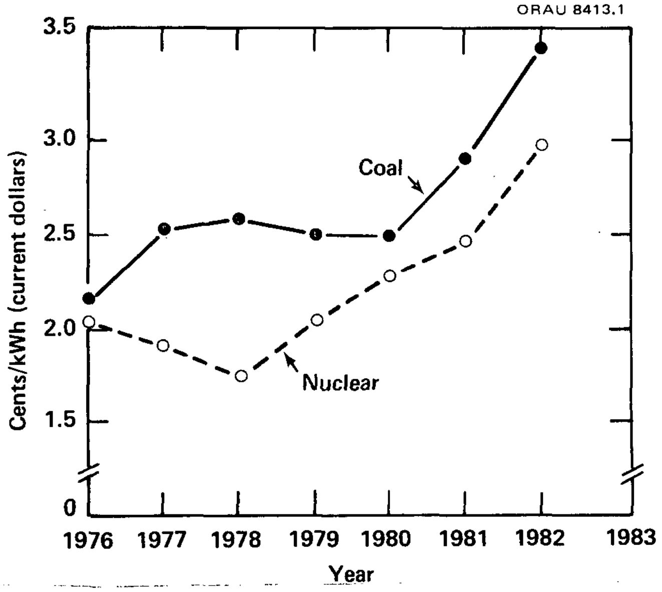


FIGURE 8. TRENDS IN AVERAGE COSTS OF COAL AND NUCLEAR ELECTRICITY IN THE UNITED STATES

Source: Doan Phung, Economics of Nuclear Power: Past Record, Present Trends, and Future Prospects, Research Memorandum, ORAU/IEA-83-13(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1983).

For most utilities with large nuclear, coal-fired, and oil-fired capacities, nuclear plants have economically outperformed the others. For the years 1981 and 1982, the nuclear electricity generated by the Tennessee Valley Authority was cheaper than coal-fired electricity by 45 percent and 47 percent,[110] respectively. At Commonwealth Edison, the generation cost from six nuclear reactors was only half that of either six comparable coal-fired plants[111] of the same size and vintage or of the systemwide coal-fired capacity (1980).

The majority of these operating reactors were on-line before 1978. Most were ordered in the late 1960s when utility executives' and public confidence in nuclear power was high. Licensing at that time was relatively simple. Reactors were simpler than today's new plants. Vendors were selling reactors inexpensively, partly because of their inexperience and partly because they expected a robust nuclear market. Interest rates were generally below 8 percent per year. As a result, the capital cost of these reactors at the time of commercial operation was low. For example, the two Dresden reactors cost $146 per kW in 1971, the two Point Beach reactors cost $160 per kW in 1972, the two Zion reactors cost $279 per kW in 1974, the three Oconee reactors cost $181 per kW in 1974. In terms of 1983 dollars, nineteen General Electric operating reactors cost an average of $482 per kW, nine operating Babcock and Wilcox reactors cost an average of $614 per kW, seven operating Combustion Engineering units cost an average of $715 per kW, and 24 operating Westinghouse reactors cost an average of $622 per kW.[112]

The reactors built in earlier years have been extensively retrofitted. Data for 35 reactors indicate that an average of $156 per kW or 28 percent of the adjusted initial capital cost have been or are in the process of being spent on retrofits. Over 60 percent of the costs are attributed to regulatory requirements, most notably on items related to fire resistance (following the Browns Ferry incident), BWR containment (Mark I) modifications, earthquake resistance, emergency power reliability, and security assurance. Less than 40 percent of the retrofit costs were initiated by the owner-operators to improve operability. Utility-initiated retrofits include expansion of onsite spent fuel storage, steam generator and condenser fixes or replacement, and facilities for the increased number of onsite personnel.

Surprisingly, TMI-related retrofits do not appear to be as expensive as is often claimed by industry. For the Northeast Utilities' three reactors (Connecticut Yankee, Millstone 1, and Millstone 2), the TMI-related retrofits constitute $25 per kW, or 12 percent of all retrofit costs; other regulatory retrofits and utility initiated retrofits make up 50 percent and 38 percent, respectively. For the Commonwealth Edison six nuclear plants (Dresden 2 & 3, Quad Cities 1 & 2, and Zion 1 & 2), the TMI fixes cost $12 per kW, or 16 percent of all retrofit costs. Other regulatory and utility retrofits amounted to $50 per kW (66 percent) and $14 per kW (18 percent), respectively.[113]

The availability factors of the operating reactors on the average have been slightly over 70 percent, the capacity factors around 56 percent.[114] The difference between availability factor and capacity factor is the result of operation at below rated load at the discretion of the utility or because of NRC-mandated cutbacks. The shortfall in the average capacity factors--about 15 points below the best reactors--is due to a variety of reasons: pipe cracking in the primary circuits, water chemistry in the power conversion circuits, steam generator deterioration, steam turbine warping, generator instability, refueling, and NRC-mandated cutbacks. As the reactors mature and retrofits are made, these problems lessen, but it is doubtful whether the overall lifetime capacity factors of these reactors would be much over 65 percent. There are exceptions: the Connecticut Yankee (600 MWe PWR) has been operating since 1968 at the cumulative capacity factor of 75 percent. The six reactors in Minnesota and Wisconsin have been operating since the early 1970s at a cumulative capacity factor of 73 percent.[115]

The overall availability and capacity factors of nuclear plants are on the average equivalent to those of coal-fired plants. The National Electric Reliability Council[116] has compiled these factors for coal-fired and nuclear units in several size categories. The conclusion is that for the period 1971-1980 nuclear reactors smaller than 800 MWe performed better than comparable coal-fired units, while those larger than 800 MWe performed slightly worse than comparable coal-fired units. Both types of generation provide capacity factors averaging 55 to 60 percent in the United States.

Nuclear fuel costs have been around 0.3 to 0.6 cents per kWh, less than half those of coal during the 1970s. Uranium prices rose precipitously in the mid-1970s but fell back to less than $25 per pound of yellow cake when it was clear to the commodity market that there was plenty of uranium supply for the projected nuclear capacity. Enrichment cost increases (to above $125 per separative work unit) and cost allowances for spent fuel storage and long-term radioactive waste disposal have more than offset reductions in yellow cake prices. Nevertheless, for plants already on-line as of 1982, the fuel portion of nuclear electricity averages only about 25 percent of the generation cost, while that of coal represents about 50 percent. Operation and maintenance (O&M) costs were about 0.2 to 0.3 cent per kWh. These costs have increased faster than general inflation due to increased requirements: more and better operators, high maintenance costs, and special technical services. The O&M costs are expected to increase further to 0.5 to 0.6 cent per kWh due to the TMI actions and to the increased requirements for and availability of insurance.

Economics of Nuclear Plants Under Construction

About 57 reactors are now in advanced stages of construction.[117] Reactor licensing became increasingly complicated as new regulations were imposed on plants under construction. Requirements for concrete, steel, cables, engineering man-hours, and labor man-hours to build a typical reactor plant have doubled or even tripled over a ten-year period because of the increased regulatory requirements and the inefficient use of labor resulting from constantly changing designs (Table 1). The interval from decision to commercial operation also doubled, from approximately six to seven years to as long as fourteen years. Interest rates on borrowed funds to pay for construction have increased, sometimes to above 15 percent per year.

The management of nuclear projects has been of variable quality. Some aggressive utilities such as Commonwealth Edison, Florida Power and Light, and Arizona Public Service (and partners) were able to build their nuclear plants within reasonable schedules and costs (six to seven years and $1200-$1500 per kilowatt). (The Arizona Public Service's Palo Verde project has apparently experienced a six-month delay because of primary pump defects. This setback has been estimated to increase capital costs about $200 per kilowatt.[118]) Others ordered a nuclear plant for the first time and tended to treat nuclear projects in the same way small coal-fired plants were handled in the era prior to the National Environmental Policy Act. They relied heavily on architect-engineers, consultants, and contractors, some of whom were not themselves well prepared to design and

TABLE 1. INCREASED REGULATORY, MATERIAL, AND LABOR REQUIREMENTS FOR U.S. NUCLEAR PLANTS

Escalation of codes, standards, regulatory guides, bulletins

	No. of Standards	NRC Guides & Positions
1970	400	4
1973	1074	68
1975	1624	157
1978	1800	304

Increased material requirements

	Concrete (cu yd)	Steel (t)	Cable (yd)	Cable Tray (yd)	Conduits (yd)
1973 estimate of 1981 operation	90,000	15,400	670,000	8,400	58,000
1978 estimate of 1985 operation	162,000	34,200	1,267,000	27,000	77,000

Increased labor requirements (man-hour/kW)

	Engineering	Craft	Total
1967 estimate	1.3	3.5	4.8
1972 estimate	3.4	6.2	9.6
1978 estimate	5.5	13.0	18.5
1980 estimate	9.2	19.3	28.5

Source: D.L. Phung, Economics of Nuclear Power: Past Record, Present Trends, and Future Prospects, Research Memorandum, ORAU/IEA-83-13(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1983), p. 14.

build nuclear plants in a changing licensing and social environment. Some of the consequences were mistakes, delays, workers' unrest, citizens' protests, litigation, stopped work, and rework. Costs spiraled to twice or more those of the best projects.

The unfavorable factors caused a cash flow shortage in most utilities that have nuclear plants under construction. Local public service commissions and/or state legislatures have often disallowed rate increases and funding of construction work in progress (CWIP). As a result, bonds of many utilities have been derated and market prices of stocks in many cases are below book values. Under these circumstances, many utilities have had to delay, mothball, or cancel reactors under construction, many in advanced stages. The Tennessee Valley Authority (TVA) is writing off \$2 billion expended on four reactors canceled while under construction; four others are deferred. The Washington Public Power Supply System (WPPSS) has had to cancel or defer four of its five reactors and was forced into default on some of its bonds.

The approximately 57 surviving reactors that will go commercial within the next five years will double the nuclear plant capacity from the current 64,000 MW to about 123,000 MW.[119] Their costs will range from \$1100 per kW to \$3500 or more per kW, with the average around \$1700 per kW (1983 dollars). The lower costs are those of reactors such as Braidwood 1 & 2, St. Lucie 2, Palo Verde 1, 2, & 3 (assuming the pump problem is not too costly), which were well managed, purchased at favorable terms, engineered by experienced architect-engineers, and suffered relatively few problems during construction. The higher costs are those of reactors such as Shoreham, South Texas 1 & 2, Midland 1 & 2, and Zimmer, which have suffered extensive problems with quality assurance, poor management, labor unrest, citizen protest, and regulatory confusion.

While regulatory-mandated retrofits are expensive to operating reactors (about 28 percent of original cost adjusted to 1983 dollars), the impacts of increased safety requirements on reactors under construction have not been quantified. The Atomic Industrial Forum (AIF) estimated that the post-TMI improvements cost these reactor operators about $40 million for each reactor,[120] or approximately 2 to 3.5 percent of the capitalized cost.

These new reactors, when brought on-line, will cost four to six times the costs of older reactors. When adjusted to include inflation and backfits, the cost ratio is still about three. The sudden inclusion of such huge new capital outlay into the rate base, often increasing it as much as 100 percent, results in a very substantial sudden increase in electric rates ("rate shock"). Thus, nuclear plants, touted earlier as generators of cheap electricity, in a number of cases are bringing about large rate increases.

Even so, the majority of reactors that are about to go commercial will probably generate electricity at a cost equal to or cheaper than that of comparable coal-fired plants. Even if the coal-fired plants are only two-thirds as capital intensive as nuclear reactors, the cost of coal must stay below 2.5 cents per kWh (or $2.5 per million Btu) in 1983 dollars for the next 30 years in order to be competitive with these reactors. But the price of coal will almost surely rise: acid rain abatement, railroad rate increases, scrubber slurry disposal, and coal mine reclamation are but a few factors that will contribute towards cost increases of coal-generated electricity. For example, National Economic Research Associates, Inc.,[121] estimated for the Edison Electric Institute that passage of acid rain legislation now pending before Congress would cause electric bills at 24 utilities east of the Mississippi to rise between 5 and 38 percent per year (on the average less than 10 percent) over the first five years of adoption.

Trends Affecting the Economics of Nuclear Power

A recent DOE comparison of projected capital cost for 1995 coal and nuclear plants is given in Table 2. The expected capital costs in 1995 dollars are rounded to $4700 per kilowatt for nuclear and $3000 per kilowatt for coal. These costs presume a status quo in both regulation and

TABLE 2. POWER PLANT CAPITAL INVESTMENT COST ESTIMATES FOR COMMERCIAL OPERATION IN 1995
(dollars per kWe)

	Nuclear 1 x 1200 MWe	Coal 2 x 600 MWe
	Direct costs (January 1982 dollars)	
Land and land rights	5	5
Structures and improvements	190	75
Reactor/boiler plant	240	340
Turbine plant	190	160
Electric and other	155	105
Subtotal (direct costs)	780	685
	Indirect costs (January 1982 dollars)	
Engineering and construction services	495	135
Owners' costs	125	85
Subtotal	620	220
	Total Costs (January 1982 dollars)	
Direct and indirect costs	1400	905
Contingency allowance	210	135
Total "overnight" cost (Jan. 1982 dollars)	1610	1040
	Time-related Costs (in mixed dollars)	
Escalation (as-spent dollars)	1440	1155
Interest (as-spent dollars)	1610	755
	Total Costs (1995 dollars)	
Plant capital cost at time of commercial operation	4660	2950

Key assumptions:

inflation rate, 6% per year
escalation rate of power plant construction cost, 8% per year
average cost of money, 11.9% per year
overall schedule, 12 years for nuclear, 8 years for coal

Source: Energy Information Administration, Projected Costs of Electricity from Nuclear and Coal-fired Power Plants, DOE/EIA-03561 (Washington, D.C., August 1982).

institutional arrangements. Under these circumstances, nuclear power and coal are roughly competitive at coal prices of $2.50 to $3.00 per million Btu (1982 dollars) presuming coal price inflation at 1.5 to 2 percent above general inflation. The cost of generation from these plants is projected to be 5 to 5.5 cents per kWh in 1982 dollars (nearly twice the average nuclear generation cost in 1982).[122]

Utility executives are not likely to commit their companies to build any further nuclear reactors in the short term, possibly up to 1990. There is an excess of capacity, sometimes as much as 40 percent on many systems. Reduced economic activity, price-induced consumer conservation and active utility-sponsored conservation programs continue to keep growth in demand low. Reactor licensing, while showing some stability, is still far from predictable. Capital cost estimates for new projects are high (as illustrated above), while projected cash flows are uncertain. Reactors are too large in size relative to projected firm load growth, are too complicated, and pose a high financial risk.

On the other hand, there are trends encouraging to the future economics of nuclear power. Inflation has been drastically reduced since 1981, and it appears that it may stay low for some years to come. Interest rates were extremely high between 1981 and 1983 but have come down to the 12-14 percent range. The public utility commissions (PUCs) in many states are sympathetic with the plight of electric utilities and have allowed sizable rate increases; for example, $6 billion in 1980 and $8.3 billion in 1981. Some PUCs, such as those of North Carolina and Pennsylvania, allow a rate of return on stockholders' equity up to 16 to 17 percent. Other PUCs allow an incentive payment to utilities that complete a construction project within a specified cost range.

Allowance for construction work in progress (CWIP) is now increasingly accepted as a means to limit capital cost increases and future rate shock. In 1967, only 6 percent of the $170 billion of capital outlay was covered by CWIP. In 1973, 18 percent of $225 billion was covered by CWIP, and in 1981, 25 percent of $280 billion.

CWIP would shave as much as 30 percent off the capitalized costs of power plants at the time of their commission and would thus avoid rate shock and would save money in the long run. Nuclear plants benefit more than coal-fired plants because of their higher capital cost--nuclear plants cost 30 percent to 50 percent more than coal-fired plants. However, Asbury[123] of Argonne National Laboratory has calculated that 100 percent CWIP allowance would increase electric bills of current consumers by 5 to 14 percent per year. Rate-setting bodies constantly face the dilemma of balancing high costs today against higher costs in future years.

But better times for nuclear energy could be just beyond the horizon. Factors influencing this prospect include a grassroots tendency towards electrification (i.e., industrial processes, residential space heating), improved management of the nuclear enterprise, legislation designed to resolve radioactive waste management, licensing reform, and better reactor designs.

In 1982 at the instigation of the White House (Vice President George Bush) several U.S. agencies under the leadership of the Department of Energy undertook a study on the adequacy of electricity supply in the United States to the year 2000 and beyond.[124] The study found that while there is a current surplus of installed capacity, 25 percent of the capacity is still fired by oil and gas and 25 percent is over 20 years old. At a medium demand growth rate of 3 percent per year, 330,000 MW of capacity should be built by the year 2000. In addition, high market prices of oil and gas dictate that some 40,000 MW of capacity that burn these fuels should be replaced. Replacement of older units would require a further 70,000 MW. Thus, a total of about 440,000 MW of capacity might be required by the year 2000, of which only about 150,000 MW have been ordered, leaving some 290,000 MWe to be ordered, perhaps by the late 1980s. A 2 percent growth scenario would lead to approximately 160,000 MW to be ordered.

We note that these forecasts of the U.S. Department of Energy study are not universally accepted, even within DOE. The projected needs for new baseload plants might be reduced by recession, increased conservation, more reliable operation of the existing plants, more power interchanges, cogeneration, and so on.[125] On the other hand, current electric load forecasts are too low should the U.S. economy continue to expand. The point is that load growth is a necessary but not sufficient condition for a Second Nuclear Era. Should load growth occur, then we hope that the government, the industry, and rate-setting bodies would work together to improve the economic framework for nuclear (and coal) power delivered to the consumer.

Prospects of Nuclear Power Economics in the Second Nuclear Era

By the start of the Second Nuclear Era (say, the year 2001), the first generation of nuclear plants and many coal plants will have mostly been paid for. If demand growth has been limited to 2 to 3 percent per year, electricity rate increases to consumers will probably be modest. Indeed, if the generating system continues to operate well, the real cost, if not the price of electricity may actually fall.

The technology now exists to build better and safer reactors. The Advanced Pressurized Water Reactor (APWR) now under design by Westinghouse and Mitsubishi and the Advanced Boiling Water Reactor (ABWR) now under design by General Electric and Toshiba both have superior safety features that reduce the median core-melt frequency to perhaps 10^{-6} per reactor year. The High-Temperature Gas Cooled Reactor (HTGR) appears to be as safe as the safest LWR and appears less susceptible to massive fission product releases thanks to the superior temperature resistance and high heat storage capacity of the large graphite-moderated core. The small modular HTGR provides "walkaway" safety and is much safer than a large HTGR. The Process Inherent Ultimately Safe (PIUS) reactor appears to be incapable of a core melt under even the most adverse conditions, such as sabotage, abandonment (for up to 7 days), and conventional acts of war.

Will these new reactor designs be economic? The competitive nature of our economy suggests that the APWRs, ABWRs, and coal will be priced to be competitive. The Gas-Cooled Reactor Associates (GCRA),[126] under a grant from DOE to study the feasibility of an HTGR for South Florida, believes that the equilibrium HTGR (not the first-of-a-kind) would be competitive with the PWR, i.e., about $1450 per kilowatt (1982 dollars) based on an 800 MWe size. A widely held belief among many people, however, is that the large HTGR is somewhat more expensive than the LWR and does not have comparable operating experience. The costs of the HTGR might be made more competitive if licensing requirements recognized the HTGR's intrinsic resistance to massive release of fission products.

Similar economic uncertainties face the modular HTGR. While there are no unresolved questions regarding process parameters for fail-safe designs, there are large uncertainties in the design details and the fabrication and erection procedures which may lead to low costs. These uncertainties can be narrowed only through practical experience.

Economic uncertainties face the PIUS as well but even more severely because this reactor does not yet have a proof-of-principle demonstration. Will the hydraulic balance system work, or will it keep the reactor shut down most of the time? Will the thermal efficiency be as high as 30 percent? How does one maintain and repair equipment of the primary coolant system which is immersed deep in the pool of borated water?

Our first principles analysis indicates that there is hope that the PIUS may cost less than the large HTGR or even the APWR or ABWR. The major new cost of PIUS is its prestressed concrete reactor vessel (PCRV); however, the PIUS PCRV is much less complicated than the HTGR PCRV because it has fewer internal cavities. The construction of the PIUS PCRV appears to be easier and to take less time and should cost less per unit of concrete and steel.

Although a thorough licensability study needs to be made with the cooperation of the Nuclear Regulatory Commission, the basic design of the PIUS obviates the need for a separate emergency core cooling system, a dedicated residual heat removal system, a high-pressure containment building, and a high-reliability emergency power supply system. These systems together are estimated to have a direct cost of $275 to $360 million, or \$230 to \$315 per kW for a typical 1139 MWe PWR[127] (roughly equivalent to the reactor of Table 2). We believe the PIUS PCRV should cost about \$150 per kW (the equivalent of \$2,000 per cubic yard of materials); this is to be compared with the PCRV cost of \$66 per kW (\$2400 per cubic yard of materials) GCRA estimates for the 855 MWe HTGR.[128] Since the PCRV cost is expected to be well below the cost of the safety systems it more or less replaces, the chances of the PIUS being economic are reasonable.

When one compares the scope and complexity of today's 1100-1300 MWe reactors with the smaller, simpler, more easily built and operated reactors of the late 1960s and early 1970s, an obvious question is, should the industry not look harder at making tomorrow's reactors look more like yesterday's? Indeed, a recent Westinghouse study[129] now claims that its two-loop plants are competitive with larger LWRs. With the exception of ASEA-ATOM's study of the PIUS concept, the industry has not looked seriously for a design with the few basic safety functions (shutdown, primary water supply and level measurement, decay heat removal, and containment) provided in a simple and rugged way (and not necessarily satisfying all of NRC's current regulatory guides).

THE NUCLEAR FUEL CYCLE

The primary focus of the present study has been on the technology of the reactors used to generate power. However, a Second Nuclear Era cannot be carried out without consideration of the nuclear fuel. Where is it coming from? What will be done with the wastes?

This section of the report presents our views on nuclear fuel supply assurance and nuclear waste management and siting.

The Assurance of Nuclear Fuel Supply

The supply of uranium fuel for the commercial life of a power reactor has always been of concern to the owner. Most utilities enter into long-term contracts for uranium supply at a favorable price. During the early development of nuclear power, it was commonly believed that converter reactors,* such as LWRs, would become obsolete when low-cost uranium supplies were depleted. At present, the capital costs of new reactors have increased so much relative to fuel costs that obsolescence of LWRs no longer appears to be a threat.

There is no apparent physical limitation to the life of an LWR, provided equipment is renovated or replaced as it wears out. In this respect it is similar to a hydroelectric dam, although a nuclear plant requires more extensive repair and replacement based on current experience. The plant will become obsolete only when the cost of continued operation (primarily fuel cost for a future when uranium costs are much increased) is greater than the cost of replacing it with an entirely new plant. We can envision extracting uranium commercially from low-grade sources (shales, phosphates, or sea water) for $1000 per kg or less for a very long time. At such a uranium price the fuel cost in LWRs with fuel recycle is about 2.5¢ per kWh.[130] This fuel cost compares to a current LWR capital cost of 4.4¢ per kWh ($1500 per kWe, 18 percent fixed charge rate, 70 percent capacity factor). The nuclear plant ought therefore to continue to be a source of cheap power and not become obsolete, provided costs of renovation remain acceptably low. When high-grade uranium resources are depleted, the reactors will continue to be provided with fuel produced in breeders or by low-grade uranium sources if necessary.

A conventional light water reactor operating with uranium fuel of low enrichment utilizes about 5600 ST (short ton) U_3O_8 (4300 tonnes U) in a 30-year life (1000 MWe, 70 percent capacity factor). If one accepts the most recent Organisation for Economic Cooperation and Development estimate of 5×10^6 tonnes of U (assured resource at costs below $130 per kg U) in

---

*A converter reactor is a nuclear reactor that converts fissionable material (e.g., ^{235}U) to heat to generate steam and thence electricity. "Burner reactor" is another term for converter reactor. A breeder reactor is a nuclear reactor that generates new fissionable material (more than it consumes as it operates).

the non-Communist world,[131] that would be sufficient to fuel 1160 GWe of nuclear power for 30 years. A recent careful estimate of nuclear power prospects for 1999 indicate a free world total of 410 ± 40 GWe.[132] The OECD anticipates nuclear power capacity will double or triple between 2000 and 2025.[133] Matching the low-cost uranium resources against this projected increase in nuclear power use leads us to infer that there could be a nuclear fuel supply shortage or substantial uranium price increase sometime after 2025, and probably not before.

We do not advance this argument to support a contention that breeders are not necessary. Rather, we believe that breeders will produce nuclear fuel to be consumed in converter reactors more cheaply than the equivalent of $1000 per kg U we might project for "burning the rocks." And the environmental impacts would obviously be less. The point of the argument is that we do not envision any future lack of fuel for the reactors of the First Nuclear Era or for the converter reactors of the Second Nuclear Era.

We looked briefly at the prospects for breeders, of which four types are apparent:

a. fast breeders, principally the liquid-metal fast breeder reactor (LMFBR)

b. fission-fusion hybrids

c. accelerator-driven breeders

d. thermal breeders

Fast breeders are on the threshold of commercial application with the advent of large prototypes in France and the USSR. The LMFBR is a promising technology for maintaining low fuel costs and moderate electricity costs in an expanding nuclear economy.[134] For scenarios with low nuclear growth, it will be necessary to bring their capital costs down for them to compete with improved converter reactors. We hope that through studies such as the Rockwell and Argonne National Laboratory effort,[135] LMFBR capital costs can be brought down to approach those of LWRs.

Fission-fusion hybrids[136] are believed by some to be the most feasible embodiment of fusion technology. If so, one might envision nuclear fuel factories based on fusion neutrons. These plants might produce little or no surplus power, but one reactor might support a dozen or more converter reactors. The fuel factory would contain a complete set of fuel reprocessing, fabrication, and high-level nuclear waste treatment facilities. The choice of LMFBR versus the hybrid would clearly be based on economic and commercial feasibility, not to speak of the technical feasibility of fusion.

The "electric" breeder based on the use of neutrons produced in accelerator targets might be developed.[137] The scientific feasibility of this approach is well established and the technology of high-energy, high-current accelerators continues to improve. There is no evidence that this type of fuel production would be economic, but if the other breeder concepts fail, accelerator-produced fuels may be able to compete with or supplement uranium from ore.

The expected impact of more costly uranium on converter reactors would be the adoption of more efficient fuel cycles. Fuel recycle based on reprocessing would be adopted. The enrichment plant stripping of ^{235}U from tailings combined with fuel reprocessing and recycle could readily improve the fuel utilization of LWRs by a factor of two. An additional factor of 1.3 might be gained by spectral shift control as envisaged for the Westinghouse APWR. More radical changes, such as the tight-pitch lattices investigated in the DOE light water breeder program, are possible, but the economics of these designs have not been adequately explored. Heavy water reactors and HTGRs have historically been regarded as efficient machines for fuel recycle.

Finally, thermal breeders represent an ultimate evolution of thermal reactors. The U.S. Department of Energy has operated the Shippingport PWR with a ^{233}U-thorium core intended to demonstrate thermal breeding. We are not convinced that even for high-cost uranium it would ever be economic to breed in light water, heavy water, or gas-graphite reactors. However, it could well become economical to consume

10 percent of the source material (uranium plus thorium) in efficient converters, as compared to 0.6 percent in present LWRs or 60 percent plus in breeder cycles. Another potential thermal breeder system was operated successfully in the Molten Salt Reactor Experiment (1965 to 1969). This concept is based on a circulating fuel consisting of a mixture of fluoride salts and a graphite moderator. We continue to regard molten salt reactors as practical breeders should they be developed.

The breeder would be needed as a commercial entity before 2035-2050 to support rapid growth of nuclear power if fossil fuel consumption were reduced by government edict because of environmental or national security considerations. Though this now appears unlikely, the U.S. government and the governments of other industrial nations believe the development of renewable, ultimate energy sources is sufficiently important to justify R&D expenditures on such technologies of about $2 billion per year. This is not an unreasonable sum in relation to the current cost of the world's energy, roughly $1 trillion per year.

Nuclear weapons proliferation is a risk which must be considered in long-term planning of the nuclear fuel cycle. In general, recent United States and international studies[138,139] have concluded that diversion of weapons material from a civilian nuclear fuel cycle is not an attractive route for the production of nuclear weapons. Furthermore, continued use of the LWR fuel cycle as envisioned for the Second Nuclear Era tends to be as proliferation-resistant a choice as can be made.

From this analysis of the options for assessing adequate supply of uranium, we conclude

1. A Second Nuclear Era based on converter reactors is likely to last a very long time. R&D funds should therefore be spent to ensure that the reactors are the ones we want.

2. Breeders are unlikely to compete with LWRs for the next fifty years unless their capital costs are low. Achievement of such low capital costs should be a primary goal of breeder development.

Nuclear Waste Management and Siting

Nuclear waste management is driven by several forces, none of which supply clear guidance for immediate action. These forces are (a) the desire to demonstrate that high-level wastes can be managed permanently in an environmentally acceptable way and actually to implement a high-level waste disposal project, (b) the uncertainty about the timing and form of fuel recycle, and (c) the nuclear weapons proliferation risk of the plutonium contained in growing national stocks of spent fuel.

The passage of the Nuclear Waste Policy Act of 1982[140] represents the most important action yet taken by the United States toward resolving the waste issue. The Act provides a schedule for the siting, construction, and operation of repositories that will protect the public and the environment from any hazards of high-level waste. It also establishes the federal responsibility for disposal of such waste. It defines the relationships between federal and state governments. Finally, for financing the program it establishes a superfund collected from the utilities generating nuclear power.

The implementation of the Act would demonstrate the feasibility of high-level waste disposal in a U.S. setting. We are concerned that the Act provides no clear mechanism for adjudicating a governor's veto of a site other than a Congressional override. However, the legislation contains provisions for possible substantial inducements to communities and regions for their participation. We recommend that such inducements conceived imaginatively be offered to the states and localities designated as waste disposal sites.

We are impressed with the progress being made in Sweden toward high-level waste disposal.[141] The national government is setting up facilities, in rock, for the interim storage of spent fuel for up to 60 years. At that point, the radioactivity would have decayed to a level where only minimal heating would occur in a permanent repository, also being set up by the Swedish government.

Aside from the mandated demonstration of permanent disposal of a portion of the U.S. waste, we believe that most of it should be stored for 50 to 100 years to decay. This would allow time for sorting out the reprocessing questions and for optimizing the permanent storage technology. In the interim, wastes could best be stored at the reactor sites (which are already likely to be dedicated to long-term nuclear use). There may be a need for some centralized interim storage facilities to be owned by the federal government, also provided for in the Nuclear Waste Policy Act.

The Institute for Energy Analysis has for a number of years advocated a nuclear siting policy which concentrates reactors into relatively few dedicated sites.[142] Concentrated siting would be safer as well as more economical than our current dispersed siting of reactors. Such a policy could be implemented in the United States by adding reactors to the existing 100-odd sites. It would confer an element of permanence to the sites and thereby open new options for waste management and reactor decommissioning. This concentrated siting policy fits well into our strategy of a Second Nuclear Era.

CHAPTER III. INSTITUTIONAL ISSUES FOR A SECOND NUCLEAR ERA

Institutional issues are covered in several papers supporting the study of a Second Nuclear Era.[143,144] The institutional considerations, however important, were not studied in sufficient depth to justify strong recommendations. However, we provide a brief overview of our findings in this chapter.

LICENSING AND REGULATION

A Second Nuclear Era will require regulatory stability and predictability; their absence today is one of the factors which inhibits utilities from committing to multibillion dollar nuclear investments. Efforts to produce greater regulatory stability and to streamline the licensing process have been launched repeatedly during the 1970s and 1980s. Licensing reform bills are currently before Congress. Despite support from both Democratic and Republican administrations these efforts have not yet gained the approval of Congress.

Licensing and regulatory reform measures have not gained favor because when promoted in isolation they engender public suspicion. They might better be brought forth in association with a commitment from the nuclear industry for producing greater safety margins. Licensing reform might be feasible only if it is part of broader regulatory and safety reform.

There are a number of desirable licensing and regulatory reforms being currently proposed,[145] including the following:

1. early site review and approval
2. one-step licensing, eliminating the need for obtaining an operating license
3. state takeover of various NRC responsibilities (e.g., environmental impact assessment and determination of need for power)
4. prohibition on retrofitting, except (1) at the request of the owner-operator or (2) when it can be shown by the NRC that there would be a cost-effective reduction of risk

These licensing and regulatory reforms are commonly associated with the development of standard plants. Standard plant designs could be given early generic approval. Early site approval combined with early design approval of a standard plant could substantially reduce the time between a utility's decision to build a plant and its commercial operation.

INDUSTRY AND REGULATOR

Though licensing and regulatory reforms are frequently raised in discussions of institutional or nontechnical matters, the underlying relationship between the industry and its regulator (the NRC) is not often discussed. Yet it is vital that this relationship be reassessed in any examination of a Second Nuclear Era.

Perhaps the most significant feature of the United States nuclear industry today is its fragmentation. Forty-three utilities or utility consortia own and operate commercial nuclear power units today, and it is likely that 17 more utilities will be in the nuclear business by 1990. Some of these utilities serve as their own constructors, but more frequently they contract with privately-owned architect-engineers (AEs) to design and construct the large majority of the generating facility. There are at least 12 AEs today that can perform this role. In addition, four reactor vendors provide nuclear steam supplies to the utilities. The dispersed U.S. industry contrasts sharply with the nuclear industries found in other nations. France has the most centralized nuclear industry with one nationalized utility, one nuclear steam supply vendor, and two architect-engineers. Canada's nuclear industry is also highly centralized, with most construction taking place in Ontario and under the auspices of one utility and vendor (together serving as their own architect-engineers).

The fragmentation of the U.S. nuclear industry produces two major problems. First, with a large number of organizations involved, it is exceedingly difficult to ensure a quality performance from all. Regulatory scholars have noted that members of regulated industries, across numerous fields of endeavor, invariably demonstrate differing degrees of managerial capability and dedication to safety. The poor performance of some can cast a shadow over an entire industry. Second, with fragmented responsibilities, no one organization acts as an overall integrator for safety. Reactor vendors supply the nuclear steam supply system; AEs are responsible for the design and procurement of equipment for the balance of the plant; and the utilities are responsible for quality assurance and licensing. With each organization concentrating upon its own area of responsibility, work at the interface of these activities often suffers.

Recognizing these problems and being attuned to public pressures, the Nuclear Regulatory Commission has felt obliged to play an increasing role in the nuclear business. The NRC, realizing that an accident or inadequate safety management anywhere reflects negatively upon the utility, the technology, and the NRC itself, increasingly tries to define what safety is--in innumerable rules and regulations--and aims to enforce compliance through these standards.

The strong interventionist policy of the NRC, designed to overcome the structural weaknesses of the industry, in turn produces problems of its own. First, and perhaps most deleterious, accountability, and not responsibility, becomes the industry's operating mode. Regulators and industry officials gradually come to view conformity or compliance with the rules, rather than actual performance indicators, as the measure of safety. So much time and attention are devoted to these surrogate measures of safety ("complying with the regulations") that the larger goal of such regulation may be neglected. Industry innovation does not take place perhaps because the sense of responsibility has shifted or because industry fears that these initiatives will simply be added to (not subtracted from) the requirements that the NRC already imposes.

Second, the shift in responsibility to the regulator can have serious safety implications because a central bureaucracy, no matter how capable, cannot provide consistent regulation to a diverse and varied industry at the level of detail required by NRC standards. Diverse capabilities and circumstances require a flexible approach to safety management; a central bureaucracy by its very nature is not capable of that flexibility. Third, this mode of regulation can devastate the industry's morale and its devotion to duty. Constant oversight and punitive action in the event of noncompliance with the rules produce an unhealthy spirit of skepticism and resistance toward all regulation.

Hence, while the NRC has sought to overcome institutional weaknesses, it has also created its own problems, not the least of which is the highly adversarial relationship between it and the industry.

SELF-REGULATION

In recognition of the aforementioned problems and in response to the TMI accident, the nuclear industry itself has taken a number of positive institutional safety-related steps. These measures have already been mentioned in Chapter II. They include the establishment of internal utility safety oversight organizations, INPO, NSAC, NEIL, the Industry Degraded Core Rulemaking Program, and an increase in Nuclear Utility Task Action Committees. Because of this heightened activity, it is possible for the first time to conceive of a nuclear regulatory regime that is imposed from within (industry self-regulation) as well as from outside (the NRC). Though it is inconceivable that the NRC would be removed from its statutory duties, it is possible to envision the NRC operating in a less prescriptive (more performance-based manner) than in the past due to industry self-regulating practices.

The institutional focus for self-regulation has been INPO. INPO's efforts to bring industry performance up to a uniform and acceptable level of performance have been very promising. It is not yet possible, however, to gauge the extent to which INPO has seized the attention of all nuclear utilities. It would be unrealistic to expect NRC regulation to change or diminish significantly on the basis of INPO's efforts thus far. The onus, therefore, is on INPO to demonstrate that through its efforts effective regulation is indeed taking place and can be carried out in lieu of (not in addition to) NRC regulation.

POSSIBLE INSTITUTIONAL FUTURES

It is now recognized that a successful nuclear power reactor project requires strong management and a strong technical organization. This one observation suggests that a Second Nuclear Era would not be a simple repetition of the First Era with its proliferation of designs, vendors, architect-engineers, and utility customers. The institutions will be limited by the availability of talent. One appropriate response to significant capacity expansion would be the formation of new institutional variants such as service companies, utility-owned regional companies, or even a government-owned regional nuclear power authority. Some of these entities are already emerging.

Nuclear service companies could be individual corporations that would be employed by nuclear utilities to carry out onsite technical and managerial tasks related to the construction and operation of nuclear facilities. Utilities would retain ownership and financial and liability responsibilities but would delegate safety responsibilities in selected areas (the scope of which could run the gamut from narrow, focused jobs to full and complete responsibility). Service companies are rather commonly used at large-scale and complex government-owned facilities. No service companies, with broad safety mandates, however, have yet appeared to serve several utilities.

A more ambitious institutional undertaking would be the establishment of utility-owned regional nuclear power companies (RNPCs). These companies would be formed by a group of utilities to have complete financial, operational, licensing, and safety responsibilities pursuant to the construction and operation of nuclear power facilities. Utility ownership of RNPCs would be a further extension of the now-common practice of multi-utility ownership/single utility management of existing nuclear power plants. RNPCs would generate electricity from nuclear power facilities and parcel the electricity to its utility owners, who in turn would carry out their normal transmission and distribution tasks.

An even more radical variant of the utility-owned regional company would be a government-owned regional nuclear power authority (RNPA). These organizations would be self-financed and generate power from nuclear facilities and sell it to existing utilities for further distribution.

Institutional configurations for a Second Nuclear Era are closely related to siting policy. Concentrated reactor siting, as advocated by the Institute for Energy Analysis, would probably lead to consolidation of the utility industry into relatively few operating entities, each entity capable of handling the extremely large blocks of power produced by three or four such sites.

Operation at concentrated sites should be safer than operation at dispersed sites. However, if the reactors are already inherently safe, as might be the case in a Second Nuclear Era based on inherently safe reactors, then the advantages of site concentration are less pressing. Thus we concede that the incentive to concentrate sites, just as the incentive to consolidate utilities, in some measure depends on the technology available.

CHAPTER IV. SUMMARY, RECOMMENDATIONS, AND PLANS

SUMMARY OF FINDINGS

This study sought first of all to determine whether there exist plausible concepts for intrinsically safe reactors. As a prelude to this investigation, we examined the safety of today's reactors, especially in the light of the lessons learned from the Three Mile Island-2 accident. Further, since a resurgence of nuclear energy demands that reactors be cost-competitive, we studied the economics of nuclear power today and in a Second Nuclear Era based on reactors that are more forgiving than are today's reactors.

Regulatory and other institutional improvements, though not central to this largely technologically oriented study, were given some attention, as were fuel assurance, waste disposal, and siting.

In this section we summarize our findings on each of these matters.

The Safety of Current Reactors

If we measure the safety of reactors by the median probability of a core melt as revealed by PRA, then we must conclude that every one of the commercially available reactors--LWR, BWR, CANDU, and HTGR--is quite safe, i.e., its median core-melt probability is not higher than the proposed NRC safety goal, 10^{-4} per reactor-year. We found that the core-melt probability for LWRs is on average about three- to sixfold lower today than it was before Three Mile Island because of voluntary and Nuclear Regulatory Commission-mandated changes carried out after Three Mile Island. This improvement more than compensates for the pre-TMI core-melt probabilities being higher than the median of Rasmussen's range. In addition, estimates of the source term have been reduced considerably for most accidents (by a factor of about 20), and better evacuation planning may be counted upon to reduce the consequences estimated in WASH-1400 perhaps by another factor of two. Thus, application of the methods used in WASH-1400 suggests that the likelihood of a large release that causes many casualties from post-TMI LWRs is at least an order of magnitude, and perhaps two orders of magnitude, lower than was predicted in WASH-1400. In any case, most post-TMI LWRs seem to have median core-melt probabilities that are below 10^{-4} per reactor-year.

Are Current Reactors Safe Enough?

We have accepted, somewhat arbitrarily, NRC's proposed safety goal of a core-melt probability of 10^{-4} per reactor-year. In a 500-reactor world, this implies one core melt (worldwide) per 20 years on the average.

As our work progressed, we came to realize that we must distinguish more clearly between the current period that ends with the century, when the total number of power reactors in the world will be close to 500, and the period of the Second Nuclear Era (20 to 50 years later) when the world's reactors may number several times or even ten times more. The latter contingency may seem remote now, but if the CO_2 or even acid rain issue becomes urgent within the next 20 years, pressure to move to heavy dependence upon nuclear energy might become very strong. Thus the core-melt probability of 10^{-4} per reactor year, which we accepted as a reasonable goal in a 500-reactor world, is almost surely insufficient in a world with many more reactors.

Studies of advanced PWRs and BWRs and the Sizewell-B concept indicate that light water reactors (with capital costs 20 percent higher than that of present plants) should achieve a 10^{-5} per reactor-year core-melt probability. This should make them useful in a Second Nuclear Era even if there is a large expansion of nuclear capacity. We also suggest that a core-melt probability of 10^{-5} per reactor year could be used as a safety goal for a Second Nuclear Era.

Comparison of Existing Reactor Types

We have not tried to compare PRAs for the different types of commercial reactors. The non-uniform basis and quality of existing PRAs makes a detailed comparison all but impossible. Nevertheless, our impression based on the data available to us (for LWR, CANDU, and HTGR) is that there is little difference between LWR and CANDU, but HTGR shows distinctly lower consequences for accidents that in light water reactors may cause offsite releases. On the other hand, HTGRs seem to have about the same probability of loss of the plant as do LWRs.

Prospects for Inherently Safe Reactors

Despite our finding that existing reactor types as judged by PRA are adequately safe for wide deployment in a Second Nuclear Era, we believe any such estimates will always be subject to considerable uncertainty. We therefore believe it very desirable to develop reactors whose safety is inherent and manifest and does not depend on intervention of devices, each of which has some probability of failing, or on operator skills and good judgment, which could vary considerably.

The Process Inherent Ultimately Safe reactor proposed by ASEA/ATOM appears to be inherently safe--i.e., no sequence has been identified that would lead to a core melt. Moreover, PIUS seems to be highly resistant to acts of sabotage or war and to be particularly forgiving of inadvertency on the part of the operator. If PIUS could be built as cheaply as an LWR, and if it could be operated conveniently and reliably, then it could be a means for restoring confidence, as well as increasing utility interest, in nuclear power.

While PIUS is a unique concept, we expect that it is not the only possibility for an inherently safe reactor. The fail-safe nature of small modular gas-cooled reactors has been demonstrated at the AVR in West Germany. Various pool-type breeder concepts and molten salt reactors may be inherently safe as well. The PIUS concept is recommended here because, of the inherently safe choices, it takes advantage of well-understood light water reactor technology and has the best known protection against sabotage and acts of war. Nevertheless the other systems, notably the modular HTGR, are also recommended for serious examination.

Costs

There will be no Second Nuclear Era unless the costs of nuclear power are kept under control. Perhaps as important as the absolute capital cost of reactors is predictability of capital costs: unless the cost of a new plant can be judged reliably before construction begins, few nuclear plants are likely to be ordered.

The cost of nuclear power from the plants currently in operation is low, provided average or better plant availability is achieved. By current standards, the initial investment in these plants was a bargain, and even if the order of $150 per kW has been spent on each unit for retrofitting, the plants are still very competitive with fossil plants.

The plants currently under construction have expected costs varying from about $1100 per kW to $3500 per kW or more (in 1983 $). At the low end of the scale, nuclear power is competitive with coal; at the high end of the scale, nuclear power is unattractive.

The increased cost of nuclear plants is attributed to many mutually reinforcing factors: increased materials and labor costs resulting from regulatory pressures, poor labor productivity, higher interest rates, extended construction schedules, and general inflation. In a Second Nuclear Era it should be possible to improve at least some of these factors: reduced labor content through standard designs and reduced interest and escalation through improved construction schedules. In the case of inherently safe reactors, the balance-of-plant costs should be reduced significantly by use of standard commercial equipment and construction practices; this would compensate for any increased cost of the nuclear steam supply.

Reactor Regulation

The cost of nuclear plants is sensitive to their regulation. Only if requirements imposed by the NRC do not change during construction are firm estimates of capital cost possible. Thus a Second Nuclear Era will require regulatory procedures that are stable.

We are not prepared to say whether the incrementally improved LWRs can be proven in advance to have no deficiencies that would be revealed after construction has begun. Were such deficiencies to be found, expensive and unexpected retrofits might be required. On the other hand, the improved LWRs, meeting as they do stringent safety criteria, ought to be less liable to expensive retrofits than are existing reactors. We would hope that the NRC, in promulgating its regulations, will take full account of the improvements being incorporated in newer LWRs.

If reactors are indeed becoming as safe as PRAs predict and since utilities are increasing their competence, we find the NRC's present approach to regulation becoming unnecessarily burdensome. We believe a more performance-based approach to regulation will lead to safer, more operable plants and better relationships between the NRC and the utilities.

Should inherently safe reactors become commercial, we would expect the regulatory burden for those plants to become far less than it now is. Perhaps more accurately, such concepts can become competitive only if their inherent safety is recognized by the NRC and resulted in a relaxation of prescriptive regulatory restrictions as compared to those imposed upon reactors that depend on active safety systems.

Assurance of Fuel Supply, Waste Disposal, and Siting

Assurance of fuel supply, waste disposal, and siting, though not directly affecting safety of reactors, nevertheless is central to the long-term future of nuclear energy. Though we have devoted relatively little study to these issues, we offer the following observations with regard to them.

Assurance of Fuel Supply

When breeders were first proposed, reactor capacity was expected to expand rapidly, and this was expected to exhaust the known uranium resources. Rapid development and commercialization of the breeder appeared to be the only way to assure fuel for a rapidly expanding nuclear industry.

Considerable worldwide progress has been made in breeder technology and commercial-scale prototypes will soon be in operation. The capital costs of breeders have thus far been too high to support immediate widespread deployment. Moreover, the slower-than-anticipated growth of nuclear capacity has provided time for emergence of other alternatives, including the following:

1. more efficient use of uranium in converter reactors
2. uranium from sea water and other low-grade sources
3. fission-fusion hybrids
4. accelerator-driven breeders

Alternative 1, the high gain converter, has always been an option but does not provide an essentially inexhaustible energy source.

Though enthusiasm for fission-fusion hybrids and for uranium from sea water run high in some quarters, we consider a shift in emphasis away from the breeder in favor of these still speculative possibilities to be unjustified. With respect to fission-fusion hybrids, we believe the proper time to initiate major efforts is after, not before, a plasma usable in a fission-fusion hybrid has been demonstrated. With respect to uranium from sea water, we remain skeptical of the claims that the sea can yield an essentially inexhaustible supply of uranium at less than $200 per pound of U_3O_8. The large Japanese pilot plant for recovery of uranium from sea water is scheduled to operate by the mid-1980s.[146] At that time a reassessment of the prospects for uranium from the sea is indicated.

We have been unable to find a basis for enthusiasm over the economics of the accelerator breeder and therefore find no basis for development at this time. Nevertheless, it cannot be ruled out as a long-term option.

Since nuclear energy worldwide is growing slowly, the pressure for greatly extending the fuel supply has relaxed. Nevertheless, we recognize that incentives to deploy reactors rapidly could develop again, and therefore assurance of fuel supply could once more become a pressing concern. We therefore recommend

1. continuing development of breeders,
2. continuing development of more efficient converter fuel cycles,
3. continuing assessment of the fission-fusion hybrid, the accelerator breeder, and extraction of uranium from the sea.

Waste Disposal and Siting

The passage of the Nuclear Waste Policy Act of 1982 represents the most important action ever taken by the federal government toward resolving the waste disposal issue. The 1 mill per kWh assessment on users of nuclear power will yield about $300 million per year (increasing to some $600 million by the 1990s) for waste disposal and should go far toward ensuring serious, adequately funded attention to waste disposal.

We believe that irradiated nuclear fuel should continue to be stored for a long time (50 to 100 years) at the reactor site to reduce the risks of fuel transportation and of potential overheating of the rocks surrounding the nuclear waste repository. In effect, we would be dedicating the reactor sites to more or less permanent use by the nuclear industry. Though we mention this siting policy in the context of storage of spent fuel, we point out that the longevity of these sites implied by this strategy makes these sites well suited for accommodating additional reactors. We point out that multireactor sites are the rule rather than the exception almost everywhere, except in the United States. We would encourage such siting policy for the United States in a Second Nuclear Era.

We are concerned that the Nuclear Waste Policy Act provides no clear mechanism for adjudicating a governor's veto of a site other than a Congressional override. To avoid such confrontation, we recommend that imaginative inducements, including liberal financial ones, be offered to states and localities designated as waste-disposal sites. The exact nature of such inducements would have to be worked out by the managers of the Federal Radioactive Waste Disposal Program. We urge that this matter be given priority so that the federal government is not forced to initiate poorly analyzed remedies should it be confronted with a governor's veto of a proposed waste disposal site.

RECOMMENDATIONS

Conclusions and Bases for Recommendations

Based on the findings just summarized, we have come to two main conclusions and recommendations:

1. That incrementally-improved, post-TMI light water reactors pose very low risks to the public even in a world with several times as many reactors as are now operating. However, investor risk and high, uncertain capital cost may limit their market.

2. The development of a Process Inherent Ultimately Safe (PIUS) reactor or other inherently safe concepts should be undertaken to provide a technological alternative with intrinsic safety as an option for widespread deployment in the future. If preliminary development of the system continues to show promise, a prototype of such a reactor should be built to better determine its operability and economics and to prove its safety characteristics.

The development of very safe reactors is already taking place with the development of ABWR, APWR, and Sizewell B. Thus an LWR adequate for a Second Nuclear Era ought to be available well before the year 2000. If the incrementally improved LWR is to be the only option available for a Second Nuclear Era, there may be little that government or the nuclear enterprise need do beyond what is now being done.

We are unconvinced that such a laissez-faire approach provides an adequate range of options or is an optimal course for extensive deployment of reactors in a world where there is extensive concern about the safety of nuclear plants. With acid rain and CO_2 continuing to accumulate and with the other nonfossil sources of electricity beset with uncertainties, we believe it necessary to consider what more could be done to ensure a successful Second Nuclear Era. We therefore offer the following observations both on the design of the Second Nuclear Era and on measures to be taken by the various actors to ensure a successful Second Nuclear Era.

Our considerations are largely confined to the United States; yet because the United States is so well endowed with coal, the case for nuclear energy is not as strong here as it is in much of the rest of the world. As of this writing, more nuclear power is being generated outside than inside the United States. Moreover, the capacity factors of reactors in a number of European countries, as well as in Canada, are significantly higher than in the United States. These trends augur a future in which the United States becomes a bystander in nuclear energy. Thus a Second Nuclear Era may, in countries such as France or Japan or the Soviet Union, simply be a continuation of the current era; whereas in Sweden, the United States, and the Netherlands, a Second Nuclear Era may require more positive public perceptions of nuclear energy.

An Inherently Safe Prototype Reactor Should be Built

We urge development of PIUS or an equivalent inherently safe concept, possibly a modular HTGR, to a stage where its practicality can be determined. This would require a prototype--say, 100 MWe. Such an undertaking might be international, and we can envisage private sources providing some of the funds.

We are not unmindful that this recommendation could be interpreted to imply that we do not believe current reactors are safe enough. On the contrary, we are convinced that existing, post-TMI reactors pose low risks to the public. We believe, too, that evolutionary changes to LWRs could make them safer still. However, the evolutionary changes to LWRs have tended to improve safety at the expense of greater complexity and cost. We believe that a reactor that derives safety from simple features that are inherent in the system could profoundly increase the acceptability of nuclear energy.

The considerations that justify the government's pursuing inexhaustible long-term energy sources for possible deployment 20 or even 50 years from now also justify development of PIUS for possible deployment in a world where a forgiving reactor may find a large market and increase the usefulness of the nuclear option. The safety of the PIUS reactor is transparent and relies on the inherent design, in contrast to the safety of conventional reactors which require elaborate safety systems. It should therefore be possible to design a relatively simple and, we hope, cheap reactor. Being smaller than conventional LWRs, a smaller investment would be committed per unit. The risk of losing the investment or not being able to complete the plant would be small. The technical expertise and security force required to operate the plant safely would be much less than for a conventional LWR. Finally, the availability of a forgiving reactor may contribute to public acceptance of nuclear power.

We estimate that to develop and then build a 100 megawatt PIUS reactor might cost $500 million and might require 10 to 12 years from the time the project started. Such a project would be carried out in stages. The first stage would involve conceptual studies with the intent of selecting the best inherently safe concept. The second stage would involve system and hardware development to prove the underlying principle to be sound. The final, and most expensive stage would include the detail design, licensing, and construction of the reactor.

Would demonstration of PIUS compromise the existing reactor industry? We do not believe this to be a realistic concern now, since there is so little prospect for new reactors in the United States at present. Should PIUS turn out to be cheap, as well as inherently safe, it would undoubtedly become an opportunity for, as well as a challenge to, existing reactor manufacturers. The skepticism of some reactor vendors does not in itself constitute sufficient reason for ignoring PIUS.

A demonstration of PIUS would be a necessary step in proving both technical and commercial feasibility of the concept. A prototype of the modular HTGR would also be necessary as a step toward commercialization and to demonstrate its inherent safety.

PLANS FOR A SECOND NUCLEAR ERA

In this section we visualize a plausible institutional framework for the Second Nuclear Era, and offer some observations on how the transition to this era may be achieved. We assume, based on our previous findings, that both inherently safe and improved LWRs will be available within the next 15 years.

Time Horizon

The depressed demand for new nuclear power plants makes it unlikely that there would be many new orders before the 1990s. Considering the time lag for plant construction, we then get to the turn of the millenium before new plants are in operation. If there is to be a Second Nuclear Era in the United States, a convenient target date is the year 2001.

If current projections of continued but slow energy growth are correct, the United States would require on the order of 500 GWe of nuclear capacity in the first half of the 21st century. The ultimate capacity might be greater if fossil fuels are to be phased out of baseload electricity generation or if the trend toward electrification continues to be strong.

The converter reactor technology to be deployed will have a long useful life, especially if efficient fuel recycle technology is developed.

Depending on the ultimate uranium resources, breeder technology would be phased in to maintain fuel supply.

Leadership

The original leadership for nuclear power came from the Joint Committee on Atomic Energy and its agency, the Atomic Energy Commission. The industry developed with the incentive provided; however, the political encumbrances of nuclear power have hindered the private sector from taking over leadership in the same sense that it leads the oil business.

Since the demise of the Joint Committee and the split-up of the AEC, leadership has been widely diffused, but the NRC appears to have more than its share of the initiative with the industry in a reactive mode. The absence of positive leadership has allowed the technology to drift into an uneconomic mode--turning off the future growth of the industry.

In an ideal world, the utility industry itself would take all the necessary measures to preserve the nuclear option as one of the two major generation technologies it needs. In a practical sense, that industry is too fragmented and in too weak a financial position to undertake such a long-term commitment.

We believe the utilities should be held accountable for a more limited, but still vitally important role. We are referring to their prime responsibility for safe and economical operation of their plants. We believe they should accept more responsibility for strengthening their management and technical capabilities, for initiating desirable improvements to their plants, and in supporting the efforts of the reactor manufacturers to develop better products. The industry should motivate the federal government to adopt policies conducive to the expansion of electric power facilities generally and nuclear power in particular.

If the government wishes to preserve a nuclear option, it needs to create leadership within the government to balance the regulatory mandate of the NRC. There is currently no government agency that dares to be innovative or to promote nuclear energy. Without such initiative by the government, the current de facto moratorium is likely to continue. The logical agency to provide leadership is DOE, reinforced by friendly committees in Congress.

Reactor Technology

Given favorable operation of the present plants, continued use of conventional LWRs is likely; the newer ABWRs and APWRs would involve a lower risk than present reactors, even in a world containing many more reactors than now exist. Nevertheless, we consider reactors that are as forgiving as PIUS, or possibly the modular HTGR, provided they are economical and practical, to be even more desirable than are the incrementally improved LWRs represented by ABWR and APWR.

The most important goal during the next decade is good operation of the existing power reactors; we cannot stress too strongly the importance of avoiding another TMI-like episode. With post-TMI improvements in place, a core melt during the next 20 years is unlikely, at least as judged by PRA. Nevertheless, we believe certain changes in the organizations and policies responsible for nuclear energy are desirable. They are as follows:

Regulation

The NRC's role must be defined in relation to the inherent safety of reactors: the greater the inherent safety, the smaller is the NRC's role. This central principle will have to be recognized if the advantages of inherently safe reactors are to be realized. Nevertheless, the NRC should continue to be the center of regulation in the United States; however, greater use should be made of incentives for self-regulation by industry organizations. For example, INPO should be allowed an expanded role in operator training and qualification, and its venture into construction auditing should be encouraged. No one has more to gain from safe, efficient operation and sound construction management than the owners of the plants. The insurance underwriters are another potential source of self-regulation by the industry.

The licensing of new plants, generally of standard designs, should be "one stop." The requirements should include, but not be limited to, satisfaction of safety goals. Once a license is granted, only cost-effective retrofits should be considered.

States or regional organizations should have a major role in determination of the need for power and siting.

Siting

It should be possible to get preapproval of sites for standard plants. In general, reactors should be located in clusters on land permanently dedicated to nuclear power. Low-level wastes and spent fuel should be stored onsite for long periods of time. Most of the reactors for the Second Nuclear Era could be placed on existing sites. The relatively few new sites that may be required should be selected to minimize risk to the general public as judged by PRA; however, safety goal criteria should be used to balance expenditures on risk reduction against other economic requirements.

The Industry

One cannot but envy the utility organization in France, England, or Ontario; in each instance a single powerful utility manages as many as 60 reactors, most of the reactors being identical. The opportunity for learning rapidly by transfer of information from one station to another is obviously very great.

Were the United States utilities organized along these lines, with very few generating entities each operating many reactors of standard type, we would be more comfortable with the prospects for a trouble-free Second Nuclear Era. Unfortunately, the utility industry in the United States is fragmented and is likely to remain so for the next 20 years.

What integration it possesses must be imposed by entities such as INPO, NSAC, and owners' groups that lie outside the regular utility framework.

Should continuation of the nuclear industry be based on large LWRs, we believe the marketplace is likely to limit new projects to utilities with demonstrated capability to manage reactor financing, construction, and operation. The government should encourage such consolidation. We hope that eventually in the Second Nuclear Era there will be no more than 20 companies generating nuclear power. If the total nuclear capability of the United States reaches 500 GWe, each company might generate 25 MWe--less than half of the nuclear power Electricité de France will be generating by the end of the decade.

On the other hand, a more diverse structure would be possible should an inherently safe reactor become available. There is no reason that the LWRs and the PIUS reactors could not compete, with the strong utilities having a wider choice of product.

Standard reactor designs would be developed principally by the reactor vendors based on owner-operator criteria and with architect-engineering support. Responsibility for construction management would be the utilities', who may choose to contract with a vendor for erection of a standard plant. However, the role of the architect-engineer would be reduced in that many identical plants would be built from one set of plans.

The industry would be supported by fuel cycle service vendors, EPRI (R&D), INPO (operations and construction standards), other technical service companies, and by an insurance pool. The amount of insurance available should equitably apportion the costs of a core-melt accident within the industry (without having to go to the politicians for contributions, as at TMI 2).

Fuel Assurance

Fuel assurance for the initial decades of the Second Nuclear Era is not a major concern. Spent fuel is stored onsite. If it is economic to reprocess fuel, some reactors might be dedicated to fuel recycling using high conversion fuel configurations. High-level waste from the reprocessing plants is placed into government-operated waste repositories.

Depending on fuel supply prospects, breeder technology would be developed and demonstrated in an international framework.

THE FUTURE OUTLOOK

This study has indicated a direction that, if taken, we believe will contribute to the success of a Second Nuclear Era in the United States. Overall leadership must come from the government. The various government agencies and the nuclear industry must work together to create the technology and the institutions. This will take time, and fortunately, the current de facto nuclear moratorium gives us some time. We hope it will be used wisely.

REFERENCES

1. Energy Information Administration, Monthly Energy Review, DOE/EIA-0035(83/06), June, 1983, p. 80.

2. Ibid.

3. "World List of Nuclear Power Plants," Nuclear News, August 1983, pp. 83-102.

4. Institute for Energy Analysis, Oak Ridge Associated Universities, Economic and Environmental Implications of a U.S. Nuclear Moratorium 1985-2010, Second Edition (Cambridge, Massachusetts: MIT Press, 1980).

5. David Lilienthal, Atomic Energy, A New Start (New York: Harper and Row, 1980).

6. M.J. Ohanian, ed., An Acceptable Future Nuclear Energy System, Condensed Workshop Proceedings, ORAU/IEA(R)77-26 (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1977).

7. M.W. Firebaugh and M.J. Ohanian, eds., An Acceptable Future Nuclear Energy System, Condensed Workshop Proceedings, ORAU/IEA-80-3(P) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1980).

8. M.W. Firebaugh, ed., Acceptable Nuclear Futures: The Second Era, Minutes from Workshop, ORAU/IEA-80-11(P) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1980).

9. "World List," Nuclear News.

10. Ibid.

11. A.P. Fraas, "Survey and Assessment of the Technological Options Available to the Nuclear Industry in the 1980 to 2000 Period," prepared for the Office of Technology Assessment, 1983, to be published as a working paper, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 1984.

12. Westinghouse Electric Corporation, Systems Summary of a Westinghouse PWR Nuclear Power Plant (Pittsburgh, Pennsylvania, 1971).

13. U.S. Nuclear Regulatory Commission, "Acceptable Criteria for Emergency Core Cooling Systems for Light Water-Cooled Nuclear Power Reactors," 10 CFR Part 50, Appendix A (Docket No. RM-50-1) (Washington, D.C., 1973).

14. M.L. Myers, private communication, October 11, 1983.

15. D. Phung, *Economics of Nuclear Power: Past Record, Present Trends, and Future Prospects*, Research Memorandum, ORAU/IEA-83-13(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1983).

16. Ibid., p. 5.

17. William L. Rankin et al., "Nuclear Power and the Public: An Update of Collected Survey Research of Nuclear Power," Battelle Memorial Institute, Human Affairs Research Center, Seattle, Washington, December 1981.

18. U.S. Nuclear Regulatory Commission, *A Survey by Senior NRC Management to Obtain Viewpoints on the Safety Impact of Regulatory Activities from Representative Utilities Operating and Constructing Nuclear Power Plants*, NUREG-0839 (Washington, D.C., August 1981).

19. L. Martel, L. Minnick, and S. Levey, *Summary of Discussions with Utilities and Resulting Conclusions*, EPRI (RP 1585) (Palo Alto, California: Electric Power Research Institute, 1982).

20. Energy Information Administration, p. 71.

21. U.S. Atomic Energy Commission, *Civilian Nuclear Power--A Report to the President* (Washington, D.C., 1962).

22. Phung, "Economics of Nuclear Power," pp. 4, 5.

23. Energy Information Administration, p. 80.

24. Atomic Industrial Forum, INFO 168, September 1982.

25. Energy Information Administration, p. 4.

26. Ibid., p. 70.

27. "World List," *Nuclear News*, pp. 98-101.

28. U.S. Congress (97th), "Nuclear Waste Policy Act of 1982," Public Law 97-425, Washington, D.C., 1983.

29. Energy Information Administration, p. 70.

30. K. Hannerz, *Towards Intrinsically Safe Light Water Reactors*, Research Memorandum, ORAU/IEA-83-2(M)-Rev. (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1983).

31. C. Fisher et al., The HTGR--An Assessment of Safety and Investment Risk, GA-C16928, prepared by GA Technologies, 1983, to be published as a Research Memorandum (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

32. R. Reutler and G.H. Lohnert, "The Modular High Temperature Reactor," Nuclear Technology 62(July 1983):22-30.

33. Fisher.

34. E. Siddall, The CANDU-PHW Reactor in Relation to a Second Nuclear Era, Research Memorandum, ORAU/IEA-83-11(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

35. J.N. Barkenbus, Prospects and Opportunities for Nuclear Power Regulatory Reform, Research Memorandum, ORAU/IEA-83-5(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1983).

36. J.N. Barkenbus, "An Assessment of Institutional Alternatives for Nuclear Power," prepared for the Office of Technology Assessment, 1983, to be published as a working paper (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

37. Union Electric Co., Preliminary Safety Analysis Report: SNUPPS, (Calloway 1) Docket 50-483, 1979.

38. D.L. Phung, Assessment of Light Water Reactor Safety Since the Three Mile Island Accident, Research Memorandum, ORAU/IEA-84-3(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

39. R.R. Mathews, Current CEGB Safety Policy and Criteria, International Conference on Nuclear Power Experience, IAEA-CN42/126, September 13-17 (Vienna: International Atomic Energy Agency, 1982).

40. Westinghouse Electric Corporation, Sizewell B Probabilistic Safety Study, WCAP-9991, Rev. 1, Vols. 1, 2, and 3 (Pittsburgh, Pennsylvania, 1982).

41. Phung, "Assessment Since TMI," pp. 57-59.

42. Fraas, p. 3.

43. Ibid., p. 7.

44. F. Bevilacqua and J.L. Van Fleet, "Design Features of System 80 Nuclear Steam Supply System," TIS 7040, Combustion Engineering, Inc., presented at American Nuclear Society Nuclear Technology Exhibit, Beijing, People's Republic of China, October 23-31, 1981.

45. Fraas, p. 3.

46. Ibid., p. 3.

47. Ibid., p. 13.

48. Ibid.

49. Phung, "Assessment Since TMI," p. 58.

50. K. Paulsen, private communication, December 21, 1983.

51. Westinghouse Electric Corporation, Westinghouse's New 2-Loop Nuclear Power Plant, draft report, Water Reactor Division (Pittsburgh, Pennsylvania, 1982).

52. Babcock and Wilcox, 400-MWe Consolidated Nuclear Steam System (CNSS)--1255 MWt CNSS Design/Cost Update, BAW-1754, work performed for Oak Ridge National Laboratory, ORNL/Sub/8217456/1 (Oak Ridge, Tennessee: Oak Ridge National Laboratory, July 1983).

53. Martel et al., pp. A-6, A-7.

54. D.R. Wilkins et al., "A Post-TMI Look at Boiling-Water Reactor Plant Protection, Proceedings of IAEA Conference on Current Nuclear Power Plant Safety Issues, Stockholm, Sweden, October 20-24, 1980, pp. 103-120.

55. General Electric, BWR-6 Standard Safety Analysis Report, 50-531, February 13, 1975, San Jose, California.

56. Ibid.

57. D.R. Wilkins, "Advanced Boiling Water Reactor," General Electric, unpublished document, San Jose, California, August 1982.

58. L.R. Quarles, "Nuclear Station Achievement 1983," Nuclear Engineering International, July 1983, pp. 15-16.

59. "World List," Nuclear News, pp. 83-90.

60. Siddall.

61. C.E. Till and Y.I. Chang, "Heavy Water Reactors: Some U.S. Perspectives," *Proceedings of the Annual Meeting of the American Association for the Advancement of Science*, Toronto, Canada, Washington, D.C., January 3-8, 1981.

62. Siddall.

63. Combustion Engineering, Inc., *Conceptual Design of a Large HWR for U.S. Siting*, work performed for U.S. Department of Energy, Vol. 1-4, CEND-379 (Washington, D.C., September, 1979).

64. Electric Power Research Institute, *Study of the Development Status and Operational Features of Heavy Water Reactors*, EPRI NP-365 (Palo Alto, California, February 1977).

65. General Atomic, *HTGR Steam Cycle-Cogeneration Lead Plant Design and Cost Report*, work performed for U.S. Department of Energy, PC 0000040, GA Project 6654 (Washington, D.C., July 1982.)

66. Fraas, p. 3.

67. Fisher, Section 1, p. 7.

68. Phung, "Economics of Nuclear Power," p. 25.

69. Fraas, p. 32.

70. Fisher.

71. Reutler and Lohnert.

72. S. Untermyer, *Large Natural Circulation Reactors*, GEAP-32 (Class II) (San Jose, California: General Electric Atomic Power Equipment Department, September 28, 1959.)

73. S.N. Tower, letter to A.P. Fraas describing a deep-well reactor concept, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, November 4, 1982.

74. E. Lantz, "Inherently Safe Nuclear Power Plants," letter to the editor, *Nuclear Safety* 21(Jan.-Feb. 1980):25.

75. Rockwell International and Argonne National Laboratory, "Large LMFBR Pool Plant," presentation of Energy Systems Group, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 27, 1983.

76. Adolph Birkhofer, "The Use of PRA for Safety Evaluation," *Proceedings of International Meeting on Thermal Nuclear Reactor Safety*, NUREG-CP0027, Chicago, Illinois, August 29-September 2 (Washington, D.C., 1982).

77. M.A. Schultz and M.C. Edlund, *The Case for an Indestructible Reactor*, prepared for Institute for Energy Analysis, 1982, (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984.)

78. E. Teller, in David Okrent, *Nuclear Reactor Safety, On the History of the Regulatory Process* (Madison, Wisconsin: University of Wisconsin Press, 1981), p. 6.

79. Willard F. Libby, letter to Senator Bourke Hickenlooper, in David Okrent, p. 24.

80. Code of Federal Regulations, Title 10, Part 50 (10 CFR 50), Washington, D.C.

81. Ibid.

82. D.L. Phung, *Review of Light Water Reactor Safety Through the Three Mile Island Accident*, Research Memorandum, ORAU/IEA-84-2(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

83. Tennessee Valley Authority, *Preliminary Safety Analysis Report* (Brown's Ferry) (General Electric), Docket 50-259, 1971.

84. Portland General Electric, *Preliminary Safety Analysis Report* (Trojan), Docket 50-344, Update, 1982.

85. Consumers Power Company, *Preliminary Safety Analysis Report* (Palisades) (Combustion Engineering), Docket 50-255, 1968.

86. Tennessee Valley Authority, *Preliminary Safety Analysis Report* (Bellefonte) (Babcock and Wilcox), Docket 50-438, 1978.

87. J.W. Minarick and C.A. Kukielka, *Precursors to Potential Severe Core Damage Accidents: 1969-1979, A Status Report*, ORNL/NSIC-182 and NUREG/CR-2797 (Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1982).

88. Institute of Nuclear Power Operations, Nuclear Safety Analysis Center, *Analysis and Evaluation of the Crystal River 3 Incident*, INPO-1, NSAC-1 (Atlanta, Georgia, March 1980.)

89. U.S. Nuclear Regulatory Commission, *Annual Report* (Washington, D.C., 1980), pp. 88-90.

90. Institute of Nuclear Power Operations, Analysis of Steam Generator Tube Rupture Events at Oconee and Ginna, INPO 82-02 (Atlanta, Georgia, November 1982).

91. "Failure of Salem 1 to Scram Lends Urgency to--But Will Slow--ATWS Rule," Inside NRC 5, March 7, 1983.

92. Code of Federal Regulations, Title 10, Part 50, Appendix R, Washington, D.C.

93. Atomic Energy Commission, Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants, WASH-740 (Washington, D.C., 1957).

94. U.S. Nuclear Regulatory Commission, An Assessment of Accident Risk in U.S. Commercial Nuclear Plants, WASH-1400 (NUREG-75/014) (Washington, D.C., 1975).

95. F.L. Leverenz and R.C. Erdmann, Critique of WASH-1400, report prepared for Electric Power Research Institute, Science Applications, Inc., EPRI 217-2-3 (Palo Alto, California, June 1975).

96. Henry W. Kendall et al., The Risks of Nuclear Power Plants: A Review of the NRC Reactor Safety Study (Cambridge, Massachusetts: Union of Concerned Scientists, 1977).

97. H.W. Lewis et al., "Report to the American Physical Society by the Study Group on Light Water Reactor Safety," Reviews of Modern Physics, Vol. 47, Supp. 1, September, 1975.

98. J.G. Kemeny et al., Report of the President's Commission on the Accident at Three Mile Island (Washington, D.C.: U.S. Government Printing Office, 1979).

99. Mitchell Rogovin et al., Three Mile Island, A Report to the Commissioners and to the Public, NRC Special Inquiry Group (Washington, D.C., January 1980).

100. Institute of Nuclear Power Operations, Annual Report (Atlanta, Georgia, 1981).

101. John Higgins, Nuclear Insurance Newsletter, February 1983.

102. E.L. Zebroski, "The Dynamics of Institutional Changes Following the TMI Accident," Progress in Nuclear Energy 10.

103. I. Spiewak, An Investigation of the Nuclear Source Term, to be published as a Research Memorandum, ORAU/IEA-84-5(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1984).

104. Ibid., p. 18.

105. Phung, "Assessment Since TMI."

106. Minarick and Kukielka.

107. Power Authority of the State of New York and Consolidated Edison Company, Indian Point Probabilistic Safety Study, Vols. 1-12. (New York, New York, 1982).

108. Philadelphia Electric Company, Limerick Generating Station Probabilistic Risk Assessment, Vols. 1 and 2 (Philadelphia, Pennsylvania, June 1982).

109. Peter Groer, private communication, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 1983.

110. Tennessee Valley Authority, Annual Reports, Knoxville, Tennessee, 1981, 1982.

111. Gordon R. Corey, "An Economic Comparison of Nuclear, Coal, and Oil-Fired Electric Generation in the Chicago Area," Ann. Rev. Energy 6(1982):417-443.

112. Phung, "Economics of Nuclear Power," p.4.

113. Ibid., p. 6.

114. Quarles, p. 37.

115. Phung, "Economics of Nuclear Power," p. 6.

116. National Electric Reliability Council, The National Electric Reliability Council Equipment Availability--Composite Unit Summary, SR-82-99, prepared for Energy Information Administration, U.S. Department of Energy (Washington, D.C., 1982).

117. "World List," Nuclear News, pp. 97-101.

118. "Palo Verde Cited As Still Relatively Cheap Despite Pump Problems," Nucleonics Week, September 15, 1983, p. 5.

119. "World List," Nuclear News, pp. 97-101.

120. Atomic Industrial Forum, Inc., The New Reality: Update on Nuclear Plant Safety (Washington, D.C., March 1983).

121. National Economic Research Associates, Inc., report on Edison Electric Institute Study of Impacts of S. 768, "Impacts of the Bill on Acid Rain," Committee on Environment and Public Works, EEI News Release, Washington, D.C., June 28, 1983.

122. Energy Information Administration, Projected Costs of Electricity from Nuclear and Coal-Fired Power Plants, DOE/EIA-03561 (Washington, D.C., August 1982).

123. J.G. Asbury et al., A Case Study of Rate of Return Regulatory Policy Alternatives for Electric Utilities, ANL/EES-TM-198, (Argonne, Illinois: Argonne National Laboratory, August 1982).

124. U.S. Department of Energy, Office of Policy, Planning, and Analysis, The Future of Electric Power in America: Economic Supply for Economic Growth, report of the Electricity Policy Project, DOE/PE-0045 (Washington, D.C., June 1983).

125. John R. Siegel, "Changes in the Real Price of Electricity: Implications for Higher Load Growth," Public Utilities Fortnightly, September 15, 1983, pp. 32-42.

126. Gas-Cooled Reactor Associates, HTGR Steam Cycle/Cogeneration Lead Plant Design and Cost Report, GCRA 82-010, Vol. 1-3 (San Diego, California, July 1983).

127. M.L. Myers, private communications, October 11 and 17, 1983.

128. Gas-Cooled Reactor Associates, pp. 3-11.

129. Westinghouse Electric Corporation, Westinghouse's New 2-Loop Nuclear Power Plant.

130. G.R. Smallen and J.G. Delene, Power Generation Costs for Alternate Reactor Fuel Cycles, ORNL/TM-7376 (Oak Ridge, Tennessee: Oak Ridge National Laboratory, September 1980).

131. OECD Nuclear Energy Agency and International Atomic Energy Agency, Uranium, a joint report (Vienna, 1982).

132. Karl Cohen, "Global 2000 Revised Nuclear Power," draft, 1983, to be published (Washington, D.C.: The Heritage Foundation).

133. OECD Nuclear Energy Agency.

134. International Atomic Energy Agency, *International Nuclear Fuel Cycle Evaluation*, Summary Volume, INFCE/PC/2/9 (Vienna, January 1980).

135. Rockwell International and Argonne National Laboratory.

136. H.A. Bethe, "Fusion Hybrid," *Physics Today* 32(May 1979):44-51.

137. Energy Research and Development Administration, *Proceedings of an Information Meeting on Accelerator-Breeding*, CONF-770107, held at Brookhaven National Laboratory, January 18-19 (Upton, New York, 1977).

138. U.S. Department of Energy, *Nuclear Proliferation and Civilian Nuclear Power*, Vol. 1, Program Summary, Report of the Nonproliferation Alternative Systems Assessment Program (Washington, D.C., 1980).

139. International Atomic Energy Agency.

140. U.S. Congress.

141. Swedish Atomic Forum, *Swedish Nuclear News* No. 2 (October 1983), p. 5.

142. C.C. Burwell and J.A. Lane, *Nuclear Site Planning to 2025*, ORAU/IEA--80-5(M) (Oak Ridge, Tennessee: Institute for Energy Analysis, Oak Ridge Associated Universities, 1980).

143. Barkenbus, "Prospects and Opportunities."

144. Barkenbus, "An Assessment of Institutional Alternatives."

145. Barkenbus, "Prospects and Opportunities."

146. Atomic Energy Society of Japan/International Atomic Energy Agency, International Meeting on Recovery of Uranium from Seawater, October 17-19, 1983, Tokyo, Japan. (Proceedings to be published).

COMMENTS BY MEMBERS OF THE SECOND NUCLEAR ERA ADVISORY COMMITTEE

At the final meeting of the Advisory Committee of the Second Nuclear Era Project (in the summer of 1983) members of the committee were invited to submit their own personal comments on the study. Three members of the committee did prepare personal comments which follow.

Comments by Hans A. Bethe, Professor of Physics, Cornell University

Like the authors of this report, I believe that nuclear power will be increasingly important in the future but that for the next five or ten years there will be a hiatus in orders for nuclear plants in the United States. This is a very good opportunity to assess the present status of nuclear power and possible changes to prepare for the resumption of nuclear power construction in the future.

This is an excellent report, based on very thorough research, and I was very much impressed by the thorough discussion of nuclear safety. The method of probability risk assessment (PRA) was used in the analysis. It was found that before the TMI accident the accident probability was higher than had been estimated in WASH-1400. But since TMI, partly because of orders by the Nuclear Regulatory Commission, but partly by voluntary action of the utilities, the risk has been greatly diminished so that it is now rather lower than WASH-1400 indicated. Further, additional safety measures for future light water reactors have been conceived. Therefore the report concludes that the present reactors are certainly safe enough for a world with 500 reactors, i.e., in the next 20 years. I concur in this conclusion, and it is my impression that reactors may still be safe for a world with many more in the future.

Especially important is the great reduction of the source term in view of the TMI experience. It seems that the release of radioactivity in a reactor accident is likely to be much less than was expected in WASH-1400 and that accidents with very large releases and high hazards to the public are by now exceedingly improbable. This should be well publicized and might contribute to alleviation of public anxiety.

In spite of my assessment of nuclear safety which is more optimistic than that of the report, I concur that it would be highly desirable to design and build a supersafe reactor of the PIUS type. The money which the government has saved by the cancellation of the Clinch River Breeder Reactor could very profitably be spent on the PIUS Project.

The report rightly emphasizes that perhaps the most important reason for the lack of orders for reactors in the United States is economics. The median cost of new reactors is too high, and especially, it varies too much from case to case and is too unpredictable. Standardization of the design would help greatly, as it has helped in countries like France where nuclear power is proceeding at a rapid rate.

In conclusion, I hope this report will be widely read by all groups concerned. It is an invaluable source of information.

Comments by S. David Freeman, Director, Tennessee Valley Authority

The heart of this study directed by Alvin Weinberg is its recommendation that a prototype of the PIUS reactor--or an equivalent inherently safe reactor--should be built at once. It is a bold recommendation from a leading member of the "nuclear family" who is still open to new ideas.

The Weinberg study makes a solid case for its recommendation. Indeed it significantly understates the need for the development of an inherently safe reactor concept.

The prevailing opinion in the nuclear industry is that marginal improvements on existing reactor designs will be good enough. This opinion is at odds with prevailing public opinion. The large numbers of people concerned about nuclear power and their representatives in Congress have little or no faith in "event tree" analyses that failed to predict TMI. In my view the public will be unmoved by being told that there will be reactor failure every 10^5 years rather than every 10^4 years.

People think that anything that can go wrong will go wrong. That commonsense judgment of public opinion may well be better than the "event tree" analysis that does not fully reflect the extent to which some operators will make mistakes, to which some plants will be poorly built, and to which management attention to safety may be lax at some of the 60 utilities that will soon be operating nuclear units.

The industry criticizes NRC licensing, but the regulatory process simply mirrors the lack of public confidence in the existing reactor designs and reflects the real need for expensive safeguards to try to reduce the risks to levels the public may accept. That same regulatory process would also be responsive to the far less stringent safeguards needed for a reactor that does not pose the awesome risk of a meltdown and cannot be the victim of operator error.

In my view, developing an inherently melt-down proof nuclear reactor is a useful option for the nation to help reduce oil imports that add to the risk of war in the Middle East and to reduce our consumption of air-polluting fossil fuels that pose dangers from acid rain and CO_2 buildup. This need for a safer nuclear option will exist for decades even if we launch an all-out conservation program and accelerate the R&D to harness the sun and develop a sustainable source of energy.

The future for the nuclear option in the United States is in great jeopardy today because the existing designs require so many protective add-ons to be made safe enough that the designs have become uneconomical for new plants. The value of this report is that it suggests there are technical options that can be safe enough as well as economical.

The future of nuclear power may very well rest on the manner in which this excellent report is received, especially by the proponents of nuclear power. The R&D necessary to perfect these options is a federal responsibility, but the federal government cannot be expected to fund it if the nuclear industry does not realize that the development of these concepts is a life and death matter for them as well as useful for the nation.

Comments by H.G. MacPherson
Consultant to the Institute for Energy Analysis

In my opinion this is an excellent summary of the various factors involved in our current nuclear moratorium and of the prospects for emerging from it. I agree in general with most of what is said, including the two main conclusions, although I differ in emphasis and in some details, as indicated below.

The impressive efforts by INPO to improve nuclear utility management, combined with some of the changes in reactor hardware and control room equipment now being made, have decreased the likelihood of a core damaging accident by at least the factor of three to six cited in the report. With the probability of such an accident solidly below 10^{-4} per reactor year, there is no objective reason why a utility executive should fear losing his investment in a nuclear reactor from an accident. Furthermore, with the new, more realistic estimates of the amount of radioactivity that might escape in case of such an accident, the risk to the public is much lower than any limit that might be logically set. If the numbers given on pages 58-59 are multiplied out, it becomes clear that, among the many possible dangers faced by mankind, concern with harm from a reactor accident deserves no more than a few minutes attention.

However, I differ rather strongly with the statement on page 88 that, as more reactors appear on the world scene, additional safety is required. I see no rational basis for such a statement.

In coming to the above conclusion, I take advantage of a background that differs considerably from that of the average citizen, politician, newspaper reporter, or TV anchorman. With an engineering background I can make use of my limited knowledge of probability and statistics, I can develop an understanding of how the various safety systems work and read reports of their tests, and I even have a long familiarity with radiation and some of its effects. Therefore I feel quite confident in my perception of reactor safety.

In contrast, most average citizens, politicians, and news reporters have neither the background nor the time to make individual judgments of their own about the safety of reactors and so must depend on the advice of others. In so doing they listen to people holding views similar to mine, but they must also listen to others of the opposite view. Some of these nuclear critics appear to have formal qualifications equal or superior to my own, and thus their opinions cannot be dismissed readily. In giving voice to their opposition to nuclear power, they appear to be bucking the establishment. Since anti-establishment views are considered newsworthy, a number of them have gained national reputations and appear repeatedly in supposedly impartial debates. The net effect of this dichotomy of opinion is that the public is sharply divided and it may not be possible to gain a rational consensus. Thus, present-day reactors may not be acceptable, no matter how safe I say they are, and it may be that a new reactor that is transparently much, much safer is needed.

At the start of the Second Nuclear Era study I had little confidence that it would be possible to find any reactor that was demonstrably enough safer than LWRs to make any real difference in its acceptability. I was at least moderately familiar with essentially all reactor types that have been constructed or seriously proposed, and although some of them have what are called "inherently safe" features, they all are subject to some conceptually possible accident that would release at least moderate amounts of radioactivity. It was therefore exciting to hear from K. Hannerz about the PIUS reactor, which I consider to be qualitatively different from any other proposal in the field of reactor safety. The essential feature is the open coupling of the reactor to an alternate cooling system that takes hold automatically should any disturbance of normal heat transfer occur. The alternate cooling water contains boron to provide automatic reactor shutdown. By placing the system in a large concrete bottle, cooling for a number of days is provided and the system is made relatively resistant to terrorist attack. Saboteurs could shut down the power production but they could not readily cause radioactivity to escape.

I do not agree with the implication of the statement on page 45 that "there may be a number of avenues to" a supersafe reactor. In my opinion the PIUS concept is unique in this respect. The other reactor concepts discussed on pages 40-45 are all vulnerable to readily imagined core damaging accidents for which prevention of public exposure would depend on engineered safeguards of some kind. I am especially puzzled by the discussion of an "inherently safe" LMFBR. Fast reactors are inherently plagued with the specter of a reactivity excursion, about which there is a large volume of technical literature. Although a fast reactor can probably be made as safe as an LWR, I don't see how public fears can be completely eliminated.

I strongly support the proposal for the development of the PIUS reactor. It may be needed for the revival of our nuclear power industry, and it would certainly be useful in places where political stability cannot be guaranteed.

I believe we are in agreement that eventually the world will need to use the energy contained in ^{238}U and thorium. At the start of this study I wondered whether it was worthwhile to develop any new reactor that was not capable of breeding. Would there be a useful period between completion of its development and the appearance of a scarcity of uranium? In the section on fuel assurance it is shown that with present trends for the rate of increase in usage of electricity the date at which uranium becomes very expensive is "sometime after 2025." Even then the very high capital cost of the LMFBR, the only breeder being actively developed, would probably prolong the economic preference for converter reactors for decades beyond that. Thus there would appear to be a substantial time window during which the PIUS reactor would be viable.

I do not have a better analysis to present, but I do call attention to the fact that the extrapolation of present trends can be treacherous. In fact, it was in large part the extrapolation of the 7 percent per year increase in electricity use beyond 1973 that brought on the present moratorium on power plant orders. Despite this reservation about predicting the future, I agree that it may very well be the middle of the next century before breeders are needed badly. But eventually, breeding will be needed and I strongly support the recommendations on page 94, although I would be more specific in suggesting that the next years be devoted to exploring alternates to the LMFBR. All of the evidence to date indicates that the LMFBR will continue to cost about twice as much as an LWR, and it will be nearly impossible for uranium to cost enough to make the overall economic comparison favorable to the LMFBR. For years, optimists have been predicting that the cost will come down, but such a trend would be counter to that experienced with LWRs. Among the alternate potential breeders I personally favor the molten salt reactor which could reasonably be expected to cost less than the LMFBR. The gas-cooled fast reactor should also be a candidate to see if its distinguishing features can lead to lower costs.