Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors

A Report Prepared by the

Committee on Fusion Hybrid Reactors
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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PREFACE

This study, under the Energy Engineering Board of the National Research Council, examines the outlook for fusion hybrid reactors. It resulted from a desire by the U.S. Department of Energy for an independent review of the technical and economic merits of this energy option. The study evaluates the status of fusion hybrid technology in the United States and analyzes the circumstances under which such reactors might be deployed. The study also examines a related concept, the tritium-breeding fusion reactor.

The technology required for fusion hybrid reactors rests to an important degree on efforts in pure fusion technology, which are necessary to the hybrid as well. These are scheduled over the next 20 years and will be paced largely by technological results. Further time for developments specific to the hybrid may be needed before that technology might become available. Thus, the study had to examine different scenarios for electricity use extending over a considerable period of time. These scenarios assumed various growth rates for the generation of electricity between now and 2065--and various fractions of that electricity that might be generated using nuclear energy. Since many of the quantities in the scenarios could not be assigned with certainty, it was necessary to vary them over a wide range to explore the sensitivity of the economic conclusions to the assumptions. An assessment was also made of the environmental and societal acceptability of the fusion hybrid.

The study examined two potential applications for fusion hybrid technology: (1) the production of fissile material to fuel light-water reactors and (2) the direct production of baseload electricity. For both applications, markets were sufficiently problematical or remote (mid-century or later) to warrant only modest current research and development emphasis on technology specific to the fusion hybrid reactor. For the tritium-breeding fusion reactor, a need for tritium for use in nuclear weapons might arise well before the middle of the next century, so that a program of design studies, experimentation, and evaluation should be undertaken.

The report responds to a request from the Director of Energy Research, U.S. Department of Energy, who is concerned with the broad implications of fusion hybrid technology. The report seeks also to inform persons who deal with nuclear power in other government agencies, the Congress, and electric utilities. In addition the material here may be helpful to others interested in technologies for the generation of electricity, although it presupposes some sophistication on the part of the reader.

Alvin W. Trivelpiece, John F. Clarke, Robert J. Dowling, and Gregory M. Haas, of the Office of Energy Research, U.S. Department of Energy, have given valuable and substantive support throughout the study. The committee also acknowledges with gratitude the timely participation and contributions of the many experts who provided briefings and written material as inputs to the study. In particular, continuing cooperation and assistance have been provided throughout the study by Ralph W. Moir and T. Kenneth Fowler, of Lawrence Livermore National Laboratory. The study was initiated by Dennis F. Miller, Executive Director of the Energy Engineering Board. John M. Richardson served as Study Director, with professional assistance from Robert Cohen. Carlita M. Perry, of the committee staff, provided invaluable administrative support from beginning to end.

John W. Simpson, Chairman
Committee on Fusion Hybrid Reactors

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EXECUTIVE SUMMARY

It is possible to use a nuclear fusion reactor, of a somewhat less technologically challenging design than that contemplated purely for the generation of electricity, by employing fusion-derived neutrons to drive useful nuclear reactions. One device based on this concept is called the fusion hybrid reactor, or, perhaps more explicitly, the fusion-fission hybrid reactor. Neutrons from a fusion core would react with fertile and fissile material in a blanket surrounding the core, with the consequent creation of both fissile material for conventional nuclear reactor fuel and heat for generating electricity. Another such device, called the tritium-breeding fusion reactor, would breed tritium by reaction with lithium targets around the core. This report examines future circumstances in which these reactors might be needed and advantageous. Based on their technical, economic, and social aspects, it discusses the program content and pace at which these applications ought to be pursued.

FUSION HYBRID REACTORS

One prospect for commercializing fusion hybrid technology is to provide an alternative source of fissile fuel as uranium ore becomes exhausted. To examine that prospect, various U.S. electric energy generation scenarios are explored.

The rationale for introducing the fusion hybrid reactor depends largely on the hypothesis that the U.S. nuclear fission power industry will once again experience growth. In that event, known natural uranium resources will be consumed and the price of uranium will rise. At a high enough price, sources of electricity other than light-water reactors fueled by mined uranium may become economically viable. The fusion hybrid reactor provides one such nuclear option that appears to be technically feasible. The time frame in which it might become economically viable depends on its capital and operating costs, together with the future course of the price of natural uranium as its cumulative use increases. Once economic, no disqualifying environmental and social obstacles appear likely to inhibit its future deployment.

Within this framework, several conclusions and recommendations were developed.

Depending on the extent of future use of light-water reactors, the total use and commitment of known U.S. uranium oxide resources (U_3O_8) at a price less than $200 per pound could occur as early as the year 2020; that circumstance would be more likely to occur between 2020 and 2045. Availability of global uranium supplies would delay this occurrence by about 30 years. Use of a lower tails assay, recyle of spent light-water reactor fuel, and introduction of liquid-metal fast reactors would each delay the date of total use and commitment by about 5 years. The fusion hybrid option as an alternative source of fissile fuel for prolonging the use of light-water reactors would be expected to become economically viable at a sufficiently high price of uranium oxide, roughly between $100 and $330 per pound. A somewhat different fusion hybrid design, which would produce power only, would offer quite limited economic advantage over the light-water reactor, because the already small fuel cost component of the latter rises only slowly with uranium price and the capital cost of the former almost certainly would be greater.

No significant changes in overall nuclear safety would result from the introduction of fusion hybrid reactors to generate electricity or to fuel light-water reactors (where one fusion hybrid reactor supplies fuel for about ten light-water reactors), since the fusion hybrid is intrinsically at least as safe as the light-water reactor. Similarly, from an environmental standpoint, the fusion hybrid would be at least comparably acceptable. Moreover, no significant arguments concerning the effect of fusion hybrid reactors on nuclear proliferation either support or oppose their introduction.

From the current perception of electric utilities as necessary partners in electricity supply, barriers to future hybrid deployment would have to be overcome, as for any new nuclear technology, including liquid-metal fast reactors and pure fusion. These barriers stem from acceptability of complex new technology, uncertainty of capital costs of nuclear construction, and practicality of the development enterprise. Government participation in the development, prototype, and demonstration stages of fusion hybrids could help lower these barriers.

The continuing development of fusion technology on its own merits will be the major impetus required to make fusion hybrid technology available as an alternative for fulfilling future energy needs, since fusion hybrids require many of the advances in physics and technology needed to achieve pure fusion.

The foregoing conclusions lead to two principal recommendations.

Recommendation One

<u>The U.S. Department of Energy should include the fusion hybrid as one of its long-term alternatives for continuing fission power during the foreseeable era when rising prices of natural uranium oxide may prohibit economic power generation from light-water reactors operating on stand-alone fuel cycles</u>.

The U.S. Department of Energy program to pursue the hybrid should accomplish the following:

1. State the goals for research on the fusion hybrid concept and adopt a program plan to reach them, within the scope of Department of Energy objectives to develop safe, long-term alternative sources.
2. Verify and periodically reassess the time when an alternative fuel supply for light-water reactors may become economic.
3. Sponsor design studies to identify and re-evaluate the potential and features of the hybrid concept(s) that can best meet these objectives, in the context of advances in fusion technology and changes in deployment of light-water reactors.
4. Develop and test components and systems as needed to prove and refine the hybrid design(s) and to implement the hybrid technology when needed, making maximum use of the fusion technology base.

Recommendation Two

Studies of the fusion hybrid reactor should be performed by groups that include technical experts in fission and fusion reactors and their fuel cycles, bringing as much breadth, depth, and practical experience in systems engineering as possible. An effective peer review and advisory process should be adopted to evaluate the merits of fusion hybrid design studies and to recommend future research directions.

A wealth of specialized technology applicable to the fusion hybrid already exists in the fission community and should be turned to use in fusion hybrid design. Although research on fusion blanket technology is already part of the fusion program and is applicable to hybrids, hybrid blankets will require additional research, such as on fuel and target elements. Some hybrid applications would require extensive development of associated fuel-cycle operations. Hence effective development and application of fusion hybrid reactors would be facilitated by early participation of the U.S. industrial infrastructure.

THE TRITIUM-BREEDING FUSION REACTOR

A reliable source of tritium is critical to maintain the nation's stockpile of nuclear weapons. The tritium-breeding fusion reactor can theoretically produce about six times as much tritium as can a fission reactor of the same thermal power. This possibility may lead to future cost advantages. In contrast to fusion hybrid reactors or pure fusion devices, technological development of the tritium-breeding fusion reactor requires relatively modest advances over the present state of the art in fusion. However, reliability of the process is an overriding requirement for U.S. tritium production.

Mainly for the latter reason this report concludes that the concept of a tritium-breeding fusion reactor is not yet a realistic candidate for either near-term expansion or replacement of current U.S. tritium production facilities, because considerable fusion development and engineering, as well as much reliability testing, remain to be accomplished. However, the promising long-term potential of the device leads to the following recommendation:

Because the tritium-breeding fusion reactor offers promising features of yield, cost, and technology, officials in the U.S. Department of Energy concerned with the capability and security of tritium production should undertake a program that analyzes and periodically reassesses the concept, including design studies, experimentation, and evaluation, as fusion development proceeds.

COMPARATIVE ECONOMIC OUTLOOK FOR PRODUCING FISSILE FUEL AND TRITIUM

The economic prospects for production of fissile fuel and tritium may be summarized as follows:

- Current conceptual hybrid designs might produce uranium-233 or plutonium for fissile fuel at an equivalent cost on the order of 10 times the current price of U_3O_8 ($17 dollars per pound). Thus the price of U_3O_8 would have to rise substantially for this application to become economic.
- For tritium production using a fusion driver combined with existing blanket technology, the situation is different. Approximately six times more tritium is produced per unit of fusion power than per unit of fission power. Therefore, a plant utilizing fusion neutrons might produce tritium at a considerable reduction in capital cost compared to its current capital cost using fission reactors, even if the capital cost per unit thermal power of the fusion plant turns out to be several times greater than that for a fission plant.

To put the comparison succinctly, the fusion hybrid would produce fissile fuel costing substantially more than it does today, whereas the tritium-breeding fusion reactor would produce tritium costing somewhat less than it does today. Thus from the standpoint of timing, the production of tritium using fusion neutrons has a good prospect for becoming economic in the relatively near term. In constrast, fusion hybrid production of fissile fuel would become economically viable if the price of uranium reaches a high enough level, and that may take some 50 years.

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INTRODUCTION AND CONCLUSIONS

The best known peaceful application of fusion technology is to produce electricity by converting the energy of fusion neutrons and other fusion products to heat and thence to electricity. Other possible uses of the energetic fusion neutrons exist, however. Three such uses considered here are production of (1) fissile fuel, (2) fission with consequent generation of electricity, and (3) tritium. Fissile fuel, produced by neutron capture by heavy nuclei, may then be recovered for fueling ordinary nuclear power reactors. Fission, produced by fast neutrons in a blanket of fissile materials around the fusion plasma, yields more electricity than pure fusion for a fusion core of given size. Tritium, produced by reaction with lithium, may be used in fusion reactors or nuclear weapons. Devices for the first two applications may be called fusion-fission hybrid reactors, abbreviated here to fusion hybrid reactors, because they apply both fusion and fission technology. The fusion technologies required for these three applications are at various stages of development and differ in their degrees of difficulty and costs for realization.

This study examines future circumstances in which fusion hybrid or tritium-breeding fusion reactors might be needed and advantageous (as outlined in the Statement of Task, Appendix A). Based on an examination of technical options and their benefits and risks from economic and social standpoints, the report discusses program content and pace at which to pursue these fusion applications. The study includes a brief description and comparison of alternative nuclear sources of electricity, but a comprehensive assessment of these technologies is outside the scope of the effort.

This introductory chapter draws on material from the remaining chapters to bring their conclusions and programmatic recommendations to the fore. The succeeding chapters then develop the line of argument pursued by the committee. In particular, Chapter 2 presents several scenarios for uranium use, showing that natural uranium resources will be consumed and committed as time proceeds. The chapter also estimates the course of the resulting price increases, since price depends on cumulative consumption and consumption increases with time. Chapter 3 provides a brief characterization of some alternative nuclear sources of electric energy that should be considered in the face of uranium price rises. No obviously superior concepts emerge, so the hybrid will ultimately have to be weighed against these other technologies as all of them mature. Chapter 4 gives a technical assessment of fusion hybrid reactor concepts as a basis for judging their technological achievability and for describing the economic relationships within which they might have a role. Chapter 5 discusses their economic and social aspects. In particular, if the price of uranium oxide (U_3O_8) rises enough, some economic break-even point will be reached for the cost of electricity produced by LWRs and by hybrids. This break-even price of U_3O_8 is estimated. Thus, the future date when the hybrid might become important can be noted from the dependence of U_3O_8 price on time, as developed in Chapter 2. Finally, Chapter 6 evaluates the potential of a tritium-breeding fusion reactor as a supplier of tritium for use in nuclear weapons.

FUSION HYBRID REACTORS

Fusion hybrid reactors would consist of a fusion core surrounded by a blanket containing fertile or fissile material that reacts with fusion neutrons. The fertile material would breed fissile fuel, and the fissile material would produce heat. The most immediate prospect for commercializing fusion hybrid technology is to provide an alternative source of fissile fuel as uranium ore becomes exhausted. To examine that prospect, various U.S. energy scenarios are explored.

Principal Conclusions and Recommendations

Fusion hybrid reactors could be economic to fuel light-water reactors when the cost of the hybrid-produced fuel becomes competitive with that of fuel from natural uranium or other sources of fissile fuel, such as uranium from seawater. Alternatively, they might become viable to generate electricity in "stand-alone" configurations independent of light-water reactors. Other possible options for generating nuclear-derived electricity, when natural uranium prices make light-water reactors noncompetitive, are liquid-metal cooled fast reactors, advanced converters, and accelerator breeders.

Currently, over 90 gigawatts electric (GWe) from nuclear fission plants are generating about 16 percent of U.S. electricity.* Despite the fact that this is the largest installed nuclear capacity of any country in the world, the U.S. nuclear power industry is in difficulty. Some of the most recent nuclear plants have encountered increased public opposition as well as high capital costs per unit of installed capacity.

*Tables C-1A through C-33 use the slightly lower figure of 80 GWe, as appropriate to 1986.

The increased costs resulted, in part, from long delays in the construction, completion, and initial operation of new plants. Also, the abundance of coal as a fuel in the United States has made U.S. nuclear power less compelling and less competitive than in many other industrialized countries. In the current climate, it is hard to project the future of the U.S. nuclear fission industry. The continued growth of nuclear power seems considerably more assured in certain other countries.

Nevertheless, nuclear fission might reappear as an increasingly major contribution for U.S. long-term baseload electrical capacity if public opposition moderates, institutional problems are solved, and plant construction costs can be reduced. While the committee did not estimate the likelihood of this course of events, it did regard it important to consider the possible revival of the U.S. nuclear power industry, in view of nuclear fission's potential ability to meet demands for electrical capacity for many years in the future, perhaps in a more environmentally acceptable way than other options. Thus, the committee took as a plausible hypothesis that the U.S. nuclear fission industry would once again begin to experience growth. It explored the ramifications of that assumption for the development of fusion hybrid technology.

These general observations are expressed by the following conclusion:

> Fusion hybrid reactors offer additional possibilities for practical use of fusion power, in electricity and nuclear fuel production, that are worthy of continued investigation. (Chapter 4)

Assuming various U.S. nuclear power growth rates within a range of about 3 to 5 percent per year, the committee estimated that U_3O_8 would attain a price of $200 per pound (ten times its current price) in the middle of the next century as a result of the use and commitment by then of the estimated resources available below this price. By that time, hybrid reactors might supply fissile fuel (plutonium or uranium-233) at a competitive price, thus providing an opportunity to limit escalating costs of fueling light-water reactors. These scenarios, described in greater detail in Chapter 2, can be summarized by the following conclusion:

> Depending on the extent of future use of light-water reactors, the total use and commitment of U.S. uranium oxide at a price less than $200 per pound could occur as early as the year 2020; it would be more likely to occur between 2020 and 2045. Availability of global uranium supplies would delay this occurrence by about 30 years. Use of a lower tails assay, recycle of spent light-water reactor fuel, and introduction of liquid-metal fast reactors would each delay the date of total use and commitment by about 5 years. Total use and commitment of uranium resources would drive a substantial rise in the price of uranium and hence of electricity derived from light-water reactors, so alternative nuclear sources of electricity might then become commercially viable. (Chapter 2)

Even so, from an overall energy system perspective, the fuel cost will remain a small fraction of the total cost of fission-produced electricity, even at fuel prices an order of magnitude higher than current ones. A $200 per pound increase in U_3O_8 price would probably add less than 20 percent to bus-bar electricity cost, and even less to the cost of delivered electricity. Such percentage changes are far less than the range in current nuclear-generated electricity costs due to variations in reactor plant costs. In fact, recent increases in the capital costs of light-water reactors mean that the proportion of total electrical generation costs allocable to fuel is even lower now than contemplated in previous fusion hybrid reactor studies. Thus, a large increase in the price of U_3O_8would be needed before the two products of the hybrid, fissile fuel and electricity, could recover the substantial capital and operating costs of the plant. The following conclusion, pertaining to this point, is established in Chapter 5:

Fusion hybrid reactors could become economically viable, especially as a source of fissile fuel for light-water reactors, if the price of uranium oxide becomes high enough; however, this price can be estimated only roughly at present and may lie between $100 and $330 per pound. (Chapter 5)

In its societal aspects, the hybrid is not likely to have substantial advantages or disadvantages compared to competing fission reactors. One fusion hybrid reactor can supply fissile fuel for about ten light-water reactors, and it is intrinsically at least as safe and environmentally acceptable as the light-water reactor. This is the principal reason for the following conclusion:

No significant changes in the overall nuclear safety and environmental characteristics that are then existing would result from the introduction of fusion hybrid reactors to generate electricity or to fuel light-water reactors. (Chapter 5)

Whether the fusion hybrid reactor offers increased resistance to proliferation of nuclear weapons depends on the nuclear power system it would supplement or replace. If the current system evolves into one with no recycling of fissile material, then future introduction of the power-only hybrid, requiring no recycling, would not change the situation. Introduction of the fuel-producing hybrid, requiring reprocessing, would detract somewhat from the prior status. Conversely, if the future system makes use of considerable reprocessing, introduction of the power only hybrid would improve the situation somewhat, while introduction of the fuel-producing hybrid would not change it much. Further discussion in Chapter 5 about the nature of the interactions leads to the following conclusion:

No significant arguments concerning the effect of fusion hybrid reactors on nuclear proliferation either support or oppose their introduction. (Chapter 5)

Unless cost projections for hybrid reactors, as a new technology, promise more substantial economic savings than are now anticipated, utilities and other electricity producers will surely be cautious about investing in that technology. Chapter 5 also develops the following conclusion:

> From the current perception of electric utilities as necessary partners in electricity supply, barriers to future hybrid deployment would have to be surmounted. These barriers stem from acceptability of complex new technology, uncertainty of capital costs of nuclear construction, and practicality of the development enterprise. The same caution would apply to any new nuclear technology, including liquid-metal fast reactors and pure fusion. (Chapter 5)

Because this analysis reveals no overriding and imminent need or benefit, and since fusion hybrids require many of the physics and technology advances needed to achieve pure fusion, the committee came to the following general conclusion:

> The continuing development of fusion technology on its own merits will be the major impetus required to make fusion hybrid technology available as an alternative for fulfilling future energy needs. (Chapter 4)

The fusion hybrid option is unique among the various means of extending the nuclear fission era in that it could be pursued largely as a consequence of research and development for an alternative source of energy; namely, the pure fusion option for generating electricity. Thus, in a sense, two possible payoffs may come from one main line of investigation.

Taken together, the foregoing conclusions suggest two principal recommendations.

Recommendation One

> The U.S. Department of Energy should include the fusion hybrid as one of its long-term alternatives for continuing fission power during the foreseeable era when rising prices of natural uranium oxide may prohibit economic power generation from light-water reactors operating on stand-alone fuel cycles.

The U.S. Department of Energy program to pursue the hybrid should accomplish the following:

1. State the goals for research on the fusion hybrid concept and adopt a program plan to reach them within the scope of Department of Energy objectives to develop long-term alternative energy sources.
2. Verify and periodically reassess the time when an alternative fuel supply for light-water reactors may become economic.

3. Sponsor design studies to identify and re-evaluate the potential and features of the hybrid concept(s) that can best meet these objectives, in the context of advances in fusion technology and changes in deployment of light-water reactors.

4. Develop and test components and systems as needed to prove and refine the hybrid design(s) and to implement the hybrid technology when needed, making maximum use of the fusion technology base.

Although there is a substantial research content in the program to develop fusion technology, additional work to develop the hybrid is largely engineering design and development. The incremental program for the hybrid is best focused towards hybrid program objectives and paced as described above.

Our assessment of the hybrid design studies described herein leads to the following additional observations:

1. The fusion hybrid concept has enough long-term promise to justify a program as defined above.

2. An aggressive program of fusion hybrid development, incremental to that already under way for pure fusion, is not now warranted because (a) it is premature to conclude that hybrids are the earliest or the best application of fusion, (b) the time (toward the middle of the next century) projected for possible U.S. needs for hybrid applications is too far off, and (c) most of the major near-term research and development activities required to develop a fusion hybrid are those currently scheduled in the main fusion program for the next 15 to 20 years.

3. There are many diverse and interesting hybrid concepts that offer some long-term potential for power generation. At present, the hybrid concept that can best meet the defined program objectives appears to us to be a fuel-producing uranium-blanketed fusion hybrid producing fuel and electricity, rather than the thorium-blanketed concept emphasized in recent design work. A conceptual design of a uranium-blanketed hybrid supplying uranium-plutonium fueled light-water reactors should be developed and its economics analyzed.

4. There are no urgent experiments of critical importance to hybrid applications, beyond those already contemplated in the existing fusion program, that need to be performed now for the hybrid.

Recommendation Two

> Studies of the fusion hybrid reactor should be performed by groups that include technical experts in fission and fusion reactors and their fuel cycles, bringing as much breadth, depth, and practical experience in systems engineering as possible. An effective peer review and advisory process should be adopted to evaluate the merits of fusion hybrid design studies and to recommend future research directions.

A wealth of specialized technology applicable to the fusion hybrid already exists in the fission community and should be turned to use in fusion hybrid design. Although research on fusion blanket technology is already part of the fusion program and is applicable to hybrids, hybrid blankets will require additional research, such as on fuel and target elements. Some hybrid applications would require extensive development of associated fuel-cycle operations. Hence effective development and application of fusion hybrid reactors would be facilitated by early participation of the U.S. industrial infrastructure.

Auxiliary Conclusions

The committee reviewed many technical aspects of fusion hybrid reactors through expert briefings (Appendix B) and published literature. Auxiliary conclusions and the ensuing recommendations are given in the following pages.

All hybrid reactors will produce both fissile fuel and heat in the blanket, but, depending on the technical concept, in quite different proportions. One concept, a "fast-fission hybrid," would rely on fast fission in the blanket to multiply the fusion neutrons. This blanket will produce large amounts of heat and fissile fuel, in proportions that can be adjusted to emphasize either: (1) power production (the fast-fission power-only hybrid), or (2) a balanced production of fissile fuel and power (the fast-fission fuel-producing hybrid).

Another concept, the "fission-suppressed" design, seeks to minimize the relative number of fissions in the blanket so the ratio of fusion to fission energy is high, as is the ratio of fissile fuel produced in the blanket to the thermal energy deposited in the blanket. Although this hybrid configuration would generate and market some electricity, it would emphasize fissile fuel production.

An appreciation of the relative technological challenges of the hybrid reactor concepts can be gained by examining two parameters. The first parameter is the plasma power gain Q; that is, the ratio of fusion power output to the plasma heating power provided by external sources. Plasma power gain reflects the degree to which the fusion reaction heats itself. The second parameter is the neutron wall loading W, defined as the energy per unit time transported per unit area through the first wall by the kinetic energy of the fusion neutrons. Neutron wall loading is responsible for cumulative damage to the steel wall of the fusion chamber; induced radioactivity in materials in the first wall, magnets, shield, and structure; and radioactive decay heat from the induced activity. Higher plasma power gain and higher neutron wall loading usually imply physical and technological requirements that are harder to achieve. Although other parameters (for example, duration of the plasma burn, heat flux through the first wall, and magnetic field strength) are important measures of technical difficulty, Q and W are especially good indicators of its relative degree. Table 1-1 shows the ranges of Q and W encountered for pure fusion and the three fusion hybrid options.

TABLE 1-1 Approximate Fusion Performance Requirements for Several Concepts

Technology	Plasma Power Gain, Q	Neutron Wall Loading, W (MW/m^2)
Pure fusion	15 to 25	3 to 5
Fission-suppressed hybrid	10 to 15	2 to 3
Fast-fission fuel-producing hybrid (with some power output)	5	1 to 1.5
Fast-fission power-only hybrid	3	1

The Fast-Fission Hybrid

Although all fast-fission hybrid designs would produce both fissile fuel and electricity, their blankets can be designed to emphasize one or the other of these products. This report considers two contrasting fast-fission designs. The first emphasizes electricity production by burning fissile material in situ rather than producing it for sale. This concept is designated here as the "fast-fission power-only hybrid." The second design, discussed more frequently, would produce fissile fuel for roughly three to six light-water reactors of equivalent thermal power, in addition to generating electricity. It is designated here as the "fast-fission fuel-producing hybrid."

<u>The Fast-Fission Power-Only Hybrid</u> One operating concept for the fast-fission power-only hybrid allows a once-through fuel cycle. This might be the most appropriate way to operate a fusion hybrid reactor if the fuel cost for light-water reactors does not rise substantially. The initial blanket fuel load would consist of natural or depleted uranium. This concept has not been given as much design attention as the fast-fission fuel-producing hybrid. However, it offers the potential advantage of not requiring a reprocessing plant, since it would not be supplying fuel for other reactors.

For a given electric output, the large blanket energy multiplication of the power-only hybrid could make its fusion core requirements substantially less demanding than for a pure fusion reactor or a fission-suppressed hybrid, as shown in Table 1-1. The required neutron wall loadings, plasma heating, and current drive will not be stressing. Reprocessing and fissile-fuel refabrication requirements for this concept can be negligible if a once-through fuel cycle is employed.

Some important aspects of technical performance for the fusion core remain to be demonstrated: in particular, stable, long-pulse operation with a high duty factor; plasma fueling; and plasma exhaust. Moreover, in some ways the design for the power-only hybrid reactor would have to depart considerably from designs resulting from current fission reactor experience and fusion reactor designs. Some system studies show that this concept may not compete economically unless its electric output is quite large, say greater than 2 GWe. Thus, the size and nuclear power output of the fusion core and of the fission blanket could be substantial. In addition, there are difficult design problems that arise if high burnup and a once-through fuel cycle are required in the blanket. A substantial effort will be required to design cooling and safety systems appropriate to the blanket geometry.

Further exploratory work is needed before the greater ease of designing the fusion core can be quantitatively balanced against the greater complexity of the fission blanket, relative to the same subsystems of the fast-fission fuel-producing hybrid.

The difficulty in commercializing such a reactor concept is that it would then have to compete in cost-of-electricity directly with the light-water reactor. Hence, as would the liquid-metal fast reactor, it would probably have to achieve a capital cost per unit of installed capacity comparable to that of the light-water reactor. This may be a difficult challenge for any fusion-based system to meet, since the power density of fusion reactors is lower than that of fission reactors and fusion reactors are more complex. It may be that potential safety and waste disposal advantages would lead to some relative reduction in cost, and the fuel cost of the power-only hybrid would be lower than that of the light-water reactor. However, it is unlikely that these attributes could outweigh the fusion capital-cost penalty.

The Fast-Fission Fuel-Producing Hybrid The fast-fission fuel-producing hybrid is designed to produce substantial amounts of both fuel and electricity. When enough combined revenues can be obtained from the sale of fissile fuel and electricity, economic constraints on the capital cost of the fusion core are relaxed relative to those for the fast-fission power-only hybrid described in the preceding section. System studies conclude that the economics of the fast-fission fuel-producing hybrid are comparable to those described to us for the fission-suppressed hybrid that uses the thorium-232--uranium-233 fuel cycle, as described below.

The fusion core physics requirements for this concept are more rigorous than those for the power-only hybrid, as shown in Table 1-1. The neutron wall loadings and required fusion gain are moderate. On the other hand, because the fuel bred in the blanket will be removed at relatively low burnup (say, less than 1,000 MW-days/MT) for reprocessing to light-water reactor fuel, the fission blanket design can be considerably more straightforward.

Conventional reprocessing technology can be used to recover the plutonium, but the cost will be high because of the low concentration of plutonium in the low-burnup blanket fuel.

The fast-fission fuel-producing hybrid is the hybrid option most favored by the Soviet Union's fusion program. Furthermore, public statements of the Soviet fusion program indicate that there is greater emphasis on this hybrid application than on pure fusion.

The Fission-Suppressed Hybrid

For fuel from a fission-suppressed hybrid to be economically competitive with natural uranium, even assuming major hybrid design goals could be met, the price of U_3O_8, as a base for supply of slightly enriched uranium for light-water reactors through isotope separation, would have to reach some point in the range $100 to $330 per pound in constant (1986) dollars. This range of prices might be attained in the middle of the next century, depending on growth in nuclear demand and on how quickly fuel-efficient reactors, deployed in response to the uranium price rise, begin to slow the exhaustion of high-grade uranium resources.

Development of the fission-suppressed hybrid may be as technically demanding as the development of a pure fusion device, as illustrated in Table 1-1. Although the fusion plasma requirements of the fission-suppressed hybrid may be slightly less stringent than those for pure fusion, they do represent a significant advance in plasma physics parameters over currently achieved values. In short, the fission-suppressed hybrid requires a plasma where the dominant source of heating is from alpha particles produced by the fusion reactions, so that the fusion power is much greater than the plasma heating power required from external sources. This is the next step toward pure fusion as well--one that the magnetic fusion program is now attempting to take. Moreover, the neutron wall loading is almost as severe in this application as in pure fusion.

The fission-suppressed hybrid concept that has been studied most intensively operates on the thorium-232--uranium-233 cycle. The committee has strong reservations about this cycle, because it would necessitate the extra expense and formidable difficulty of developing and commercially implementing a thorium reprocessing system and a uranium-233 fuel cycle. First, the thorium-blanketed fission-suppressed hybrid and its associated light-water reactors would require development of new reprocessing and fabrication technology. Reprocessing blanket thorium to recover uranium-233 would require either pyroprocessing, about which little is known for large throughput systems, or Thorex aqueous processing technology, which has not been developed on a commercial scale. For the fuel cycle described in the hybrid design studies, reprocessing the fuel discharged from uranium-233-fueled light-water reactors would require the separation and recovery of thorium, uranium, and plutonium, and a combined Thorex-Purex separation would probably have to be developed.

A second reservation concerns the need to fabricate and handle fresh uranium-233-bearing light-water reactor fuel, which is highly radioactive from the intense gamma rays of the uranium-232 daughters.

Consequently, work on concepts requiring use of the fission-suppressed thorium--uranium-233 cycle could be substantially de-emphasized without adverse consequences.

It may be preferable to base the fission-suppressed hybrid on the uranium-plutonium fuel cycle, even though the number of light-water reactors of given thermal power supported by a hybrid of the same thermal power (the support ratio) would be less than with the thorium--uranium-233 fuel cycle. The fuel cycle operations for the uranium-plutonium fuel cycle are less expensive, and less fuel-cycle development is required. A conceptual design of such a system that is optimized for fuel production should be developed and its economics analyzed.

THE TRITIUM-BREEDING FUSION REACTOR

Tritium is a critical component in most nuclear weapons. Because tritium has a radioactive half-life of 12.6 years, the performance of many nuclear weapons would decrease drastically if the tritium were not replaced every few years. Thus, a reliable source of tritium is critical to maintain the nation's stockpile of nuclear weapons.

A tritium-breeding fusion reactor would consist of a fusion core of rather modest performance specifications, surrounded by a blanket containing lithium, which would breed tritium by reacting with neutrons from the fusion reaction. Such a device has been proposed as an economically attractive potential source of tritium production.

For an equivalent amount of thermal power output, the tritium-breeding fusion reactor can theoretically produce about six times as much tritium than can a fission reactor. This feature is inherently so advantageous that it may overcome the capital cost differential of the two reactor types. The same feature would permit tritium-production facilities covering a wide range of outputs, depending on design and operating power level.

Development of the tritium-breeding fusion reactor requires relatively modest technological advances compared to those required for pure fusion and the fusion hybrid. The necessary plasma performance appears demonstrable by the next generation of fusion experiments. Water cooling of the blanket might be similar to that used now by tritium-producing fission reactors. Technologies for lithium targets and tritium recovery would be similar to those used now. Achieving long-pulse operation for the tokamak confinement concept is the main development need.

Reliability has often been reaffirmed as an overiding requirement for U.S. tritium production. Hence, significant prototype experience with a tritium-producing fusion reactor will be needed. The currently contemplated plan for development of the underlying fusion technology, followed by some further period of specialization to the tritium-breeding fusion reactor, will delay extended prototype operation into the next century.

The foregoing considerations, more fully discussed in Chapter 6, lead to the conclusion and recommendation that follow:

> The concept of a tritium-breeding fusion reactor is not yet a realistic candidate for either near-term expansion or replacement of current U.S. tritium production facilities, because considerable fusion development and engineering, as well as much reliability testing, remain to be accomplished. (Chapter 6)

> Because the tritium-breeding fusion reactor offers promising features of yield, cost, and technology, officials in the U.S. Department of Energy concerned with the capability and security of tritium production should undertake a program that analyzes and periodically reassesses the concept, including design studies, experimentation, and evaluation, as fusion development proceeds. (Chapter 6)

2

PROJECTED AVAILABILITY OF URANIUM TO FUEL LIGHT-WATER REACTORS

This chapter considers the future availability of uranium resources needed to fuel U.S. nuclear generating plants. To do this, various scenarios are investigated that project future demand for fissile fuel. The purpose of this chapter is to estimate whether uranium consumption will rise to the point that resources become diminished, with consequent rise in price. If so, alternative nuclear sources of electricity may need to be examined, as in Chapter 3. The conclusion of the analysis in this chapter is that uranium prices about tenfold higher than current levels could occur, and that such prices may prevail sometime around the middle of the next century or later. This conclusion provides a basis for an analysis in Chapter 5 of the economic viability of the fusion hybrid concept and when it may be achieved.

BASIC ASSUMPTIONS AND APPROACH

It is essential that the United States have an adequate supply of moderately priced energy so as not unduly to constrain potential economic growth. A recent study by the National Research Council's Committee on Electricity in Economic Growth (1986) reached the following conclusion:

> Electricity use and gross national product have been, and probably will continue to be, strongly correlated. Economic growth...results from growth in capital input, labor input, and productivity. Productivity growth may be ascribed partly to technical change; in many industries, technical change also tends to increase the relative share of electricity in the value of output, and in these industries productivity growth is found to be the greater the lower the real price of electricity, and vice versa.

However, since the oil embargo of 1973 to 1974, it has been more difficult to forecast how much electrical energy may be required in the future. Whatever the relationship between electrical energy use and gross national product, it is a more dynamic one than formerly and has not been accurately predicted in the recent past. Nevertheless, even with the current lower growth rates, electricity has continued to grow with the economy, and therefore it would be prudent to take steps now that would ensure the future availability of electrical energy at a reasonable price.

In projecting the U.S. electrical energy future, this study used data concerning electrical energy sources and demand for electricity from the most reliable references available. The study projects the outlook for the fusion hybrid reactor over a range of parameters of electrical energy supply and demand.

There are almost certainly enough domestic coal resources to generate most of the electricity that will be needed in the United States during the next 200 years. That such major dependence on coal would be possible, prudent, or desirable is another issue, since extensive use of coal could cause serious environmental impacts. These considerations suggest that significant sources of nuclear-derived electricity will probably be needed in addition to coal-derived electricity. If its current cost and institutional problems are resolved, nuclear power can become an even more important supplier of electrical energy than it is now. Among nuclear options for generating baseload electricity are fission reactors, liquid-metal cooled fast reactors, pure fusion reactors, and fusion hybrid reactors. The fusion hybrid option could supply electricity, fissile fuel, or a combination of the two.

One possibility is that additional light-water reactors (LWRs), similar to those commercially deployed today, again become societally acceptable in the United States. If so, LWRs may be the baseload electrical energy source of choice, especially if their cost in constant (1986) dollars can be reduced to $2,000/kW or below. There is enough uranium available in the United States and the rest of the world to supply the number of LWRs that would be required; however, eventual increases in the price of fissile fuel might ultimately constrain the LWRs as an economic choice. This constraint will be examined in some detail in the scenarios analyzed in this chapter.

If enough natural uranium oxide (U_3O_8) from ore is not economically available to fuel the operational LWRs, then another source of nuclear energy must be used to supply that fuel, to supply electricity directly, or to provide some combination of the two. In practice, projecting the likely choice of nuclear technologies beyond the LWR is complicated by the fact that their potential technical feasibility and economic attractiveness--especially the latter--are uncertain. This will remain the case until a new nuclear technology has become mature enough that a demonstration plant and several commercial power plants have been built and substantial operating experience has been accumulated.

Among the advanced nuclear technologies presently under consideration, liquid-metal reactors, including the liquid-metal fast reactor (LMFR), have accumulated the most extensive experience base. U.S. and international experience has demonstrated that the LMFR is technically feasible. Although LMFRs typically have a low breeding ratio relative to that potentially achievable by fusion hybrid reactors, the newest LMFR designs are targeted toward achieving a capital cost comparable with that of LWRs. If this target cost is achieved, LMFRs that largely fuel themselves subsequent to installation could be phased in to augment and replace the existing generation of LWRs. Once a LMFR economy is established, there would be considerably decreased future need for natural fissile fuel, since these reactors can be run indefinitely on little more than their initial core loading.

An alternative approach would build upon the existing and future base of LWRs by seeking ways to extend and augment their fuel supply. One might envision a fission economy that utilizes a new generation of improved LWRs that are fueled by fusion hybrid reactors. This chapter maps out those future energy circumstances in which fuel produced by the fusion hybrid might be needed as uranium resources for that application become diminished.

FUEL USE SCENARIOS

To develop scenarios for the use of uranium and the consequent increase in its price, the committee originated a versatile computer program, using parameters defined in more detail in Appendix C. Use of these parameters in the computer model enabled the projection of various scenarios for estimating demand for fissile fuel.

The computer model was used to make projections as to when available U.S. resources and reserves of U_3O_8 recoverable at a forward cost less than $100/lb might become exhausted, or used and committed for future use.* The onset of such a situation, sometime in the next century, would lead to an increasing price of that ore as its reserves are exhausted. The model calculated the fissile material required to fuel LWRs and LMFRs that are projected to be operational under various assumptions of electricity demand. The model also permitted the amount of fissile fuel available from ore deposits to be supplemented by fissile material from the reprocessing of spent fuel. It further provided for different values of uranium tail assays. Employing a range of assumptions specified in scenarios described below, the model was used to project the year when the U_3O_8 inventory at a given forward cost would be exhausted, through a combination of consumption and commitment for future use ("forward commitment").

The key demand parameters used in the model were the annual growth rate for U.S. electric generating capacity and the percentages of that growth that would be supplied by baseload power from LWRs, LMFRs, and coal. Those and other parameters are defined in Tables C-1 and C-2 of Appendix C.

In deriving projections, the model incorporated the following assumptions: U.S. nuclear power capacity in the year 2000 was taken to

*The term "forward cost" is the projected future cost (in constant 1986 dollars) of mining uranium ore, without taking into account sunk costs including exploration, taxes, and return on investment. The uranium price is about twice its forward cost.

be 110 GWe, consistent with recent estimates of growth rate of electricity consumption of about 2.5 percent per year, summarized by Edison Electric Institute (1984). After 2000, net nuclear capacity additions were hypothesized to be 30 to 40 percent of the additions to electric capacity in a given year. The annual U.S. electricity growth rate was parameterized over the range 1 to 2.5 percent per year between 2000 and 2025, and over the range 1 to 1.5 percent per year between 2025 and 2065. This parametric study investigated only scenarios in which nuclear fission becomes a significant part (say, one-fifth to one-third) of total U.S. electric capacity, since the fusion hybrid fissile fuel application can be viable only in this case. For the purposes of calculating future commitments, LWR plant lifetimes were assumed to range between 30 and 60 years. LWR capacity factors were taken to lie between 70 and 80 percent.

The price of fissile fuel from a fusion hybrid reactor would have to be set by considering all capital and operating costs of the plant, including return on investment, net of revenues from selling its byproduct electricity at market. If the prices of fissile fuel from the hybrid and from, say, uranium ore become equal through price movements of either one, then a condition of indifference, or a break-even point, between the two sources exists (see Chapter 5).

Currently--in view of the slowdown in the deployment of LWRs--the market for U_3O_8 is depressed, and the market price (about $17/lb) is far below the range of break-even prices ($100 to $330/lb) envisioned in Chapter 5 for fusion hybrid designs. If nuclear fission resumes growth as a source of world electric capacity, the price of mined U_3O_8 will eventually rise. However, the rate of rise is expected to be rather slow, since estimated global uranium ore resources appear adequate to fuel worldwide operational LWRs at current ore prices for at least the next 30 years, and probably at prices competitive with other generating technologies for the next 60 to 80 years. The following analyses of ore supply treat two cases: (1) a U.S. market supplied solely by domestic uranium ore, and (2) a U.S. market as part of the global uranium ore economy. The first case might occur through a combination of legislative and external factors. Moreover, resource data for its analysis are more precisely known than for the global case.

Rather than constructing detailed supply and demand curves for the future price of mined U_3O_8, the computer model used a simple parameterization based on the latest estimates by the U.S. Department of Energy (1983) of available U.S. uranium resources at three different confidence levels. These estimates are shown in Table 2-1 and plotted in Figure 2-1. Using the rule of thumb that the price of uranium is roughly twice its forward cost, forward costs of $30/lb and $100/lb would correspond roughly to prices of $60/lb and $200/lb, respectively (Organization for Economic Cooperation and Development and International Atomic Energy Agency, 1983).

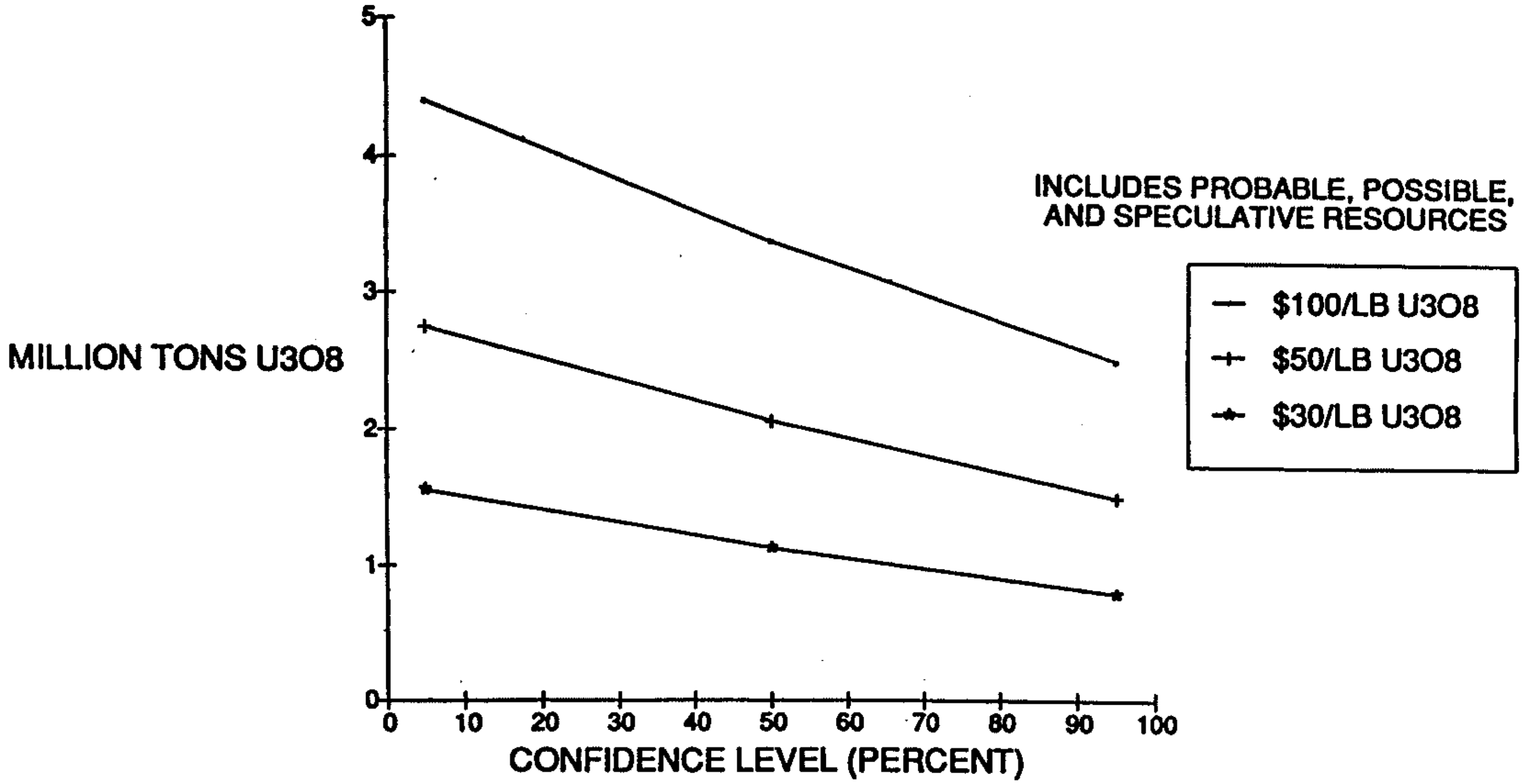
The model used the following simple parameterization for the price of mined uranium as a function of increasing U_3O_8 consumption: (1) The price of U_3O_8 remains equal to its current value ($17/lb) until all reserves at a forward cost of $30/lb have been used up. (2) Then the price rises linearly, until it reaches $100/lb when all the reserves at

TABLE 2-1 U.S. U_3O_8 Resources (in thousands of standard tons)

Confidence Level[a]	Forward Cost		
	≤$30/lb	≤$50/lb	≤$100/lb
5%	1556	2748	4403
50% (mean)	1127	2066	3381
95%	791	1502	2502

[a]In the sense that the probability is as stated that the resources exceed the quantity given.

SOURCE: U.S. Department of Energy (1983).



:GURE 2-1 U.S. uranium resources at various confidence levels (estimated as of January 1, 1983).

)URCE: U.S. Department of Energy (1983).

a forward cost of $\leq$\$50/lb have been used up. (3) From this point the price again rises linearly, until it reaches \$200/lb when all reserves with forward cost $\leq$\$100/lb have been used up. (4) Thereafter, the U_3O_8 price is again assumed linear, passing through \$400/lb when twice the reserves at a forward cost $\leq$\$100/lb have been used up. Figure 2-2 illustrates this parameterization for the three different confidence levels of Table 2-1.

This linear parameterization neglects the phenomenon that when uranium reserves begin to be genuinely depleted, the marginal cost of U_3O_8 will increase more rapidly than before. This will cause the price curves in Figure 2-2 to bend eventually sharply upward, as estimated by Piepel et al. (1981). However, Peipel et al. showed that this effect does not become significant until more than 6.5 million tons of U_3O_8 at the 50 percent confidence level (or 5.5 million tons at the 95 percent confidence level) have been recovered cumulatively. Because our models typically examine the year in which cumulative use, or cumulative use and commitment, attain about 4.4 million tons, our simple linear parameterization should remain adequate for the present analysis.

Results of the various nuclear fuel cost scenarios projected by the committee are tabulated in detail in Appendix C, along with further details on the computer model. The following description summarizes the basic assumptions and results emerging from those scenarios.

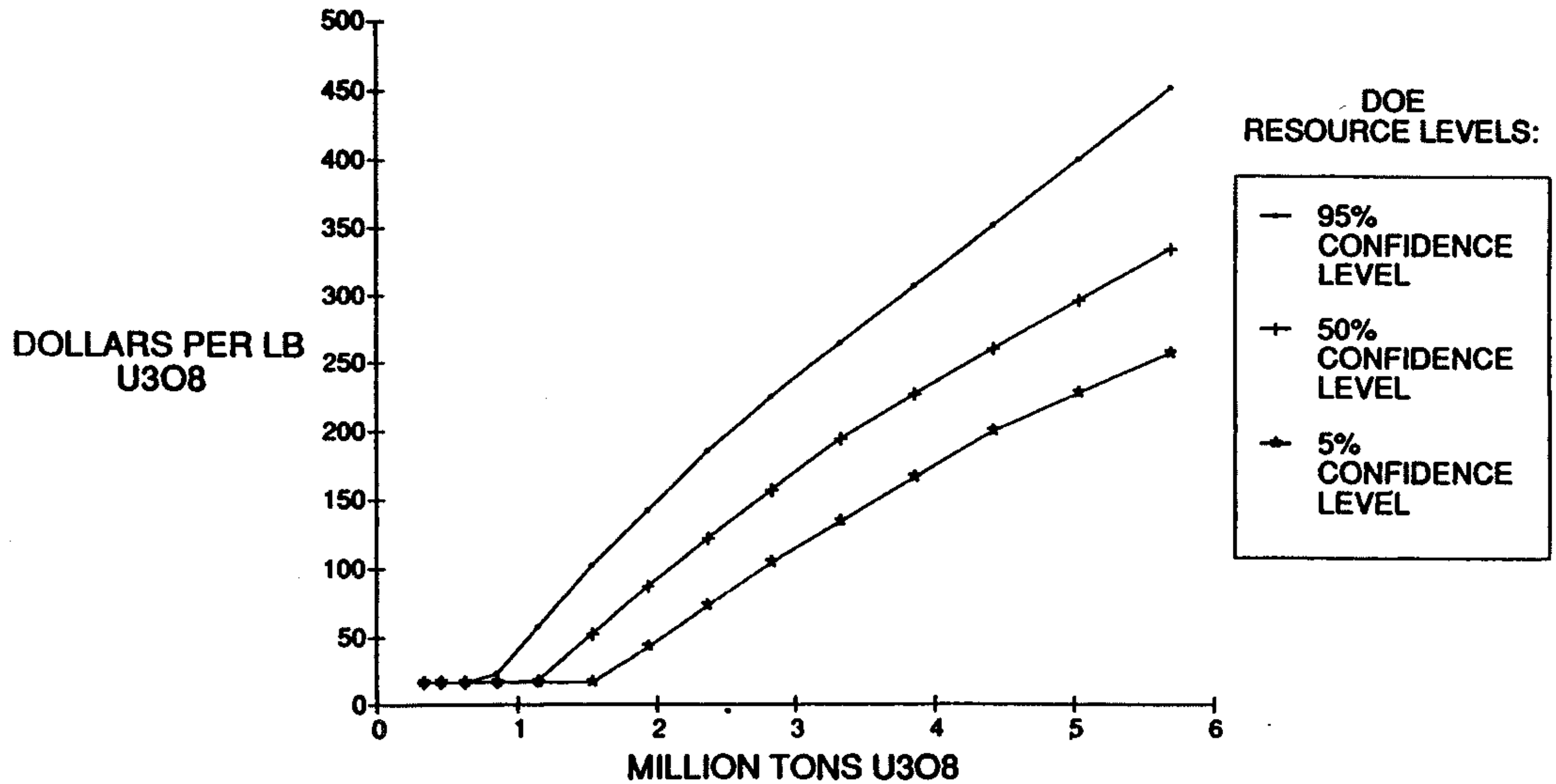
GROWTH OF NUCLEAR POWER AND URANIUM DEMAND: RANGE OF RESULTS

Table 2-2 is a summary of the scenario tables in Appendix C, ordered by the year in which U.S. uranium ore reserves priced at less than \$200 per pound of U_3O_8 (\$100/lb forward cost) are projected to be totally consumed. The scenarios detailed in Table 2-2 include a range of assumed growth rates for total electric generating capacity and for nuclear power. However, this range is restricted to those values that generate scenarios for which the fusion hybrid might be of interest and utility.

Growth of Installed Electric Capacity

Figure 2-3 illustrates the range of total U.S. electric generating capacity considered in this report for the period 2000 to 2065. (The scenario numbers in the legends of Figure 2-3 and subsequent figures correspond to specific tables in Appendix C.)

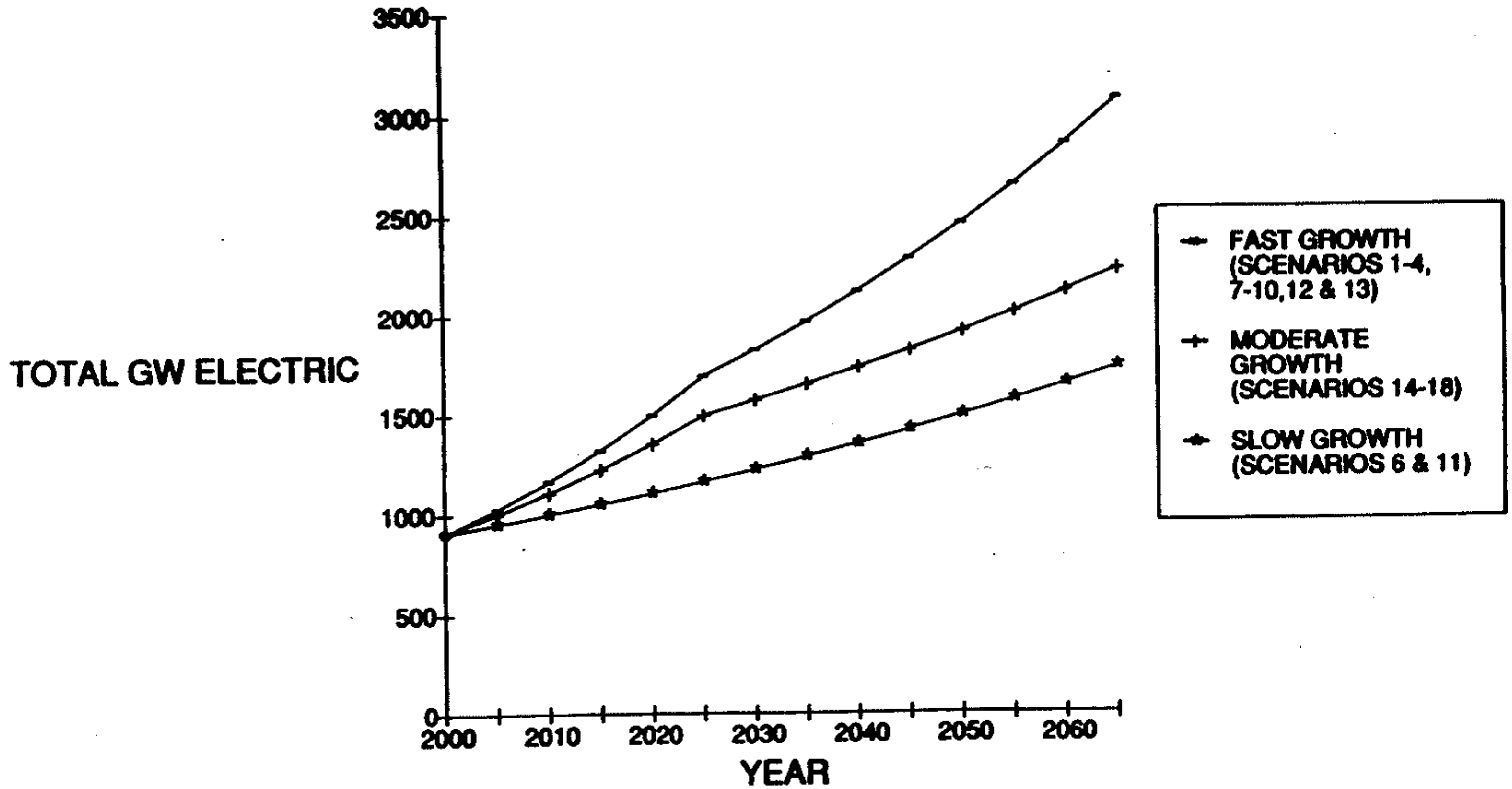
The curve labelled "fast growth" in Figure 2-3 corresponds to an electric growth rate of 2.5 percent per year between 2000 and 2025, and 1.5 percent per year thereafter. The "moderate growth" curve corresponds to growth rates of 2 percent per year and 1 percent per year in these same time periods. The curve labelled "slow growth" corresponds to a constant 1 percent per year growth rate between 2000 and 2065. The resulting U.S. electric capacities in the year 2065 range



IGURE 2-2 Simple model for price of U_3O_8 as a function of cumulative use.

TABLE 2-2 SUMMARY OF NUCLEAR FUEL USE SCENARIOS FOR U.S., ORDERED BY YEAR IN WHICH U.S. URANIUM RESERVES AT < $100/LB FORWARD COST ARE USED UP

SCENARIO NUMBER	YEAR URANIUM RESERVES < $100/LB USED UP	CONFIDENCE LEVEL FOR URANIUM RESERVES	ELECTRIC GROWTH RATE 2000-2025	ELECTRIC GROWTH RATE 2025-2065	IS COAL USE LIMITED?	NUCLEAR % NEW ELECTRIC CAPACITY	URANIUM RESERVES < $100/LB (MILLION TONS)	URANIUM TAILS ASSAY	MILLION TONS U3O8 USED CUM. IN 2065	YEARS FOR FUTURE U3O8 COMMITMENT	MILLION TONS U3O8 USED AND COMMITTED IN 2065	U3O8 PRICE IN 2065 ($/LB)	GW ELECT. IN YEAR 2065	GW LWRS IN YEAR 2065	GW LMFBRs IN 2065	COAL BURNED PER YEAR IN 2065 (MIL. TONS/YR)
1C	2037	90%	2.0%	1.0%	NO	40%	2.30	0.20	5.63	60	13.01	$494	3091	657	326	2054
3	2044	30%	2.0%	1.5%	NO	40%	3.30	0.20	6.14	60	14.29	$363	3091	731	252	2054
4	2044	60%	2.0%	1.5%	NO	40%	3.30	0.20	6.86	60	17.52	$300	3091	983	-	2054
8A	2044	30%	2.5%	1.5%	YES	40% (67% AFTER 2040)	3.30	0.30	7.10	60	20.94	$420	3091	1241	-	1644
2A	2045	30%	2.0%	1.5%	YES	40% (67% AFTER 2040)	3.30	0.20	6.12	60	14.08	$362	3091	786	455	1644
1A	2046	60%	2.0%	1.0%	NO	40%	3.30	0.20	5.63	60	13.01	$336	3091	657	326	2054
9	2049	90%	2.0%	1.5%	NO	30%	3.30	0.30	5.34	60	13.07	$316	3091	765	-	2054
7	2050	60%	2.0%	1.5%	NO	40%	3.30	0.08	5.31	60	14.19	$314	3091	983	-	2054
13	2054	30%	2.0%	1.5%	NO	30%	3.30	0.20	4.67	60	12.14	$276	3091	766	-	2054
10	2054	60%	2.5%	1.5%	NO	30%	3.30	0.20	4.67	40	9.61	$276	3091	766	-	2054
12	2054	90%	2.0%	1.0%	NO	30%	3.30	0.30	4.67	30	8.34	$276	3091	766	-	2054
18	2058	5%	2.0%	1.5%	NO	40%	4.40	0.20	5.60	60	13.01	$258	3091	687	326	2054
17	2062	60%	2.0%	1.0%	NO	30%	3.30	0.20	3.63	60	8.88	$215	2238	608	-	1910
16	2062	60%	2.0%	1.0%	NO	30%	3.30	0.20	3.63	40	6.38	$215	2238	608	-	1910
6	2064	30%	1.0%	1.0%	NO	40%	3.30	0.20	3.47	60	8.41	$206	1739	443	-	1494
15A	2065	60%	2.0%	1.0%	YES	30% (67% AFTER 2050)	3.30	0.20	3.40	40	6.17	$201	2238	429	193	1644
14	2067	60%	2.0%	1.0%	NO	30%	3.30	0.30	3.27	40	5.67	$192	2238	372	136	1910
11	AFTER 2070	60%	1.0%	1.0%	NO	30%	3.30	0.20	2.65	40	4.94	$144	1739	369	-	1494



'IGURE 2-3 Growth of total installed electric capacity.

from 1,739 GWe for the "slow growth" cases to 3,091 GWe for the "fast growth" cases, a spread of a factor of 1.8.

Figures 2-4 and 2-5 illustrate the assumed components of total U.S. electric generating capacity, for typical fast-growth and slow-growth cases, respectively. In both examples, coal is a more important contributor than nuclear throughout the time period from 2000 to 2065; at the end of that period nuclear constitutes 32 percent of total capacity for the fast-growth case, and 25 percent for the slow-growth case. "Other" electric capacity (that is, other than coal or nuclear) is assumed to be comparable to that of coal in the year 2000, but to grow more slowly than coal-derived capacity in subsequent years. It is important to note, however, that the conclusions of this chapter regarding the fusion hybrid fissile fuel application depend only on the assumed installed capacity in LWRs; the contributions of coal and "other" enter only indirectly, by determining the required rate of LWR deployment to achieve U.S. capacity needs. Only in the case where stringent limitations are assumed for coal use does the use of coal directly influence conclusions regarding the fusion hybrid.

Figure 2-6 illustrates the range of installed LWR generating capacities considered in this report. The top three curves in Figure 2-6 all correspond to the fast-growth scenario for total U.S. electric capacity, but are based upon differing assumptions regarding the fraction of total growth contributed by LWRs. Similarly, the bottom two curves correspond to the slow-growth scenario for total U.S. electrical capacity. The resulting installed LWR capacity in 2065 ranges from a low of 359 GWe for scenario 11 to a high of 1,241 GWe for scenario 8A, a spread of a factor of 3.5. Differences between these scenarios are discussed in the following sections.

Cumulative Use of U_3O_8

The relationship between new installed electric capacity and U_3O_8 used is an initial core loading of 373 standard tons per gigawatt plus reload cores of 189 standard tons per gigawatt per year. These quantities are used in the scenarios of Appendix C.

A qualitative criterion for projecting when alternative sources of fissile fuel, such as the fuel-producing fusion hybrid reactor, might be needed can be derived by posing the question, "When would domestic U.S. supplies of uranium ore at a given price be exhausted in the absence of a fusion hybrid?" Figure 2-7 illustrates projections addressing that question. The projections, except for those of Scenario 1A, assume that no LMFRs are deployed. The three horizontal lines labelled "Resources at [stated] % Confidence Level" show the cumulative U_3O_8 (Reasonably Assured Reserves, Estimated Additional Resources, and Speculative Resources) available in the United States at a forward cost of $100/lb or less. The year when domestic uranium ore is exhausted can be derived by estimating when cumulative U.S. uranium use matches available U.S. resources. If we consider the 50 percent confidence level resource line, Figure 2-7 shows that for the scenarios considered in this report, the year predicted for exhaustion of domestic uranium varies from about 2045 to 2075. This result indicates that a strong need for fissile fuel

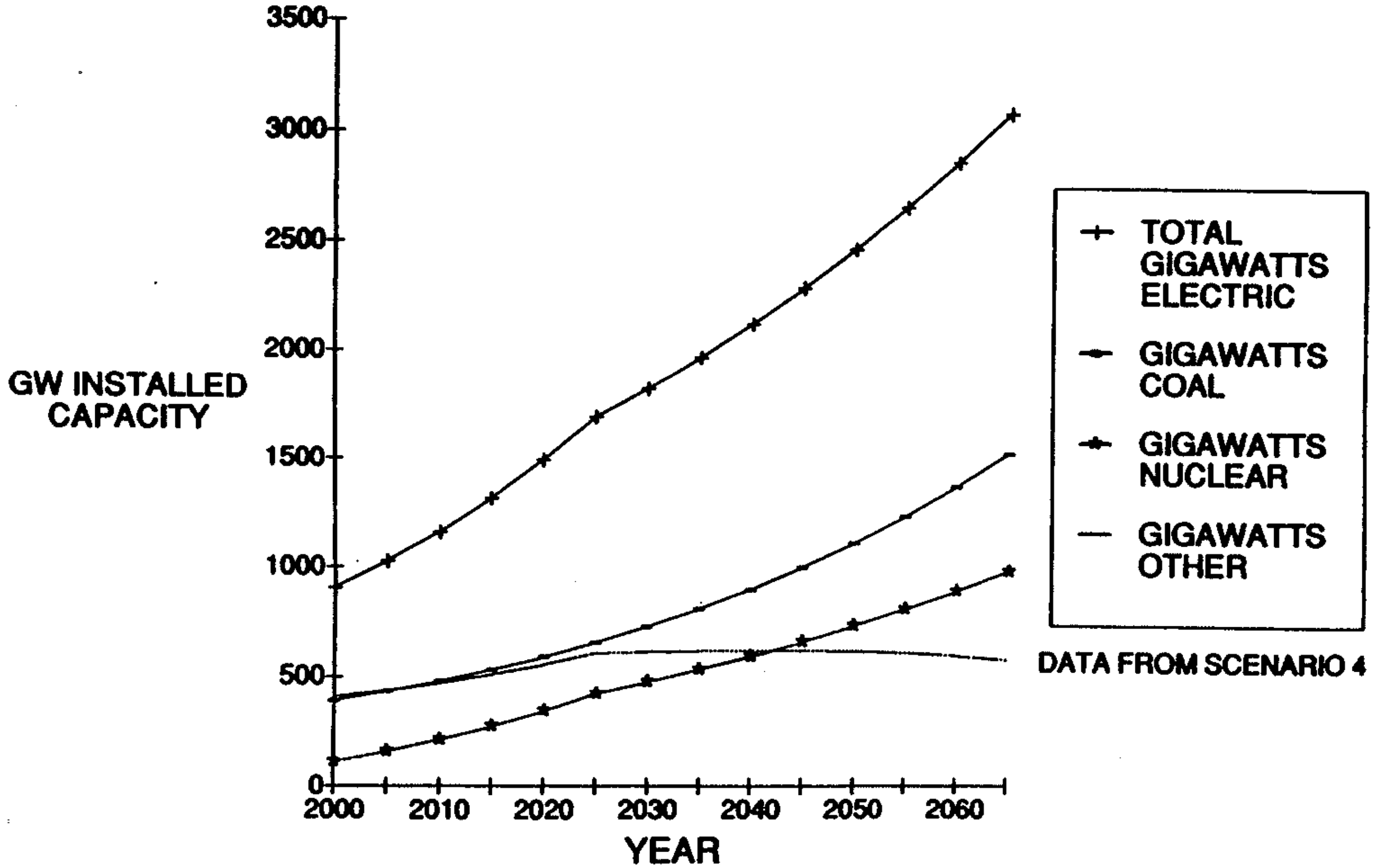
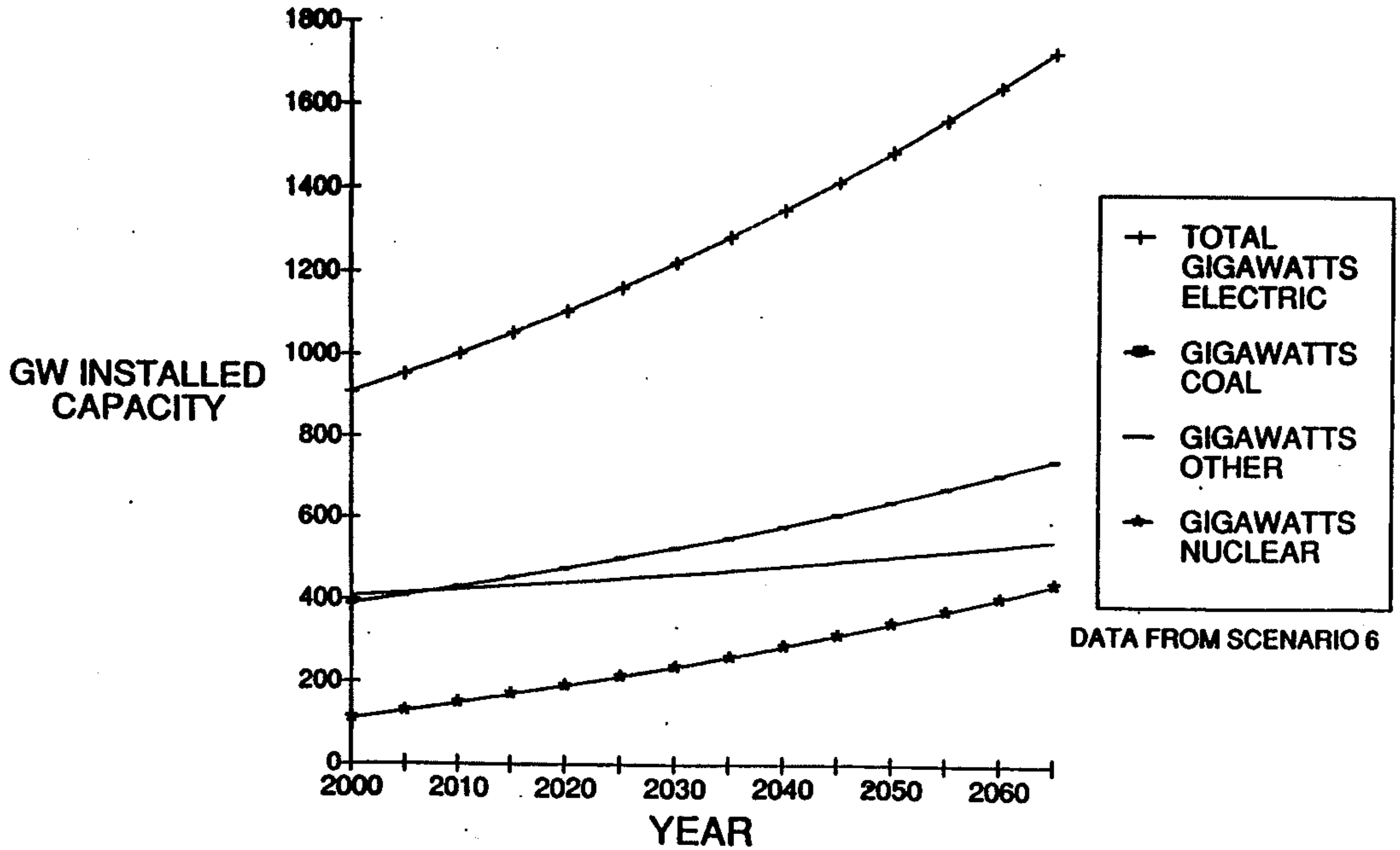
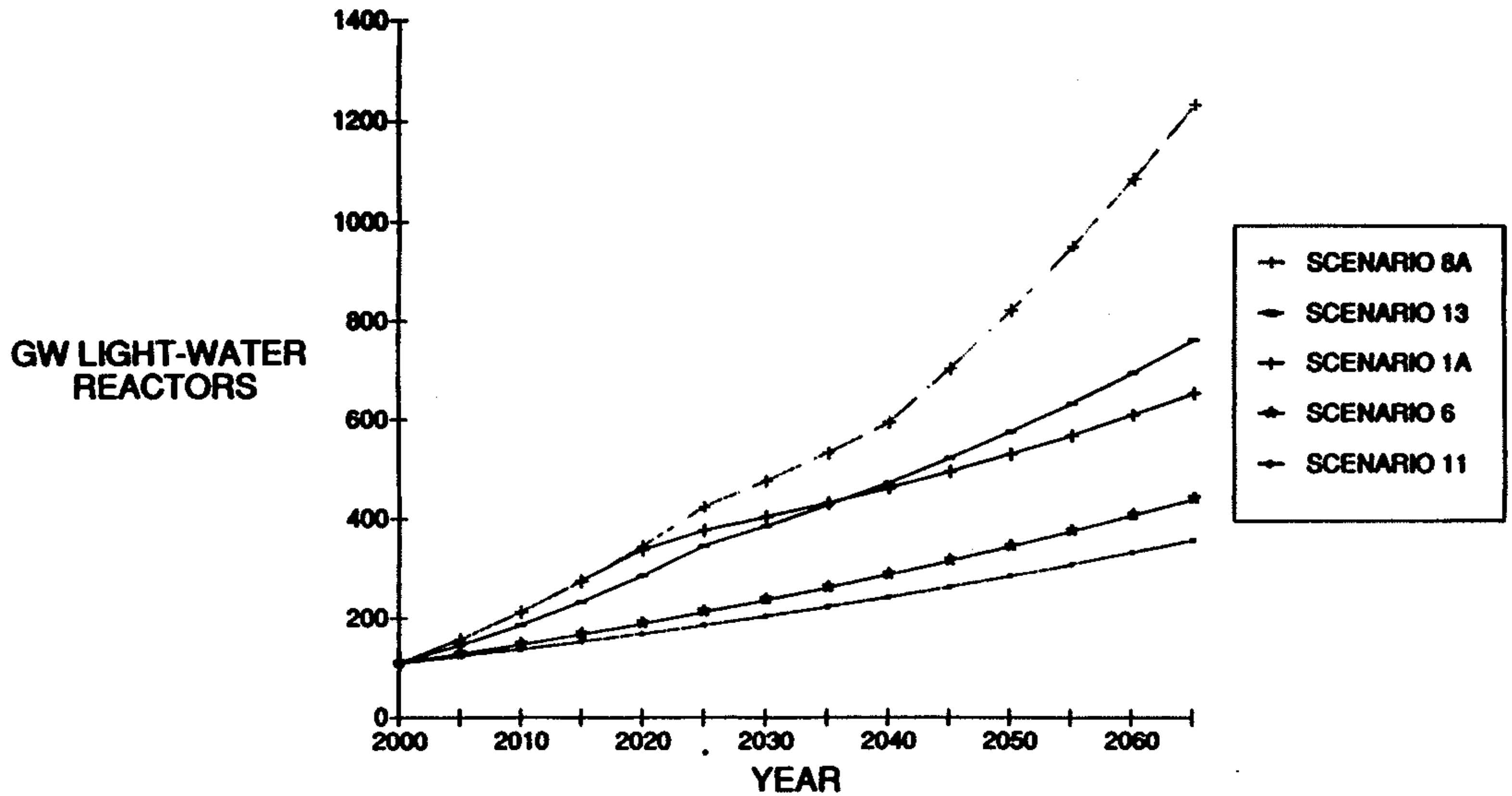


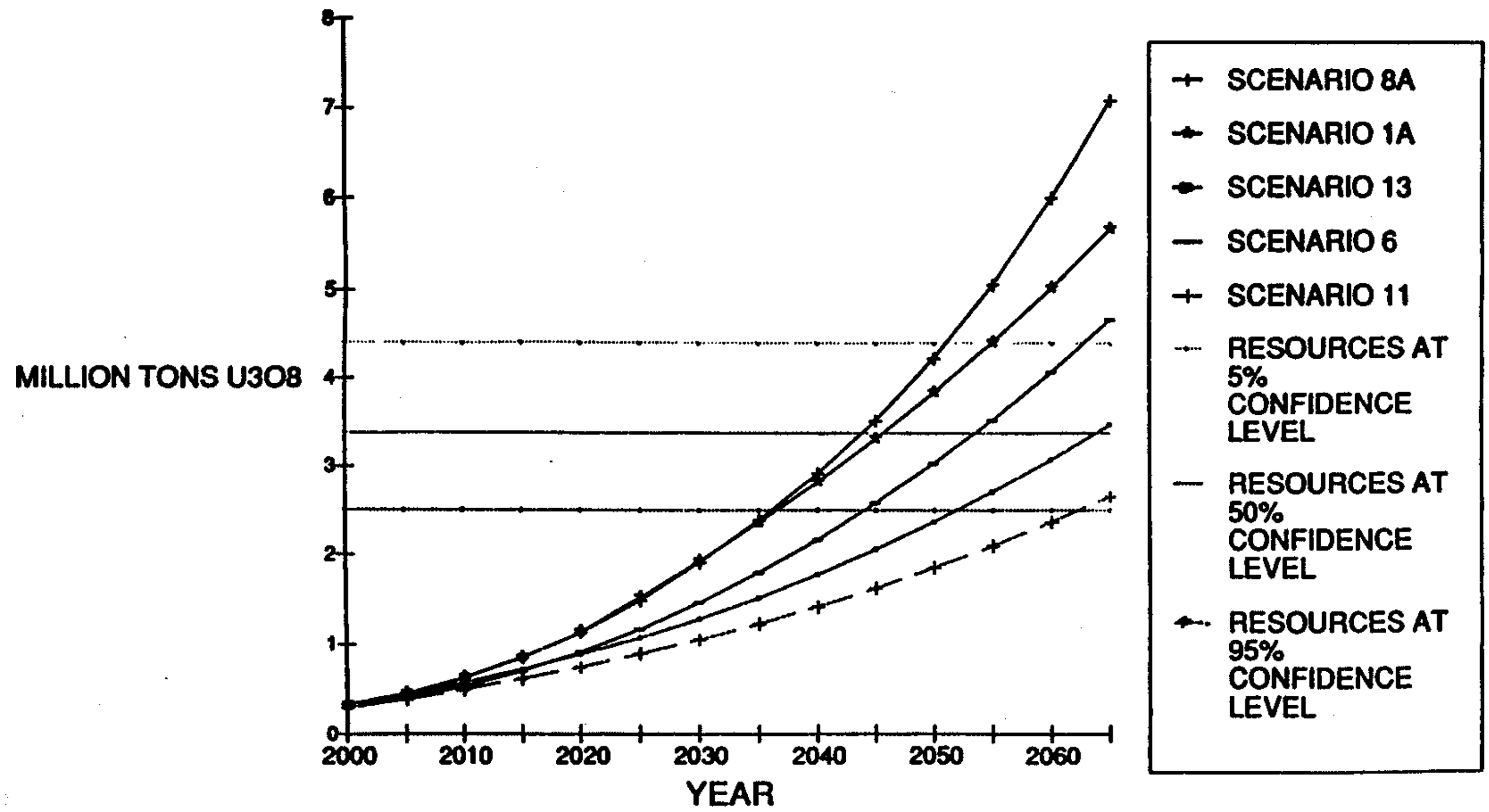
FIGURE 2-4 Growth of installed electric generating capacity for the "fast growth" case (no LMFRs).



ƷURE 2-5 Growth of installed electric generating capacity for the "slow growth" case (no LMFRs).



[GURE 2-6 Growth of installed light-water reactor electric capacity.



JRE 2-7 Cumulative U.S. resources of U_3O_8 used.

from the fusion hybrid will not arise until the middle of the next century, at the earliest.

At the 50 percent confidence level for these scenarios, there is a 30-year spread in the estimated dates when $100/lb U.S. resources will be exhausted. If the range of U_3O_8 resource estimates is broadened to include the 5 percent and 95 percent confidence level resource lines shown in Figure 2-7, the spread in the onset of U_3O_8 exhaustion increases, with the earliest year becoming about 2035 and the latest approximately 2080. Indeed, such exhaustion may not develop until even later than 2080 if U.S. LWR capacity stagnates at or near its current value.

International Scenarios for Uranium Use

One can refine these crude arguments in a number of ways. First, as with other natural resources, the import market will be a potentially important factor. To investigate this issue, we have computed four international scenarios for uranium use in the non-Communist world.

The international uranium supply data employed by the committee were derived from information published by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA) (1983), as follows: to the OECD's and IAEA's estimate of Reasonably Assured Reserves and Estimated Additional Resources (Classes I and II) were added the International Uranium Resource Evaluation Panel (IUREP) "most probable" value for speculative resources in forward cost categories $<$ \$50/lb of U_3O_8 and $<$ \$100/lb of U_3O_8, as cited in OECD-IAEA (1983). The resulting distribution of uranium resources in the non-Communist world is shown in Table 2-3. In our scenarios we have used the middle of IUREP's "most probable" range, or 22.8 million tons U_3O_8 at a forward cost $<$ \$100/lb.

The international scenarios are summarized in Table 2-4. Perusal of Table 2-4 suggests that, assuming capacity growth rates that are similar for the international ore market and for a purely domestic ore market, the supply of U_3O_8, at a forward cost of less than $100/lb, available on the international market might be expected to last 20 to 30 years longer than that available in a purely domestic U.S. uranium economy. In particular, for scenarios 31, 32, and 33 representing "fast" overall nuclear growth (rates of 5.6 and 2.7 percent per year before and after 2025, respectively), international supplies of U_3O_8 are predicted to be exhausted between 2060 and 2070. For scenario 30 representing "slow" nuclear growth (rates of 2.7 and 1.8 percent per year before and after 2025, respectively), international supplies of U_3O_8 are not exhausted until about 2092.*

*Since Table 2-4 does not allow a separate estimate of total resources at a forward cost $\leq$ \$30/lb of U_3O_8, for the purposes of calculating the future uranium price we have assumed that the price of U_3O_8 begins to rise above $17/lb (its present value) when one third of the total resources at $100/lb forward cost have been used up. Apart from this detail, the uranium price algorithm is exactly analogous to that previously described for the domestic U.S. market.

TABLE 2-3 Estimated Uranium Resources for Non-Communist World, Available at Various Forward Costs (millions of standard tons of U_3O_8)

Category of Resource	Forward Cost			
	< \$30/lb	\$30-50/lb	\$50-100/lb	< \$100/lb
Reasonably assured reserves	1.91	0.75	0.55	3.20
Estimated additional resources-I	1.19	0.40	0.67	2.26
Estimated additional resources-II	0.85	0.62	0.88	2.35
Speculative (IUREP)	← 12.5-15.7 (mean 14.1) →		0.87	13.4-16.6 (mean 15.0)
Totals	← 18.2-21.4 (mean 19.8) →		2.97	21.2-24.4 (mean 22.8)

SOURCE: Organization for Economic Cooperation and Development and International Atomic Energy Agency (1983).

TABLE 2-4 SUMMARY OF INTERNATIONAL SCENARIOS, U.S. PLUS NON-CENTRALLY PLANNED ECONOMIES

INTERNATIONAL SCENARIO NUMBER	YEAR URANIUM RESERVES < $100/LB ALL USED UP	U3O8 PRICE IN 2065 ($/LB)	COST OF ELECTRICITY IN 2065 (MILS/KWH)	U.S. ELECTRIC GROWTH RATES, 2000-2025 AND 2025-2100	U.S. NUCLEAR GROWTH RATES, 2000-2025 AND 2025-2100	NUCLEAR GROWTH RATES, NON-U.S. AND NON-COMMUNIST WORLD, 2000-2025 AND 2025-2100	TOTAL GW NUCLEAR IN YEAR 2065	URANIUM RESERVES < $100/LB (MILLION TONS)	MILLION TONS U3O8 USED BY YEAR 2065	MILLION TONS U3O8 USED AND COMMITTED BY YR 2065
30	2092	$83	48	1.0% 1.0%	2.7% 1.8%	2.7% 1.8%	1604	22.8	12.3	30.2
31	2065	$201	86	1.0% 1.0%	2.7% 1.8%	5.6% 2.7%	3880	22.8	23	66.2
32	2060	$234	98	2.5% 1.5%	5.6% 2.7%	5.6% 2.7%	4678	22.8	26.7	78.8
33	2070	$112	82	2.5% 1.5%	5.6% 2.7%	5.6% 2.7%	4678	22.8	20.2	57.6

We stress that knowledge of data on international uranium resources at the $100/lb (forward cost) level is less accurate than that on domestic U.S. resources. Speculative resources in particular are poorly known worldwide. Nevertheless, an overall figure in the range 15 to 25 million standard tons of U_3O_8 seems quite reasonable; it can be obtained through scaling the better known U.S. figures by the ratio of land areas, or by reasoning through geological analogy (Harris, 1979). Variation of the international resource estimate from 15 to 25 million tons does not qualitatively change our result, which is that for global nuclear growth rates similar to the domestic ones assumed, exhaustion of international uranium ore supplies will probably occur sometime between 2060 and 2090. This is about 15 to 35 years after U.S. domestic supplies are exhausted based on the purely domestic scenario.

The implications of this result are that as the middle of the next century approaches there will be strong pressures within the United States to import uranium. Indeed, such pressures already exist, since current U.S. resources are relatively more expensive to extract than those available, for example, from Australia or Canada.

The impact of this situation on the future U.S. need for the fusion hybrid or for LMFRs is quite unclear. On the one hand, uranium obtained from abroad can extend by some tens of years the time period when U.S. LWRs may burn mined U_3O_8, and thus delay by a similar time span the U.S. need for fusion hybrid reactors or other new nuclear technologies. On the other hand, experience since 1974 with the oil cartel of the Organization of Petroleum Exporting Countries suggests that such a dependence on energy imports can have undesirable political and foreign-policy consequences. Thus, strong noneconomic arguments may come into play toward the middle of the next century to favor use of domestic uranium and to avoid increased dependence on imported uranium. Which of these two considerations will predominate will depend on future political, economic, and strategic developments that are beyond the scope of the present study.

Cumulative Use and Commitment of U_3O_8

A second refinement to the uranium supply discussion is based on previous experience suggesting that, prior to committing to the construction of a new LWR, electrical utilities will require enough uranium to be available under a contract that assures a fissile-fuel supply for a considerable portion of the LWR's estimated economic life. Typically this requirement has been met via long-term uranium contracts with suppliers. The committee's scenarios attempted to take this into account by calculating a quantity called "U_3O_8 Used and Committed." This is the cumulative amount of uranium already consumed plus the cumulative amount that is committed to utilities during the year in which each new LWR enters into commercial service. The latter quantity depends on the assumed economic life of each LWR plant, since the commitment covers much of that period. According to this definition, the year in which all U.S. resources of U_3O_8 have been "used and committed" reflects the time when utilities will begin to perceive an impending shortage of the supply of mined uranium. Thus, in a sense, it marks the beginning of an era when a fusion hybrid or other breeder of fissile fuel will be of interest to utilities. Figure 2-8 shows that the year when U.S. uranium resources at the 50 percent confidence level are "used and committed" ranges from about 2012 for the fastest-growth case to about 2046 for the slowest-growth case. Figure 2-9 indicates that, for a given fast-growth assumption, the year when U.S. resources are "used and committed" occurs about 35 years before that when the resources have actually been consumed.

Price Increases

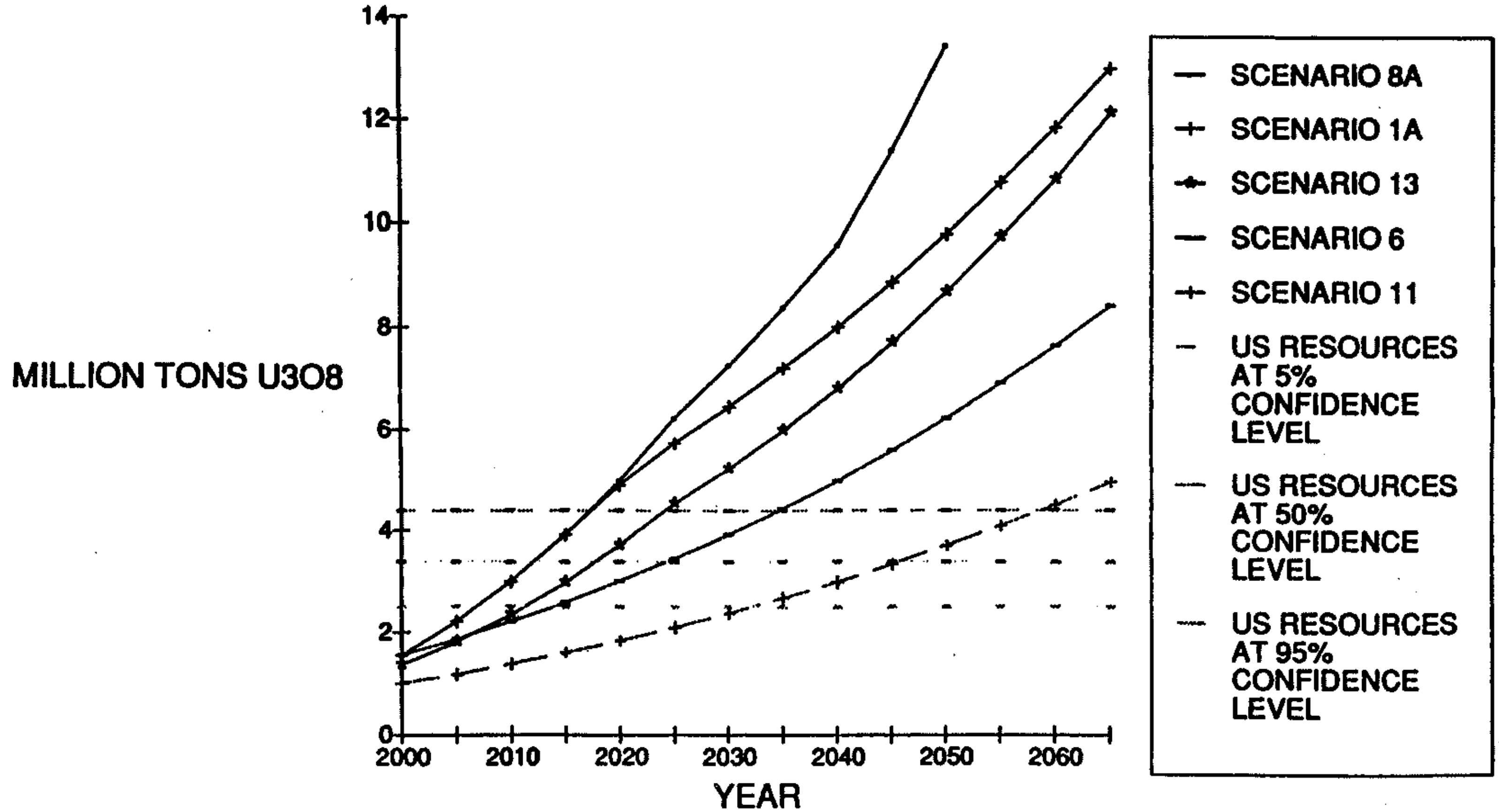
A final way of looking at when the need for the fusion hybrid fissile fuel application might arise is based on economic performance. This point is discussed in more detail in Chapter 5. Here we simply quote the rough qualitative result from Chapter 5; namely, that fissile fuel derived from the hybrid is roughly projected to become economically competitive with mined U_3O_8 when the price of the latter has risen to the range of about \$100 to \$330 per pound. This range results from a range of capital and operating costs projected for hybrid reactors.

Figure 2-10 illustrates projections for the year in which these "low break-even" and "high break-even" prices of U_3O_8 are expected to be attained, based upon the price model of Figure 2-2 for the various fissile-fuel scenarios considered in this report. The year in which the market price of mined uranium reaches the "low break-even" price for the hybrid ranges from about 2030 for the most rapid deployment of LWRs (Scenario 8A) to 2055 for the slowest deployment (Scenario 11). By contrast, the "high break-even" price is not reached even by the fastest-growth scenario until about 2055.

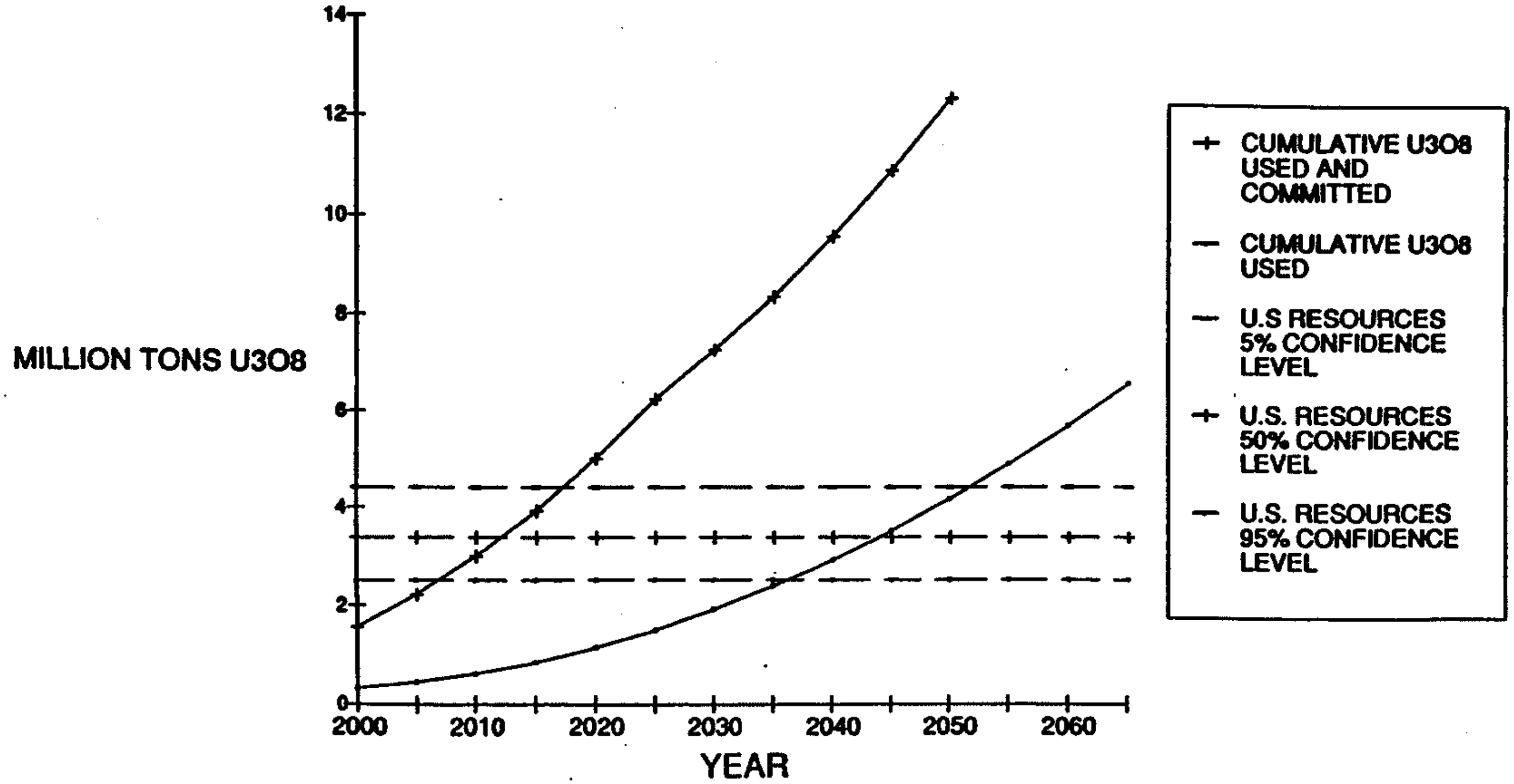
SENSITIVITY OF THE PROJECTIONS TO THE ASSUMPTIONS

Appendix C explores how the general conclusions summarized above are modified when the parameters and assumptions are varied. The strongest sensitivity is found to be to the assumed growth rate of U.S. electric capacity. The change from "fast" to "slow" growth (Scenarios 4 and 6, respectively) delays the date of uranium resource exhaustion through use by about 20 years, and the date of exhaustion through use and commitment by about 12 years. The effects of limitation on coal use, variations of tails assay, recycle of spent fuels, LMFR deployment, nuclear growth as a fraction of total growth, nuclear capacity factor, and period of forward commitment to uranium are much more modest, amounting for each to a change of 5 years or less in the projected time of uranium resource exhaustion.

In the region greater than about \$200/lb of U_3O_8, Piepel et al. (1981) estimate a considerably more rapid rise in full recovery cost, and hence price, than we have assumed. Adoption of these price estimates would advance the year when break-even prices above \$200/lb would be attained, although we have not quantified this effect.



RE 2-8 Cumulative U_3O_8 used and committed vs year.



GURE 2-9 Comparison of cumulative U_3O_8 used with U_3O_8 used and committed for the "fast growth" case scenario 4 (no LMFRs).

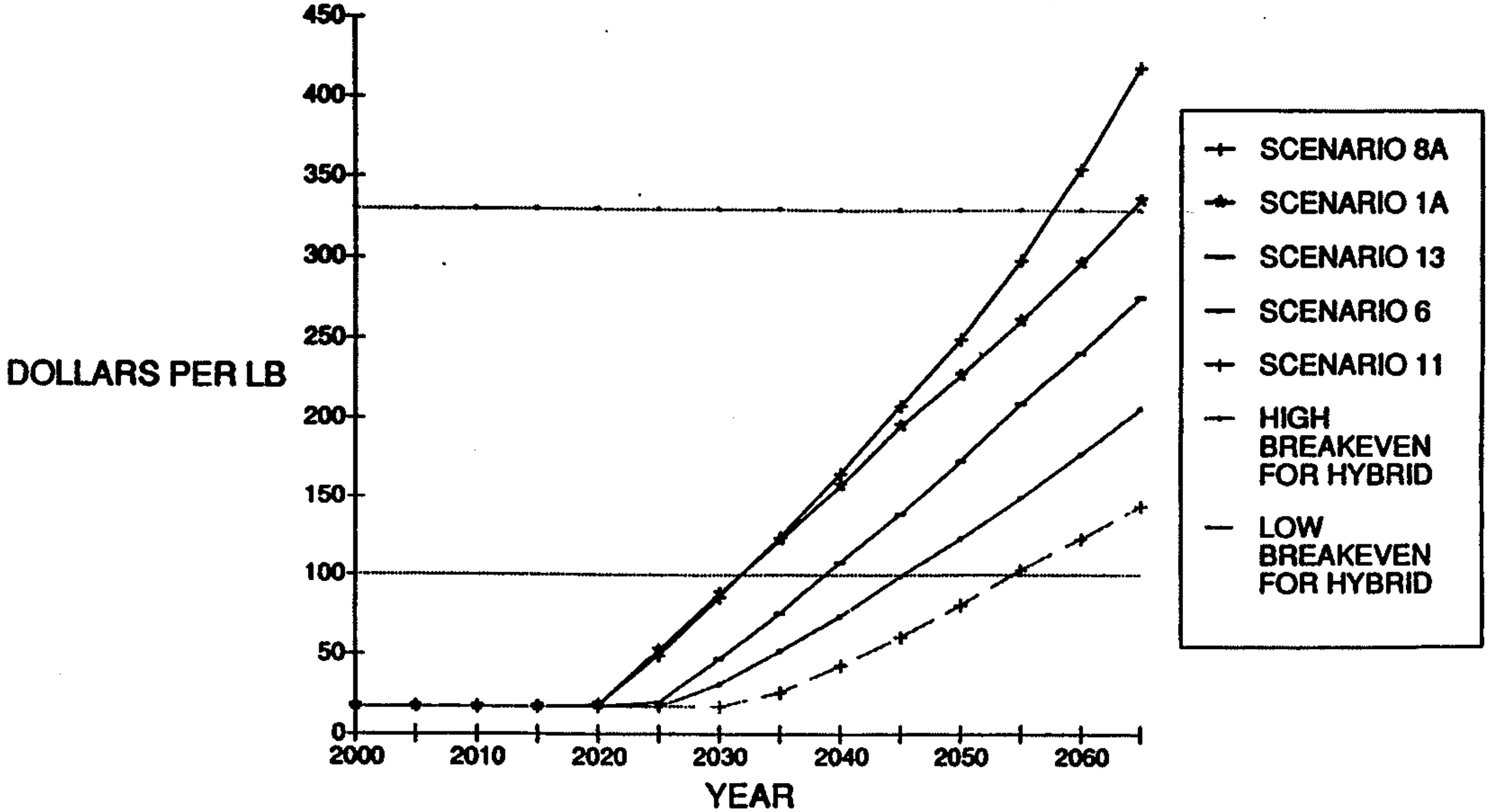


FIGURE 2-10 Projected price of U_3O_8, 2000 through 2065.

CONCLUSION

The preceding scenarios for U.S. uranium ore utilization forecast the total use and commitment for future use of that U.S. resource at a price less than $200 per pound of U_3O_8 by sometime in the middle of the next century. The limit of $200 per pound is of particular interest because it is the highest price for which resource estimates exist and it is also within the range of economic viability for hybrids, as explained in Chapter 5. The scenarios can be summarized by the following conclusion:

> Depending on the extent of future use of light-water reactors, the total use and commitment of U.S. uranium oxide at a price less than $200 per pound could occur as early as the year 2020; it would be more likely to occur between 2020 and 2045. Availability of global uranium supplies would delay this occurrence by about 30 years. Use of a lower tails assay, recycle of spent light-water reactor fuel, and introduction of liquid-metal fast reactors would each delay the date of total use and commitment by about 5 years. Total use and commitment of uranium resources would drive a substantial rise in the price of uranium and hence of electricity derived from light-water reactors, so alternative nuclear sources of electricity might then become commercially viable.

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3

ALTERNATIVE NUCLEAR SOURCES OF ELECTRICITY

The preceding chapter described some circumstances in which the supply of natural uranium might be fully committed around the middle of the twenty-first century. Alternative fuels for electricity generation would then be required, possibly nuclear, possibly not. This chapter briefly describes several of the more visible nuclear alternatives to light-water reactors (LWR) fueled from natural sources of uranium: magnetic fusion, fusion hybrid reactors, inertial confinement fusion, and liquid-metal cooled fast reactors. The overview of magnetic fusion shows its relevance both as an alternative source of electricity and as the technical and programmatic foundation to which the fusion hybrid concept is linked. This, together with the overviews of the three other alternative technologies, provides a context for the more detailed examination of the hybrid in the succeeding chapters.

MAGNETIC FUSION

In the most widely studied version of magnetic fusion, nuclei of deuterium and tritium, in the plasma state, would be confined by magnetic fields under conditions favorable for nuclear reaction. Energetic neutrons from the reaction would be used to produce heat, for electricity, and tritium, to fuel further reactions.

It is too early to make meaningful estimates of the cost of electricity from fusion. However, the use of pure fusion for electricity generation could potentially provide an inexhaustible source of energy with inherent safety and greatly reduced radioactive waste compared to fission. In normal operation there is no production of fissile materials, so concerns about diversion to terrorist and weapons uses are reduced.

Major programs in magnetic fusion are conducted by the United States, the European Community, Japan, and the Soviet Union. The U.S. program calls for achieving net output energy conditions in existing plasma experiments by the end of the decade. Ignition conditions, that is, conditions for a self-heated plasma, are predicted to be achieved in the early 1990s in a compact tokamak device. An Engineering Test Reactor (ETR), to be constructed by one of the major world programs or as an international project, is expected to be operational by the turn of the century. ETR will demonstrate long-pulse plasma operation, provide experience with systems integration, and serve as a test facility for nuclear fusion technology. Successful operation of ETR should provide the data base necessary to construct a demonstration power plant.

This section reviews briefly the current plans for magnetic fusion to give some idea of the course of its development, both as an alternative for LWRs and as a component of the fusion hybrid.

Research Concepts

There are two basic magnetic structures that are currently being pursued to confine fusion plasmas: the magnetic mirror and the magnetic torus. Each of these magnetic confinement systems has several variations, which differ in degree of plasma confinement and technical requirements for producing the magnetic fields. To date, most of the scientific progress has been made with the tokamak, a toroidal confinement device.

A fusion energy system consists of plasma, plasma support technology, nuclear technology, and balance of plant. Current world focus is on a plasma using the deuterium-tritium fuel cycle because of its more promising potential in creating and maintaining fusion reactions.

The plasma support technology includes those components necessary to confine, heat, fuel, and maintain burning fusion plasma. These components are magnets, auxiliary heating, current drive (if external), fueling, and plasma interactive components.

The primary functions of nuclear technology are fuel generation and processing, energy extraction and utilization, and radiation protection of personnel and components. The primary nuclear components are blanket and first wall, radiation shield, fuel processing and vacuum systems, nuclear elements of plasma-interactive and high heat flux subsystems, remote maintenance, and power conversion.

The balance of plant uses established technology in most fusion schemes.

Program Plans

The current U.S. strategy for magnetic fusion research and development is given in the document, "Magnetic Fusion Program Plan," commonly referred to as MFPP (U.S. Department of Energy, 1985). The Technical Planning Activity (TPA), now in progress, is delineating the technical details in support of MFPP (Baker et al., 1985; Abdou et al., 1985b; Callen et al., 1985; Dean et al., 1985; Argonne National Laboratory, 1986). The goal of the magnetic fusion program, as stated in MFPP, is to establish the scientific and technological base required for fusion energy. The focus of the remaining work necessary to reach the program goal is summarized by four key technical issues:

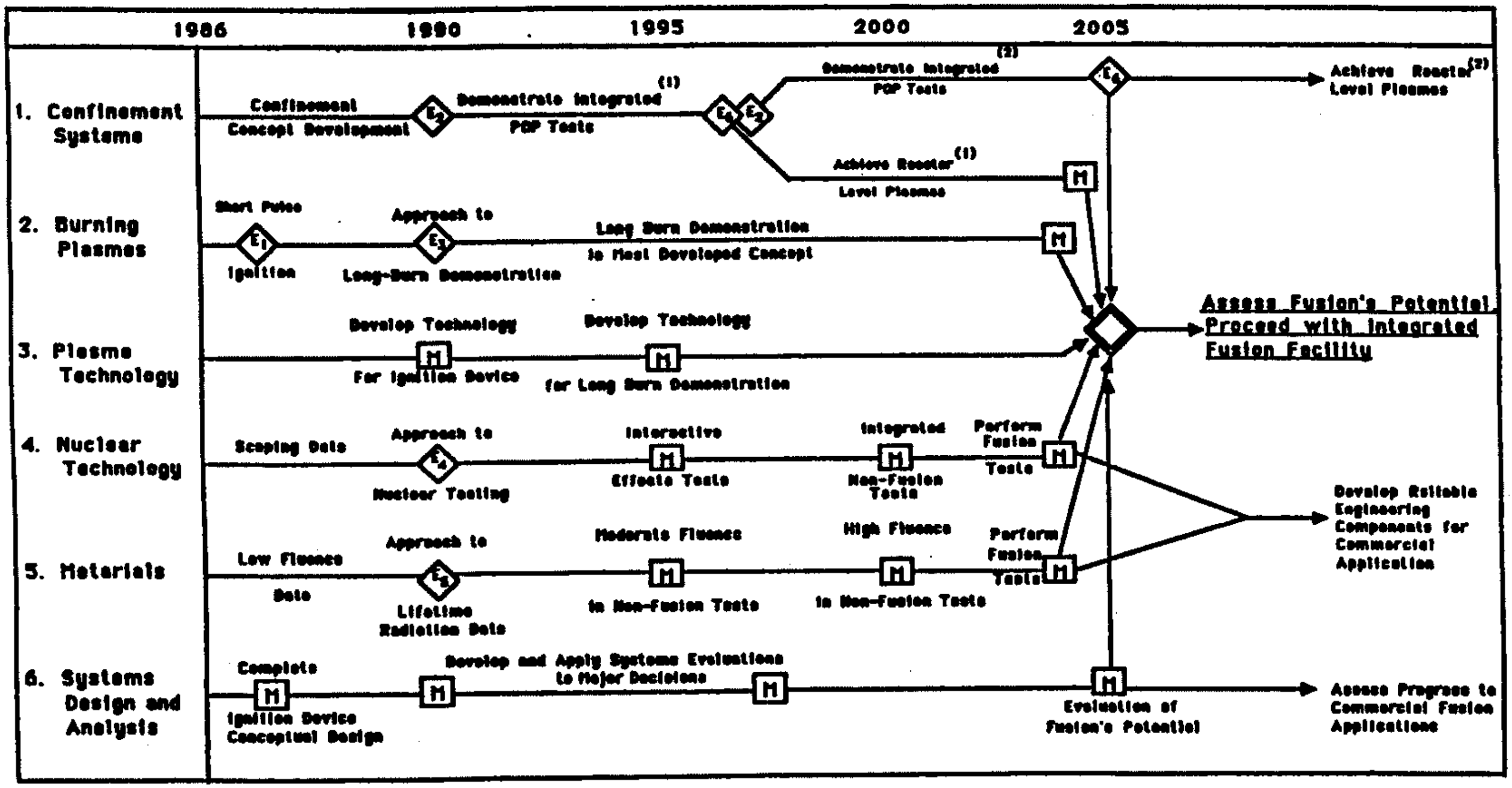
- Magnetic confinement systems--developing an understanding of plasma science leading to improved confinement concepts suitable for commercial applications of fusion energy
- Properties of burning plasmas--understanding the effects introduced when the plasma is internally heated by the fusion reaction
- Fusion nuclear technology--developing nuclear technologies unique to fusion for the commercial application of fusion energy
- Fusion materials--developing materials that will enhance fusion's economic and environmental potential.

Figure 3-1 shows an overview of a possible magnetic fusion technical plan for the next 20 years, as developed in TPA, (Argonne National Laboratory, 1986). The figure shows major activities, evaluation points, and milestones for the MFPP's four key technical issues.

The strategy, as indicated in Figure 3-1, calls for testing a variety of magnetic confinement concepts to develop a leading concept. The approach to resolving the burning-plasma issue is to rely on the currently most highly developed confinement concept, the conventional tokamak. Scientific breakeven experiments, in which the energy produced by the plasma just equals the energy supplied to heat the plasma, are planned for the next few years (Tokamak Fusion Test Reactor (TFTR) in the United States, Joint European Torus (JET) in Europe, the device known as JT-60 in Japan, and that called T-15 in the Soviet Union). These experiments are to be followed by a short-pulse ignition tokamak to start operation by about 1992.

Research and development plans for fusion nuclear technology are particularly important to the subject addressed by this committee. The basic strategy defined in the FINESSE study (Abdou et al., 1985a) and adopted in TPA, as indicated in Figure 3-1, is to proceed through approximately five-year phases of progressively more prototypical testing, culminating in tests in a fusion device. The latter could, in principle, be the ETR discussed below or a different device. Intermediate phases include scoping tests, simulations of interactive effects, and testing of integrated subsystems in nonfusion facilities. Key decision points and narrowing of technology options occur between each phase. The major, combined milestone for both nuclear technology and materials is the testing of primary options in a fusion environment by about the year 2005. In conjunction with obtaining reactor plasma data in a confinement configuration suitable for a demonstration facility, designated as DEMO, this milestone will provide the principal input to the assessment of fusion's potential and the decision on DEMO. Key intermediate milestones include verifying nuclear technology concepts in integrated tests in nonfusion facilities and obtaining high fluence data on primary candidate materials in fission reactors by the year 2000.

(1) From class of present "moderately-developed" concepts
(2) From class of present "developing" concepts



Magnetic Fusion Program Plan Overview

FIGURE 3-1 Overview of a possible U.S. technical plan for magnetic fusion for the next 20 years.

SOURCE: Argonne National Laboratory (1986).

Beyond the ignition experiment, shown in Figure 3-1 at about 1997, the next step is thought to be a more ambitious engineering test reactor. Japan and Western Europe plan for a Fusion Engineering Reactor (FER) and the Next European Torus (NET), respectively, to begin operation by about the year 1998. The possibility of multinational cooperation, previously studied by the National Research Council (1984), on an engineering test reactor is currently being explored by the United States, the European Community, Japan, and the Soviet Union. Possible features of such a multinational undertaking are shown in Figure 3-2. It is believed that an ETR-, NET-, or FER-type device can be followed by a demonstration facility.

FUSION HYBRID REACTORS

General Description

In the fusion hybrid reactor, technical details of which are described in Chapter 4, energy is produced by both fusion and fission reactions. In such a reactor the fusion process provides a source of neutrons. The hybrid applications would typically use this neutron source by surrounding the fusion core, where the fusion reaction is occurring, with a subcritical blanket. The blanket contains fertile and fissile material. Fertile material contains nuclides (for example, thorium-232 or uranium-238) that can be converted in the neutron environment to fissile nuclides. Fissile material contains nuclides (such as uranium-235 or plutonium-239) capable of being fissioned by neutrons of all energies. In the blanket region the fusion neutrons are slowed down, the resulting heat is transferred to a primary coolant, and tritium is bred from lithium, also contained in the blanket. The reactor will produce some fission of the fissile material in the blanket (for example, $n + {}^{235}U \longrightarrow$ fission products + 2.5 n) and will also produce additional fissile material from fertile material in the blanket (for example, $n + {}^{238}U \longrightarrow {}^{239}Pu + \beta^-$). In hybrid applications, fertile materials are located in the blanket in order to breed fissile fuel for use in conventional LWRs (for example, $n + {}^{232}Th \longrightarrow {}^{233}U + \beta^-$). The hybrid, together with a constellation of LWRs that it might fuel, would constitute an integrated electric generating system. Alternatively, an individual fusion hybrid might generate and market electricity, and sell fissile fuel to any qualified buyer as a byproduct.

A pure fusion reactor also has a fusion core. Each fusion reaction produces one neutron, and this neutron carries away most (about 80 percent) of the energy of the reaction. A quite different kind of

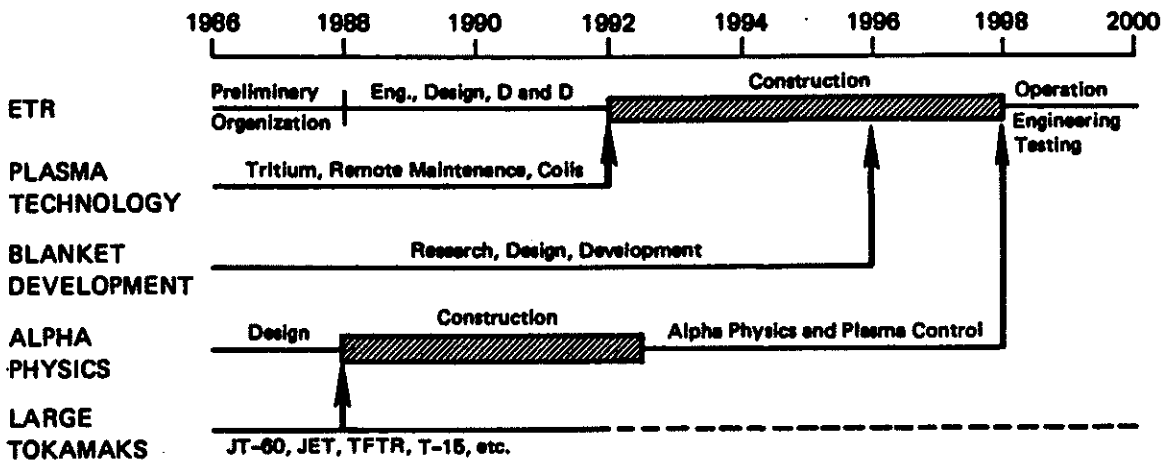


FIGURE 3-2 Features of a possible multinational activity leading to a fusion engineering test reactor.

blanket from that of the hybrid, not involving fertile and fissile material, surrounds the fusion core to slow and absorb the neutrons and to generate additional tritium to fuel the reactor. The genesis of the fusion hybrid reactor concept was the recognition that a properly designed blanket can produce, through fission processes, substantially greater numbers of neutrons than are needed to sustain the fusion reaction.

Thus the basic purpose of the hybrid concept is to combine the best features of both fusion and fission toward producing fissile fuel, power, or a combination thereof. For example, the low power density of the fusion core can be offset by the high power density of fission in the blanket, while the low neutron production of fission per unit of thermal energy can be offset by the high neutron production per unit of thermal energy from fusion. Furthermore, the two functions need not be combined in the same physical unit. For example, if the excess neutrons in the fusion system are used to make fissile fuel in the blanket, that fuel can be burned in a separate fission reactor. Once this concept has been proved, enough fissile fuel could be supplied in this way by a single fusion hybrid reactor to fuel many fission reactors.

A related figure of merit for such a hybrid reactor is known as the support ratio. This ratio is defined as the amount of external fission power producible from hybrid-derived fissile fuel per unit of power from the hybrid. Thus, the support ratio is based on total thermal power, including blanket multiplication, rather than on the fusion power of the hybrid. If all plants, both fission and hybrid, were identical in their thermal ratings, then the support ratio would be equal to the number of fission reactors that could be supplied with fuel by one fusion hybrid reactor.

Specific Features

Fertile material is processed into a form suitable for use in the blanket of the fusion hybrid, where it becomes enriched in its content of fissionable nuclides. Following enrichment and reprocessing, the resulting fissile material can be used as fissile feedstock in the conventional LWR fuel cycle.

Figure 3-3 illustrates the two major fusion hybrid concepts, the fast-fission hybrid and the fission-suppressed hybrid. In the former concept, the deuterium-tritium fusion core of the reactor is surrounded by a blanket of fertile material. The fast neutrons from the fusion reactions induce "fast fissions" in the blanket. Of the neutrons produced, at least one must react with lithium to regenerate the tritium fuel consumed in the core, while the surplus neutrons are available for breeding fissile fuel.

In the fission-suppressed hybrid, the fusion core is surrounded by a blanket of tritium-breeding material and a non-fissioning neutron multiplier. This blanket also moderates, or slows, the neutrons below the threshold for fast fission. Again, one neutron is used for tritium breeding, with the remainder available for the production of fissile

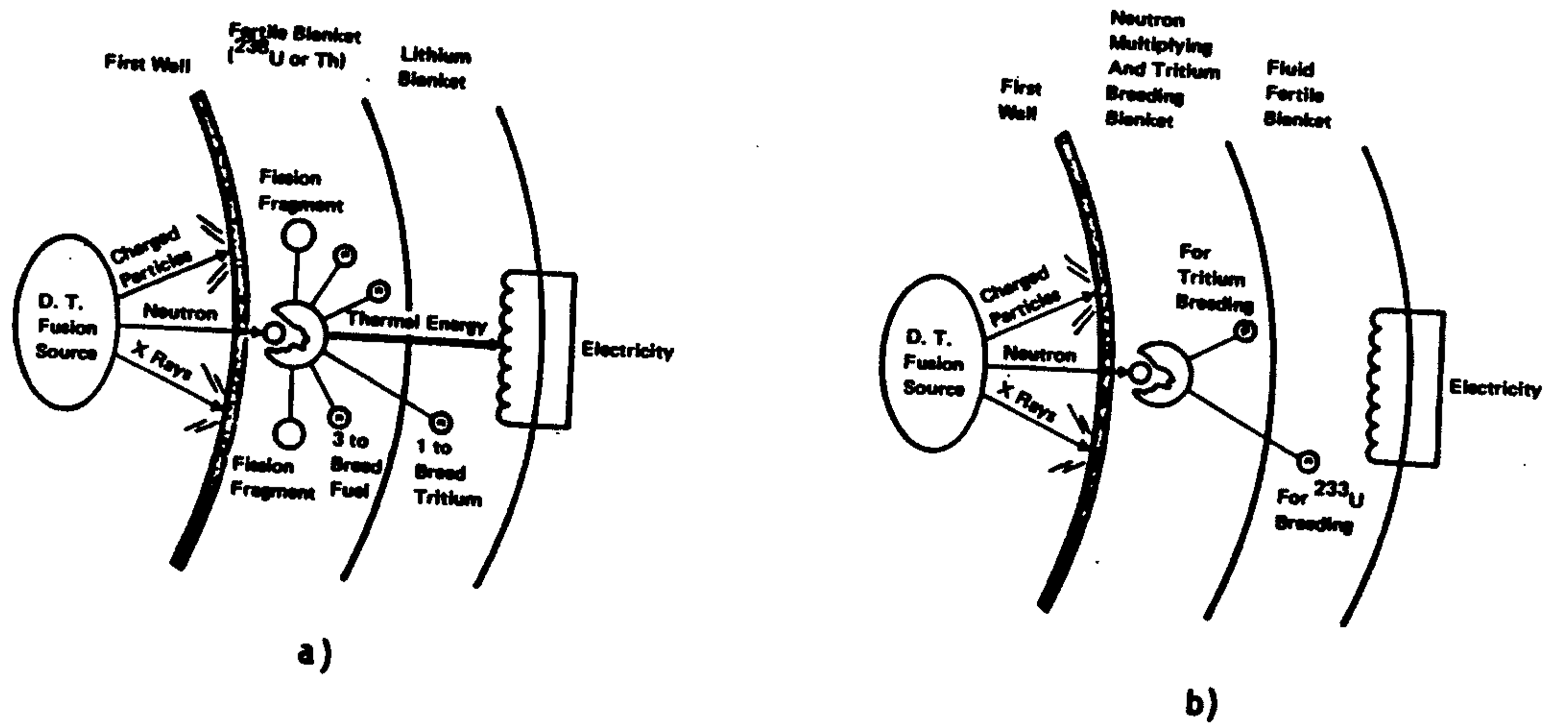


FIGURE 3-3 Fusion hybrid concepts: (a) fast-fission blankets (b) fission-suppressed blankets.

SOURCE: Electric Power Research Institute (1982).

fuel. Since most of the neutrons that enter the fertile outer region of the blanket are below the fast-fission threshold, fission energy production in this region is minimized.

Blankets for both designs can offer good fuel-breeding performance, although each approach has advantages and disadvantages. Reprocessing blanket material to recover fissile fuel figures heavily in the technology, cost, and social acceptability of the hybrid. Reprocessing also figures prominently in assessments of LWR and liquid-metal cooled fast reactor technology in an era of uranium scarcity. Further technical and cost details are provided in Chapter 4. Reprocessing as it pertains to nuclear proliferation resistance is discussed in Chapter 5, along with other economic and social aspects of the hybrid.

INERTIAL CONFINEMENT FUSION

Thus far, the fusion neutrons for driving the prospective fusion hybrid have been presumed to have been produced by magnetically confined fusion plasmas. A different concept for producing those neutrons is a process known as inertial confinement fusion (ICF), in which the U.S. Department of Energy also conducts an ongoing research program.

To compare the two approaches, magnetic fusion attempts to extract energy from fusion reactions at relatively low plasma density, operating as closely as possible to a steady state. Hence it is necessary to insulate the reacting plasma from the bulk of the reactor, since interactions with the reactor walls would produce impurities that would cool the plasma and stop the fusion reactions. An alternative means of producing fusion energy is to operate in precisely the opposite parameter regime: a pulsed ignition of high energy densities in small volumes of fuel. The objective would be to obtain rapid, highly efficient burn of a small mass of fuel and thus to avoid the need to confine the fuel at all, since the burnup would occur in a time short compared to the time for expansion of the fuel, say, less than a microsecond. This mode of operation is called inertial confinement fusion because the fusion fuel is confined only by its own inertia. Each pellet, when it burns, would thus produce a small explosion that would release an amount of energy equivalent to about one hundred pounds of high explosive.

The proposed means of attaining such a mode of operation is to deposit a large amount of energy (greater than 1 megajoule) in a small fuel pellet mass (about 1 milligram) in a short pulse (about 10 nanoseconds). Assuming the energy can be deposited with enough efficiency and symmetry in the outer regions of the pellet, compression of the fuel would be driven by the reaction of particles ablating, or vaporizing, from the surface of the pellet. The idea is to compress the fuel adiabatically, or without loss of heat, so it can attain very high density before it achieves, as a consequence of the compression, the temperature required for fusion to occur. High compressions (about 1,000 times liquid density of the deuterium-tritium fuel) would be necessary to produce efficient burn. Attainment of thermal equilibrium by the fuel prior to full compression would prevent the attainment of such high densities; thus both the design of the pellet and the means of depositing the energy pulse in it sensitively influence the obtainable gain (ratio of fusion energy out to energy deposited) of the pellet.

Two different means of depositing the requisite energy pulse in the fuel are being investigated: by short-pulse laser beams and by ion beams. The ion beams could comprise either light ions (for example, lithium) or heavy ions (for example, uranium), accelerated respectively by pulsed-power diodes or linear accelerators. Laser candidates with wavelengths in the range 0.25 to 1 micrometer are being explored.

From the point of view of fusion reactor design, ICF has an interesting potential advantage: for both laser- and heavy ion-beam drivers, the vessel in which the fusion reactions take place can be physically well separated from the laser or ion-beam driver. This means that a broader variety of reactor and blanket concepts can potentially be exploited. For example, since the first wall can be farther from the hot fusion plasma, in some concepts the lithium-7 material in which tritium is bred can be inside the first wall; thus, in principle, better tritium breeding performance might result. Similar simplification would presumably result for fusion hybrid blankets. However, in general, these ICF reactor concepts have not yet received the detailed neutronics and engineering analysis that would put them on a footing comparable to the major magnetic fusion reactor studies.

ICF will not be further considered in this report for three reasons:

1. The technical status of ICF places it behind magnetic fusion in prospects for attainment of ignition in a facility that could produce neutrons with an average fluence high enough to serve as the basis of a hybrid.

2. The systems integration aspect of ICF has not advanced enough to make meaningful assessments of its economic and social aspects.

3. The ICF program is funded entirely as a defense research program; critical elements of the program are classified. Although these features would not complicate the use of ICF for tritium production, they did limit the committee's access to information about ICF.

A separate study of inertial confinement fusion has recently been completed (National Research Council, 1986) under the chairmanship of William Happer, Jr. The first observation above, reinforced by the findings of the Happer Committee (whose deliberations were carried out on a classified basis), leads the committee to conclude that the status of magnetic fusion dominates considerations of the practicality and early availability of an operating fusion hybrid.

LIQUID-METAL COOLED FAST REACTORS

The liquid-metal cooled fast reactor (LMFR) power plant is capable of producing both electricity and some excess fissile fuel. The liquid-metal coolant is sodium. "Fast" refers to the high-speed neutrons, which facilitate the production of excess fuel, usually by converting abundant uranium-238 to fissionable plutonium. Excess fissile fuel means fissile material produced beyond that needed to fuel the reactor.

Experience

The United States was the first country to demonstrate, in the early 1950s, the technical feasibility of excess fuel production in the experimental LMFR EBR-I. U.S. LMFR technology advanced significantly while EBR-II has been in continuous service since 1963, and during the 12-year design, component development, and licensing phases of the 350-MWe Clinch River Breeder Reactor Project (CRBRP), authorized by Congress in 1972 and terminated by Congress in 1984 because of budget constraints.

The early moderate-sized test and demonstration LMFRs in this country, namely the Fast Flux Test Facility, at Hanford, Washington, and CRBRP, were not designed nor developed to be competitive in the near-term marketplace. They were designed at a time when it was expected that low-cost nuclear fuel reserves would be exhausted around the turn of the century as a result of burgeoning LWR construction activity. The general perception then was that LMFRs must be developed as quickly as possible, and there was no alternative but to design them as conservatively as possible. Fulfilling the missions identified for these projects forced design uncertainties to be addressed in costly ways. Today, it is widely recognized that LMFRs must compete on an economic basis with LWRs fueled by mined uranium at moderate prices and must be designed to take the fullest economic advantage of the underlying features that are unique to the LMFR.

Current Work

The recent technological progress in LMFR development and the availability of more time before a design concept must be chosen for prototype construction have provided an opportunity to develop new LMFR designs that emphasize improved economics, greater reliance on passive safety, modular construction, and shorter construction times. Two such designs are currently under development, PRISM by General Electric Company and SAFR by Rockwell International Corporation. Reviews of these designs have been conducted by the Nuclear Regulatory Commission (NRC), and licensability assessments are expected from NRC in 1987 or 1988. Research and development have been reoriented to support more effectively the advanced designs in long-life metal and oxide fuels, improved structural materials, passively safe reactor shutdown and decay-heat removal systems, and advanced plant control systems. The PRISM and SAFR designs would increase the capability for factory assembly of much of the nuclear island under conditions with improved quality control. Such modular assemblies could be transported by either barge or rail to suitable sites, where the non-nuclear balance-of-plant components would be constructed using normal practices in parallel with factory assembly of the nuclear island.

Experience from over 150 reactor-years of experimental and mid-size power units around the world has demonstrated that LMFRs are as easy to operate as LWRs, maintenance is easier with much lower personnel dose commitments, and the systems are quite forgiving. Fuel burnups of around 100,000 MW-days/MT were demonstrated in France, the Soviet Union, the United Kingdom, and the United States for oxide fuels, and U.S. experience with metal fuel approaches 150,000 MW-days/MT; materials research indicates considerable potential for much higher burnups.

The technical feasibility of closed and automated fuel-cycle and fuel-fabrication systems, together with long-life fuel cores, offers some reduction of the nuclear proliferation risk, although not its elimination. The LMFR fuel cycle has been closed in France and the United States on a noncommercial basis. To obtain plutonium that can be used to start up LMFRs, France has reprocessed spent fuel from LWRs on a commercial scale for over a decade, and high-level waste from reprocessing has been vitrified. Current plans call for a 60-ton per year reprocessing plant to be in operation in time to receive spent core and blanket fuel from the next large European LMFR plant.

The current economic goal for next-generation LMFR plants is a cost of less than 1.2 times that of an LWR burning moderately priced uranium. That goal is being approached in the next generation designs in France (SPX-2), Germany (SNR-2), United Kingdom (CDFR), Japan (DFBR), and the United States (SAFR and PRISM). These designs reflect the maturity of LMFR technology and take full advantage of the favorable LMFR characteristics such as low operating pressure, large thermal inertia, strong natural convection capability of the coolant, large margin to boiling, and the noncorrosive nature of the coolant with respect to structural materials. These features lead to designs that use simpler containment systems; greatly reduced need for safety-grade, fast acting, electric power supplies; and minimum on-site facilities for liquid and solid radioactive waste treatment.

The recent U.S. LMFR studies (SAFR, PRISM) indicate potential for reducing capital cost per unit of rated power capacity by taking advantage of the unique characteristics of sodium-cooled reactors. These studies indicate that balance-of-plant cost for nth-of-a-kind LMFR plant might be as low as 0.7 to 0.9 times that of the balance of plant for a LWR. Nuclear supply steam system (NSSS) cost for an LMFR appears to be approximately two to three times that for a LWR. Overall, the LMFR capital cost per unit of rated power capacity might be in the range of 1.1 to 1.5 times that of a LWR plant of equivalent size.

In summary, LMFRs are a credible alternative for meeting some of the the world's electricity needs beginning early in the next century. If economical, LMFRs can be introduced to replace retiring LWRs and to supply new energy requirements. Because the LMFRs can be fueled with already mined and separated depleted uranium for hundreds of years, and because they require far less makeup uranium than do LWRs, the cost of LMFR-produced electric energy is insensitive to the price of uranium ore. Therefore, the LMFR is an alternative means, with already advanced technology, to continue fission electric power in the future era of rising price of uranium ore.

COMPARISONS

Alternatives to LWRs, if needed, will probably come from the four technologies described above or their variants.

ICF lags the hybrid with a magnetically contained plasma core on technical grounds, so by comparison that hybrid remains an alternative worthy of consideration.

Magnetic fusion must undergo much development even to make the hybrid possible. One may ask, therefore, having completed that development, will not the choice of pure fusion over the fusion hybrid be clear? However, the remaining technological and economic uncertainties in commercializing pure fusion as a completely new technology are so great, compared with those of a hybrid supporting an established LWR economy, that the choice between them does not seem clear at this time. Thus on these grounds, the hybrid also merits concurrent consideration as an alternative.

The LMFR is perhaps the nearest competitive technology to the hybrid, being clearly more technologically advanced. Yet the LMFR is still faced with technical, economic, and political uncertainties such as breeding yield, materials, capital cost, safety, and licensability. At this writing its future as the nuclear technology of choice cannot be assured over the hybrid.

These qualitative comparisons set the stage for the more detailed discussion of the technical, economic, and social aspects of the hybrid in the following chapters.

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4

TECHNICAL ASSESSMENT OF FUSION HYBRID REACTORS

There are three generic concepts being explored for fusion hybrid reactors. These concepts are designated here as the fast-fission power-only hybrid, the fast-fission fuel-producing hybrid, and the fission-suppressed hybrid. The concepts span a significant range in the performance required of the fusion core, in the amount of fissile fuel produced by the blanket per unit of total thermal power, and in the type of reprocessing technology needed for the fusion-fission reactor system.

FAST-FISSION POWER-ONLY HYBRID

General Concept

At one end of the range is the fast-fission power-only hybrid reactor, whose uranium blanket is optimized for thermal power production. For this concept fissile fuel production is at most incidental. As described to the committee (Jassby, 1986), such a reactor would be fueled by natural or depleted uranium. The substantial power multiplication properties of its blanket would allow operation at rather low fusion wall loadings, of about 1 MW/m^2, and at modest values of the plasma power gain Q, say, in the range of 3 to 5.* These values are close to those achievable in the current generation of "break-even" tokamaks, where the fusion power produced in the plasma equals the heating power injected into the plasma. The fusion power needed is rather modest for a typical 1.5 GWe power plant, because of the high energy multiplication by fission in the blanket. For example, about 600 MWt of fusion power would drive a reactor with total electric capacity of 1,600 MWe.

Because of this high power multiplication, a fast-fission power-only hybrid might allow use of copper toroidal field coils for tokamak designs, which may result in savings in capital cost and system complexity relative to designs with superconducting coils. For similar reasons one might be able to run such a tokamak in a steady-state mode, with consequent design advantages for considerations such as cyclic fatigue and thermal pulsing.

*Plasma power gain is the ratio of fusion power output to plasma heating power provided by external sources.

The concentration of plutonium-239 in the blanket would build up to an equilibrium value of between 1 and 4 percent. Since the bred fuel can be burned up in situ, this power reactor would have the possibility of operating on a once-through fuel cycle. Because of high burnup the benefit of reprocessing of the spent fuel is minimal and might be avoided entirely. The afterheat in this design is due to the decay of the fission products. The afterheat is initially comparable to that of a fission reactor and is greater than that in the fission-suppressed hybrid designs to be described below.

Principal Designs

In the early years of interest in fusion hybrid reactors, the fast-fission power-only hybrid reactor received considerable attention. A general case favoring this type of hybrid was made to the committee (Jassby, 1986; Mills, 1985). Although the committee was informed that a brief report related to this topic is about to appear in the current literature (Jassby et al., 1986), at present we know of no extensive documented studies done in the past 5 or 10 years of blanket designs suitable specifically for fast-fission power-only hybrid reactors (as distinguished from the fast-fission fuel-producing hybrid designs discussed in the following section). Thus we cannot discuss designs for this concept in as thorough a way as we would like.

Almost a decade ago, however, Tenney led a systems study of fast-fission hybrid reactors, which came to some conclusions relevant to the power-reactor concept (Tenney et al., 1978). Tenney and his colleagues spent two years examining a wide variety of tokamak-driven fast-fission hybrid blanket concepts, and performed a quantitative analysis of the trade-off between fissile fuel production and electricity sales. They found that fast-fission power-only hybrid reactors tended to be economic (that is, to have a competitive cost of electricity) only at very large sizes, in the range of 2 to 4 GWe. This result is consistent with that of a Westinghouse study (Chapin et al., 1980), which concluded that on a cost-of-electricity basis, fission-suppressed hybrids were preferred for smaller plant sizes, fast-fission fuel-producing hybrids were preferred for intermediate plant sizes, and (by implication) fast-fission power-only hybrids were preferred mainly for the largest plant capacities.

FAST-FISSION FUEL-PRODUCING HYBRID

General Concept

Presentations to the committee made the following points. The fusion hybrid with a uranium fast-fission blanket, optimized so as to produce significant amounts of fissile fuel as well as electrical power, lies in the intermediate range of fusion core performance. The fusion core would need to have a wall loading of 1 to 1.5 MW/m^2, and the required plasma power gain Q would be between 4 and 10, and, of course, might be greater in a particular design. In typical designs, one such reactor can supply enough fuel in the form of plutonium-239 to support three to six light-water reactors of equivalent thermal power. Reprocessing of plutonium would be required, and the light-water reactors would operate on a plutonium cycle. This is the hybrid concept favored in the recent Soviet literature (Velikhov et al., 1978; Vasiliev, 1985).

Principal Designs

The fast-fission fuel-producing hybrid has been studied by many groups over the years. Here for the sake of illustration we outline a design recently proposed for a tokamak device (Jassby et al., 1986). However we point out that the design parameters for fast-fission fuel-producing hybrids have covered a variety of plasma sizes, confinement concepts, energy gains, and wall loadings, and that the blanket concepts have varied rather widely. The system described below therefore should not be regarded as prototypical, but only as an example.

In this design the plasma is ignited. The plasma current is initiated by ohmic primary windings, and ion cyclotron waves provide auxiliary heating for startup. A magnetic divertor is included for particle and heat control. Figure 4-1 illustrates a cross section through the plasma column, and Figure 4-2 shows a cartoon of the blanket configuration.

The fuel is mobile, in the form of a uranium pebble bed configuration with helium cooling. The pebble bed is designed to be changed out rapidly, allowing for lower fuel exposure (less than 2 MW-year/MT). As a result, this design has a relatively low variation in average blanket power density and output-power swing. The 20-cm pebble bed is followed by a neutron reflector.

Lithium is circulated in liquid form (liquid lithium, LiPb, or FLIBE, which is a term for a molten salt containing fluorine, lithium, and beryllium) through tubes within and behind the uranium pebble bed. Most of the lithium is located in the relatively low-energy region of the neutron spectrum; the flow rate is slow, and is determined only by the removal rate for bred tritium. The liquid lithium also provides a second, redundant cooling path for the bed. The equilibrium, overall tritium breeding ratio is predicted to be 1.01.

Thermal analysis shows that the breeder fuel must be removed relatively quickly from the blanket in the event of loss of coolant. In the current concept, a transient thermal analysis predicts that the fuel pebbles can be gravity-dumped to a separately cooled dump tank before the fuel or structure are damaged by excessive temperature rises. This ability to dump the mobile fuel form is claimed to be an important potential advantage over previous, fixed-fuel form blanket designs for fast-fission systems, since the afterheat in such systems is

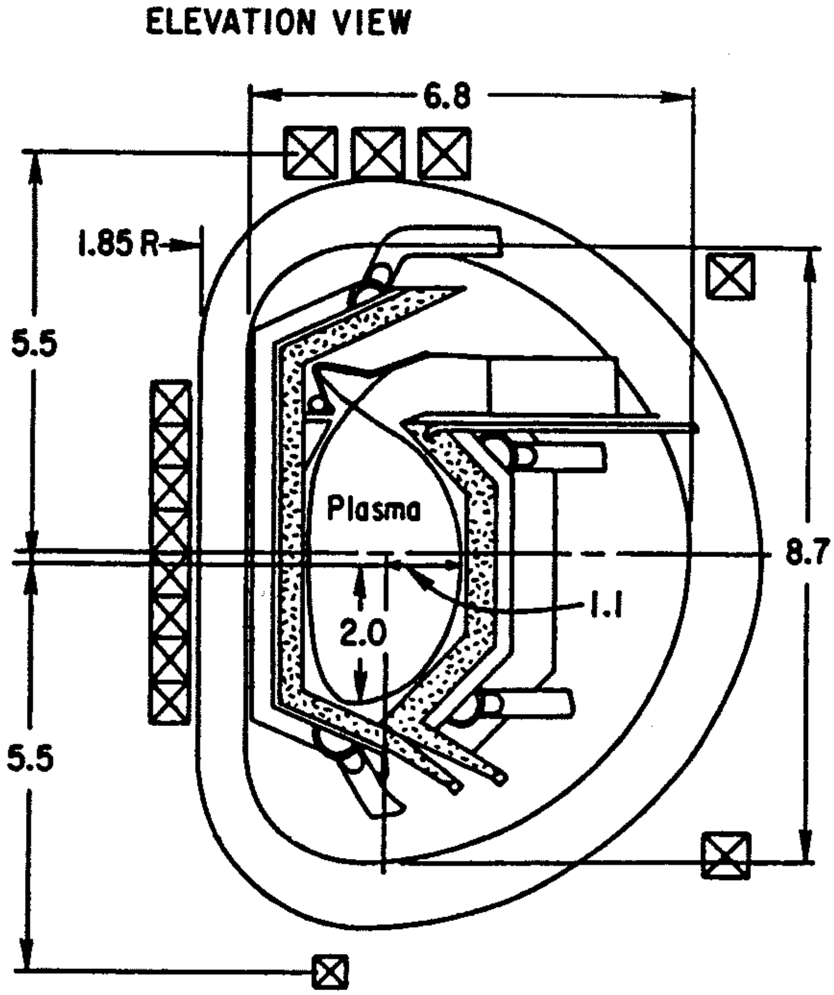

FIGURE 4-1 Cross-section elevation view through the plasma column of a tokamak reactor. Dimensions shown are in meters.

SOURCE: Adapted from Jassby et al. (1986).

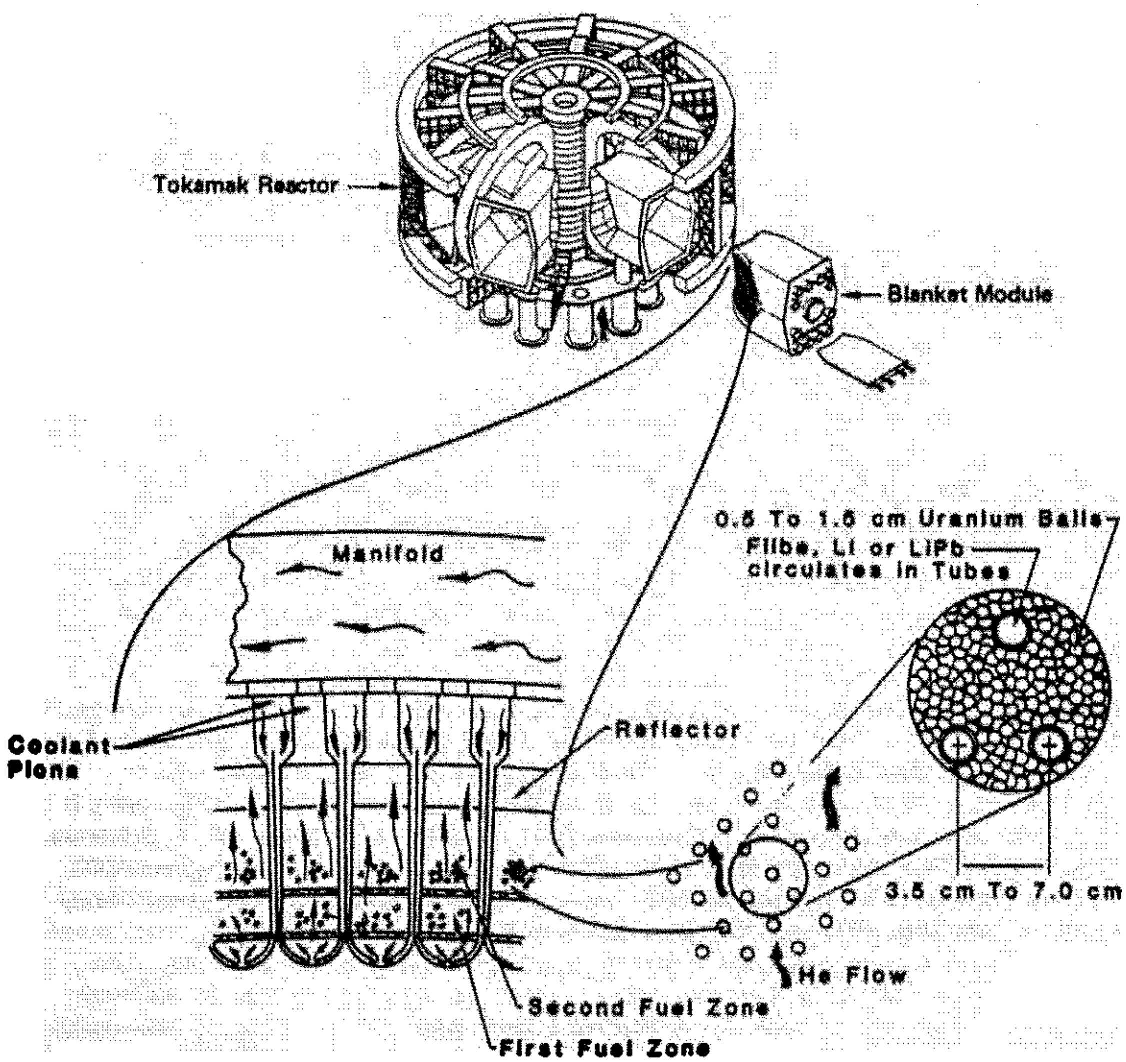

FIGURE 4-2 Schematic diagram of a fast-fission blanket configuration.

SOURCE: Jassby et al. (1986).

significant. The licensability of such a dump system for mobile fuel remains to be determined.

In this design the duration of the operating plasma pulse is 2,000 seconds, and the neutron wall load is about 1.3 MW/m^2. The total fusion power is 614 MW, 490 MW of which is carried by neutrons. The design assumes that the blanket multiplies 83 percent of this power by a factor of 11, so that the useful thermal power is about 4,500 MW. The net plutonium production at 75 percent capacity factor is 3,070 kg/year.

FISSION-SUPPRESSED HYBRID

General Concept

In the fission-suppressed hybrid the concentration of fissile materials in the blanket is kept very low (typically 0.5 percent or less), and beryllium (n,2n) reactions are used for neutron multiplication in the blanket. This produces a blanket with lower power density than in the fast-fission hybrids. The hybrid is now primarily a fissile fuel factory; it is claimed that one fission-suppressed hybrid could supply fissile fuel for 10 to 20 light-water reactors of equivalent thermal power. Information supplied to the committee indicated that the fusion core is closer to that required for a pure-fusion reactor, with wall loadings of 2 to 3 MW/m^2 and plasma power gains Q of 10 to 15. For comparison a pure-fusion reactor might have a wall loading of about 4 MW/m^2 and Q of 15 to 25. The fertile fuel that has been preferred by Lawrence Livermore National Laboratory (Moir et al, 1984b) is thorium-232, since it results in a higher support ratio; the hybrid produces uranium-233 with which to fuel a constellation of light-water reactors. This concept would require the commercial development of thorium reprocessing technology. As discussed later, the committee has serious reservations as to this fuel cycle.

Principal Designs

Three recent fission-suppressed blanket concepts have received design attention in the past few years. The descriptions are as provided by the originators of the concepts.

Liquid-Metal Cooled Blanket

The liquid-metal cooled blanket concept was developed between 1982 and 1985 (Berwald et al., in press). The design has many characteristics in common with liquid-metal cooled pure-fusion blankets. It was developed for a tandem-mirror geometry; further work would need to be done before its applicability to tokamaks could be evaluated.

The coolant is liquid lithium, which also acts as the tritium-breeding medium. The liquid lithium has a maximum temperature of 425 °C (as compared to 500 °C for recent pure-fusion designs). The lithium is flowed radially through a two-zone packed bed of small beryllium pebbles (spheres of about 3-cm diameter), with unclad thorium snap rings around their equators.

The unclad beryllium pebbles provide neutron multiplication; the thorium snap ring is the fertile fuel. Blanket geometry is illustrated in Figures 4-3 and 4-4. The pebbles are loaded into the top of the blanket and discharged at the bottom in a batch process once every one or two full-power years for the two fuel zones respectively. The neutron wall loading is 1.7 MW/m^2 with ferritic steel as structural material.

Since fission-product inventories are deliberately kept low in this design, the fission product decay afterheat is small. The designers state that the decay heat could be removed by dumping the mobile fuel pebbles to a passively cooled dump tank. Some of the important issues for the liquid-metal cooled designs include the technology for liquid lithium cooling, including materials and components; magnetohydrodynamic pressure drops of the lithium moving through the ambient magnetic fields; prospects for designing beryllium and thorium with reliable cladding; pebble lifetime and integrity; and the realities involved in developing a high throughput reprocessing technology for the thorium-based fuel at a cost that is not prohibitive.

Helium-Cooled Blanket

A helium-cooled version of the pebble blanket concept was developed in 1983 to 1984 (Moir et al., 1984a). Figure 4-5 shows a cross-section elevation view for the main tokamak design of this blanket.

This helium-cooled blanket uses the same kind of beryllium pebbles, unclad thorium snap-rings, and fueling scheme as in the liquid-metal cooled design described above. The design retains the ability to dump the fuel pebbles to a passively cooled tank below the reactor.

Tritium is bred in Li_2O in tubes that penetrate through the pebble-bed zones. These are illustrated in Figure 4-6. The internal complexity of this blanket design is greater than that of its liquid-metal counterpart.

Neutron multiplication occurs in a bed of helium-cooled 2-cm diameter beryllium pebbles. The helium outlet temperature is 500 °C. The neutron wall loading is 3 MW/m^2 and the plasma power gain Q is 9.7. Fissile fuel production is calculated to be 4,900 kg of uranium-233 per year from 3,000 MW of fusion power. The tokamak runs in a long-pulse, inductive current-driven mode, and has a single null poloidal divertor.

Some of the technical issues for this concept include first-wall lifetime and deformation, tritium breeding development, tritium control in the helium coolant, isolation of the coolant from radionuclides produced in the thorium, unclad beryllium and thorium irradiation damage and resulting pebble failure modes, pebble lifetime and thermal behavior, and prospects for economically attractive reprocessing.

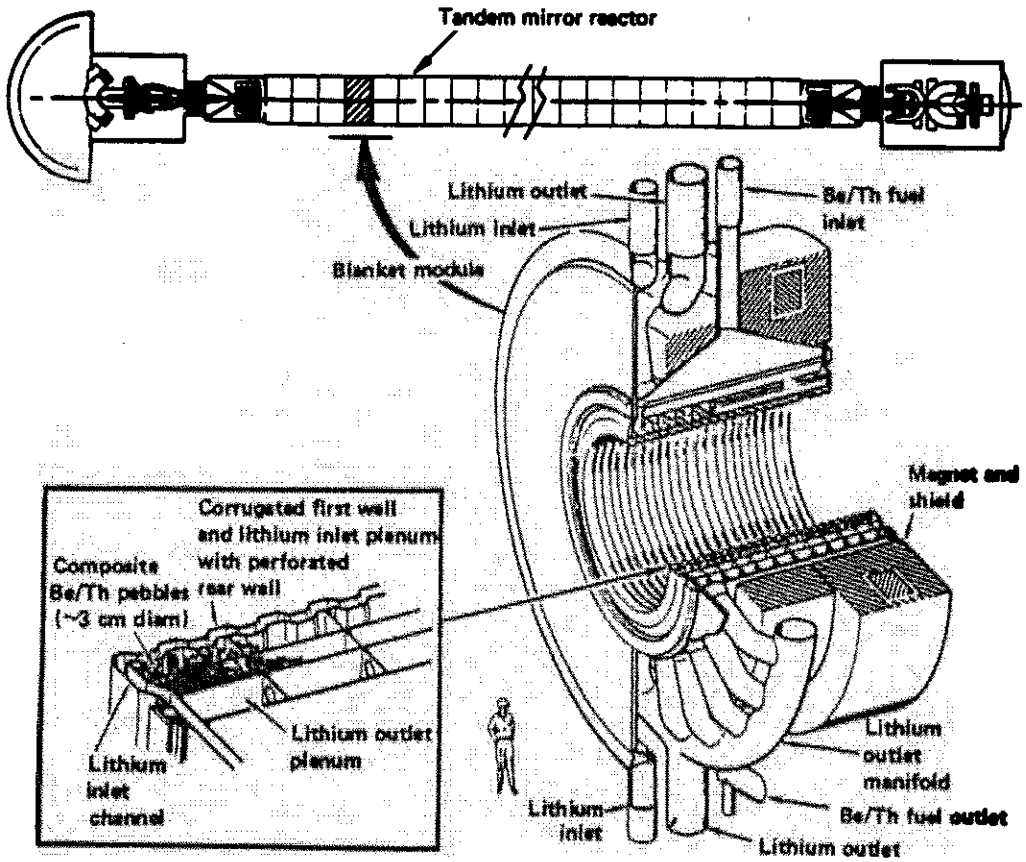

FIGURE 4-3 The reference liquid-metal cooled, fission-suppressed, tandem-mirror fusion-hybrid blanket features direct cooling of a bed of beryllium-thorium pebbles.

SOURCE: Berwald et al. (in press).

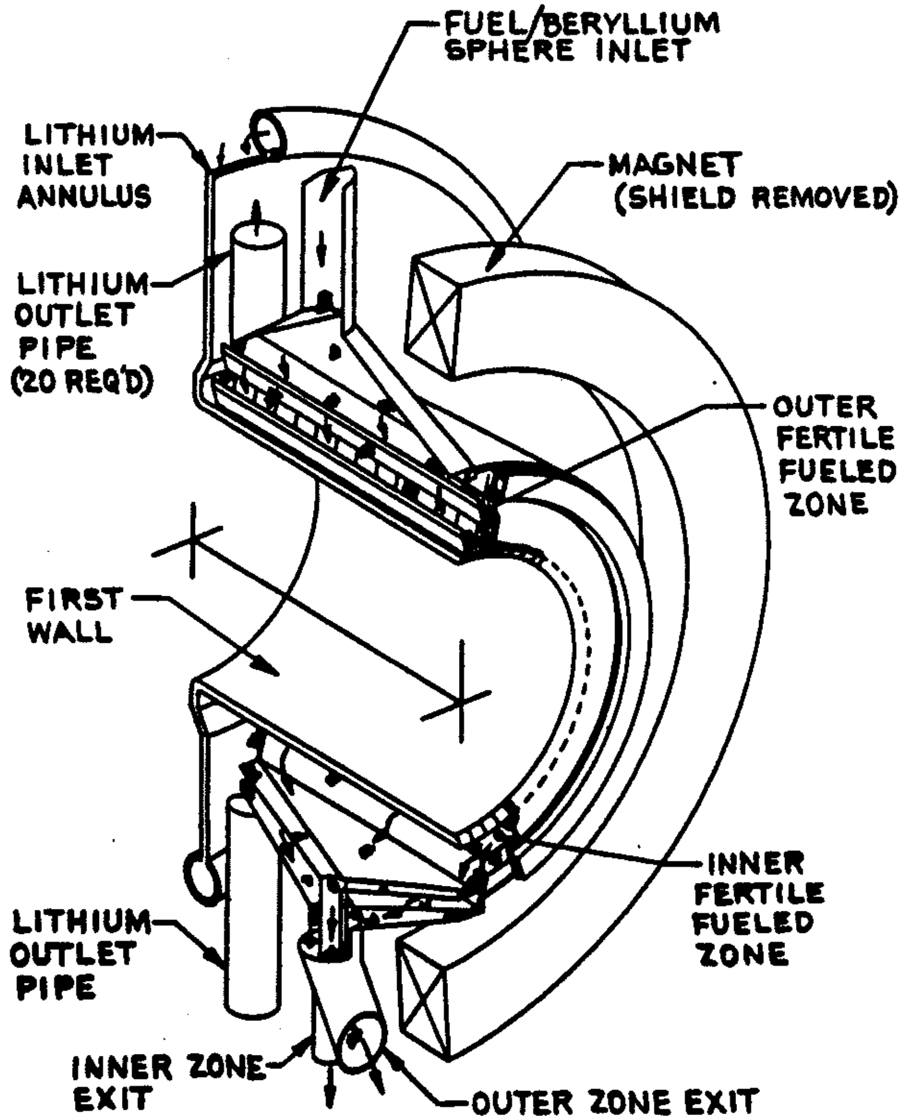

FIGURE 4-4 Trimetric of the fusion hybrid blanket module geometry, showing radial zoning and fuel sphere movement through the blanket.

SOURCE: Berwald et al. (in press).

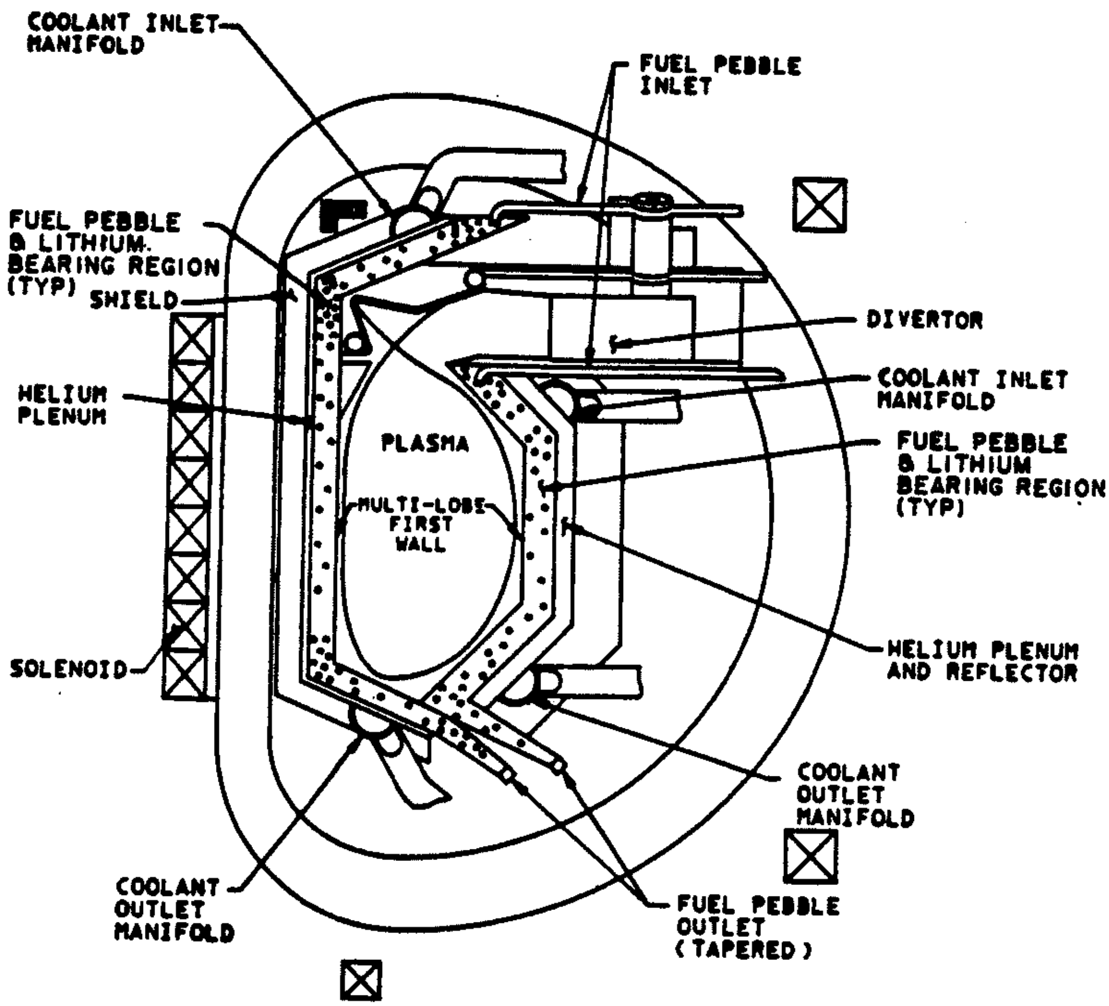

FIGURE 4-5 Cross-section elevation view of the helium-cooled fusion breeder reactor concept with a top-mounted divertor.

SOURCE: Moir et al. (1984a).

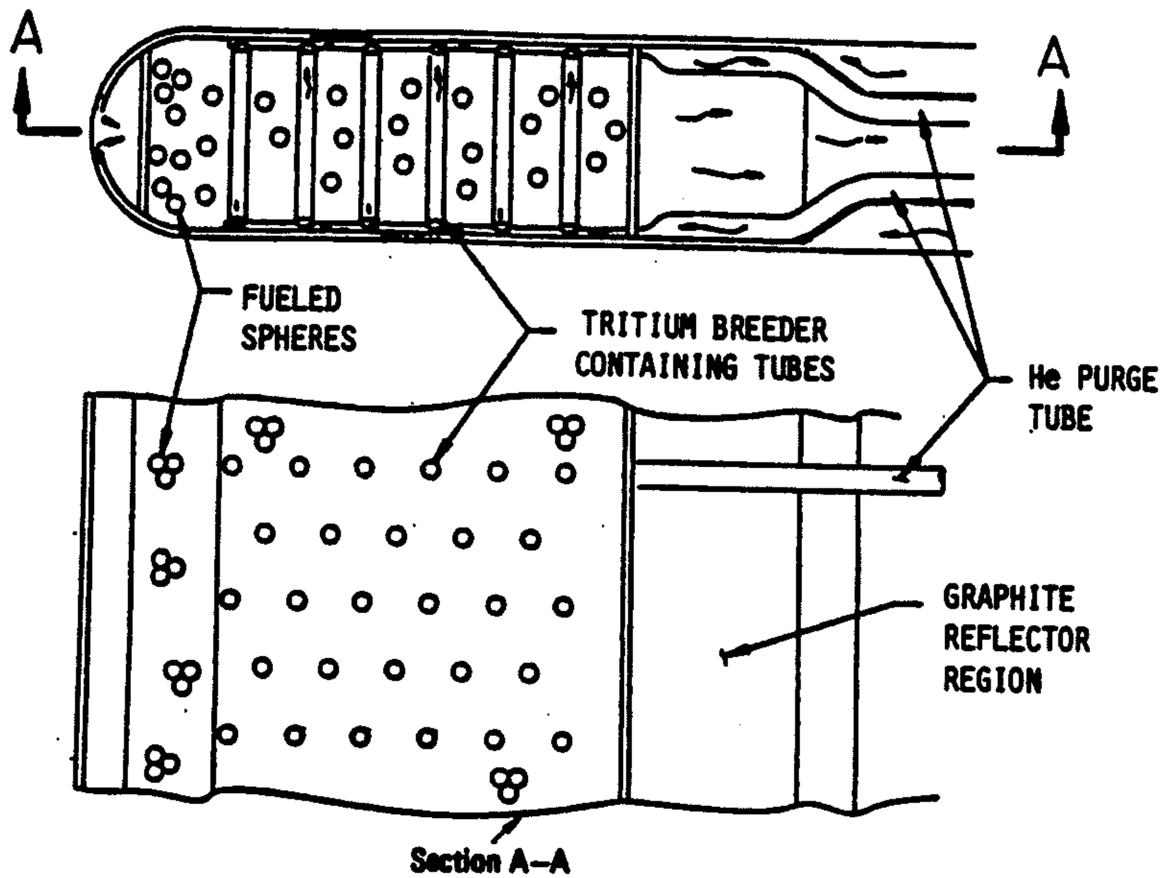

FIGURE 4-6 Cross section of outer blanket module showing tritium breeder containing tube arrangement in fueled region of blanket.

SOURCE: Moir et al. (1984a).

Helium-Cooled Molten-Salt Blanket

A variant on the previous design uses a thorium and lithium bearing molten salt (LiF-BeF_2-ThF_4). The version described here (Moir et al., 1984b) was based on the use of a tandem mirror, but it might work equally well on a tokamak.

The blanket design relies on as yet undeveloped continuous reprocessing of the molten salt by fluorination for on-line removal of the bred uranium-233.

A key issue in this design is the development of tritium permeation barriers on salt-carrying tubes and on the helium-to-steam heat exchanger tubes. Additionally, the neutronics and breeding performance of this molten-salt design are sensitive to moderation and absorption in the structural material. Among the other needed developments are technology for containing and circulating the molten salt; reliable reprocessing technology; means of handling the radioactive gases that will be liberated from the molten salt; and means of controlling low-solubility compounds formed in fission, transmutation, and chemical corrosion.

STATUS AND REQUIREMENTS

Status of Systems and Design Studies

As discussed above, a number of systems analysis and design studies have been carried out for fusion hybrids over the past 15 years. These studies developed several design concepts and identified some of the key technical issues. However, these studies to date are much less extensive than those performed by the fusion program for electricity-producing (pure) fusion reactors.

Hybrid studies have been limited in resources and have involved only a relatively small number of organizations and technical experts. Therefore, it is not clear that the economic potential for hybrids has been fully explored. Current designs should be considered as examples rather than definitive choices. Thus, the current designs are not sufficient to define a specific and comprehensive research and development (R&D) program. Moreover, experts differ on whether the time development for commercial hybrids is faster or slower than that for pure fusion. Nevertheless, reports presented to the committee suggest a number of observations on the impact of hybrids on fusion R&D requirements. These observations are summarized below.

Research and Development Requirements

Given the above status, it is hard to resolve whether the hybrid is a stepping stone to the pure fusion reactor. Some versions appear to have lower requirements in performance than pure fusion, but some seem more complex. However, hybrids appear to be an application of fusion energy that has merit under certain scenarios discussed elsewhere in this report. The R&D requirements for hybrids can be viewed in reference to those for pure fusion in the areas of plasma physics, plasma support technologies, nuclear technology, and reprocessing technology.

Plasma Physics

Plasma physics requirements for the hybrid appear to be more relaxed than those for pure fusion. The plasma power gain Q and the beta values defined in hybrids are generally less than those for pure fusion, though in some cases the difference is small.* Within hybrid designs, the requirements are less onerous for the fast-fission power-only hybrid than those for fissile fuel-producing hybrids. However, no major changes in plasma physics experiments in the near term, say over the next 10 years, can be recommended for two reasons:

1. Major advances in understanding fusion plasma behavior and operational limits are needed, regardless of the application.
2. The economics of all types of hybrids can be improved by better plasma performance. It is too early to define precisely the plasma performance levels adequate for economic competitiveness of the hybrids as producers of fuel or electricity.

Plasma Support Technologies

Plasma support technologies include those components necessary to confine, heat, and fuel the plasma and to control and exhaust impurities. The only area where a major change in the technology choices can be identified is that of magnets for confinement. Resistive, rather than superconducting, magnets could be used in power producing hybrids because a larger recirculating power can be afforded. However, superconducting magnets may be necessary for fissile fuel producers to achieve improved economics.

Nuclear Technology

Nuclear technology addresses such components as the blanket, first wall, radiation shield, tritium, and nuclear elements of in-vessel components. The R&D requirements for the radiation shield and tritium are similar for pure fusion and hybrids. The greatest difference between hybrids and pure fusion reactors is in the nature of the blanket and first wall.

A blanket can be characterized principally by the materials used and configuration selected. Some of the materials are fertile and fissile material. Others function as tritium breeder, coolant, structural

*Beta is the ratio of plasma pressure to magnetic pressure.

materials, and neutron multiplier. For the last four functions the major options that have been considered in pure fusion blankets are shown in Figure 4-7. All options that have been suggested for the same four functions for a hybrid blanket are covered as well by this figure. The major differences between pure fusion and hybrid blankets are: (1) a neutron multiplier must be used in fissile-fuel producing hybrids, while some pure fusion options do not require a multiplier; (2) the presence of fertile and fissile materials in hybrid blankets makes the preferred design configuration different; and (3) lower neutron wall load and low heat flux through the first-wall surfaces can be used to improve and optimize designs, for example to reduce temperature and stresses at the first wall. Many of the R&D tasks are not substantially different between pure fusion and hybrid concepts. The major differences are, for the hybrid, fissile fuel recovery and greater emphasis on beryllium.

A major difference in the blanket R&D programs for hybrids and pure fusion can arise if the blanket concepts use different materials, for example, liquid metals for pure fusion and molten salt for hybrids. At this stage of fusion research it seems prudent to emphasize those design concepts, critical issues, and experimental programs that can serve many end-use applications. Attempts to carry out different design concepts and experimental facilities for each different end-use application will hinder optimum progress in a constrained budget program.

Reprocessing Technology

<u>Technologies</u> The status and requirements of reprocessing technology for the fusion hybrid vary greatly with the choice of nuclear fuel cycle. For the uranium-plutonium cycle, which would probably be used in fast-fission blankets, the Purex technique is acceptable and is the best developed of any on a commercial scale. Although civilian Purex reprocessing is not currently being used in the United States, it is employed in Europe, Asia, and Latin America in a growing number of enterprises. The cost of reprocessing once-through uranium fuel discharged from light-water reactors is high enough that in some countries such reprocessing is not currently economical.

The design reports for the thorium-blanketed fission-suppressed hybrid and its satellite light-water reactors specify thorium reprocessing for the hybrid blanket and thorium-uranium reprocessing for fuel discharged from the light-water reactors fueled with hybrid-produced uranium-233. In assessing the state of technology and economic feasibility of this fusion-hybrid system, it is important to evaluate the state of reprocessing technology and the cost of bringing that technology to level of demonstrated reliability comparable to the reprocessing technology for alternative means of extending the future generation of fission power.

Aqueous reprocessing of irradiated thorium, referred to as Thorex reprocessing, was operated on a small scale to separate uranium-233 from thorium irradiated at the U.S. Department of Energy (DOE) production reactors at Savannah River and Hanford (Benedict et al., 1981). In the

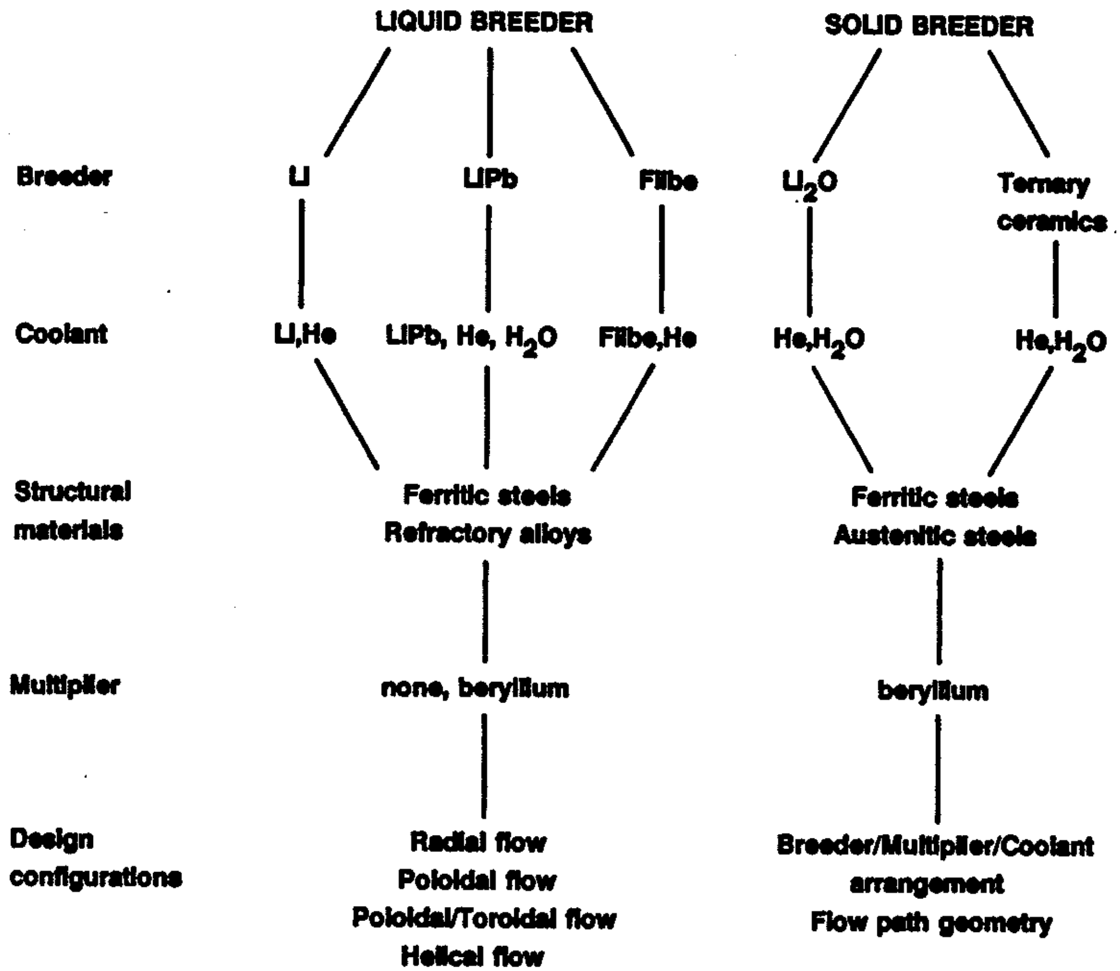

FIGURE 4-7 Major materials and configuration options that have been considered for candidate fusion blankets.

SOURCE: Abdou et al. (1985).

United States, uranium-thorium fuel from the Indian Point I nuclear plant was processed at West Valley, New York to recover uranium but without separation of thorium from fission products. Subsequent modifications were made in the process to recover uranium from highly irradiated thorium characteristic of a commercial fuel cycle, but commercial scale Thorex technology has not been developed. Thorium oxide fuel is hard to dissolve, and the dissolver solutions require expensive container materials. Separation and partitioning in solvent extraction is more difficult than in the well developed Purex process for recovering uranium and plutonium from reactor fuel. A separation of fuel from the late Elk River reactor was carried out in Italy as a pilot scale operation.

The design of the hybrid-LWR system preferred by the hybrid project suggests that uranium-233 recovered from the hybrid's blanket thorium could be isotopically diluted with natural or depleted uranium, to result in a denatured fissile enrichment of less than 20 percent to provide nuclear safeguards. This uranium would then be blended with makeup thorium to form a mixed-oxide fuel for satellite light-water reactors. High-burnup fuel discharged from these light-water reactors would be reprocessed in a separate Thorex-Purex operation to recover uranium for recycle and to recover thorium and plutonium. Plutonium formed from the uranium-238 in the LWR fuel must also be recovered in a stand-alone Purex plant, to be used in uranium-plutonium mixed-oxide fuel for other light-water reactors.

Thus, in this scenario the hybrid-LWR system for commercial power would require the development of commercial-scale Thorex reprocessing, the development of a new Thorex-Purex reprocessing system, and the existence of commercial Purex reprocessing.

Even if the fuel for the satellite light-water reactors were not isotopically diluted with uranium-238 for safeguards reasons, enough highly radioactive plutonium-238 will be made in the uranium-thorium-fueled light water reactors to justify its recovery when fuel discharged from those reactors is reprocessed, as is evidenced by the reprocessing flow sheets developed by DOE for the uranium-thorium-fueled high-temperature gas-cooled reactor (HTGR) (Benedict et al., 1981). Comparable quantities of plutonium-238 are estimated for uranium-thorium-fueled light-water reactors (Pigford and Yang, 1981). Thus, further development of the Thorex reprocessing technology may still be required.

<u>Costs</u> Delene (1985) estimates $180 per pound as the price of natural U_3O_8 such that the calculated cost of electric power from the hybrid-LWR system will be no greater than the cost of electric power from uranium-fueled light-water reactors, assuming that the cost of Purex reprocessing is $390 per kilogram of heavy metal (that is, per kilogram of uranium in the initial fuel charged to the reactor) and assuming that the cost of reprocessing the hybrid's thorium blanket and reprocessing the fuel discharged from the satellite LWRs is 60 percent greater than for Purex reprocessing. The cost of Thorex reprocessing is evidently assumed to be the same as the estimated cost of Purex

reprocessing for fast-breeder fuel, a reprocessing system that has been under intensive development by DOE laboratories.

The committee believes that these cost estimates for the Thorex process are optimistic. Wolfe (1986) quotes current estimates of commercial Purex reprocessing in the range of $600 to $1,000 per kilogram of heavy metal. A recent report (Prince, 1986) from Oak Ridge National Laboratory (ORNL), the principal developer of commercial aqueous reprocessing technology, quotes $800 per kilogram of heavy metal for Purex reprocessing of LWR fuel and $1,400 to $2,100 per kilogram of heavy metal for Purex reprocessing of fast-breeder fuel. If the reprocessing costs are as high as estimated by Prince (1986), then the estimate of cost-sensitivity presented in the hybrid-LWR system cost analysis by Delene (1985), namely, $0.628 per pound change in break-even U_3O_8 price per unit percentage change in reprocessing cost, suggests that the break-even price of U_3O_8 for the thorium-fueled hybrid-LWR system to be competitive with uranium-fueled LWRs could be as high as $260 to $330 per pound of U_3O_8. If so, the uranium-consumption estimates described in Chapter 2 then suggest that it may be 70 years or more before the price of natural uranium would rise to the level at which hybrid fueling of light-water reactors via the thorium-232 - uranium-233 fuel cycle would be as cheap as fueling those reactors with low-enrichment uranium.

To avoid such high reprocessing costs, the hybrid reactor designers suggest that pyrometallurgical processing could replace all of the aqueous processing described above and could result in a reprocessing cost as low as $175 per kilogram of heavy metal, leading to an estimated break-even price of U_3O_8 of $134 per pound. Pyrometallurgical and pyrochemical processing are not new concepts; such processes were studied intensively by many laboratories in the 1950s and early 1960s, and a form of pyrometallurgical processing was developed and used for the EBR-II reactor (as described in Benedict et al., 1981). However, demands for clean separations, versatility, and reliability led to the world-wide adoption of aqueous reprocessing technology. Estimates of the cost of such an undeveloped pyroprocessing technology are likely to be extremely uncertain; the added cost and uncertainties of developing such nonaqueous technology to the point of a demonstrated reliable process suitable for cost estimation and decision making would seriously penalize the hybrid concept.

EVALUATION OF PRINCIPAL CONCEPTS

The evaluation in this section of the principal hybrid concepts leads to the following conclusion:

> Fusion hybrid reactors offer additional possibilities for practical use of fusion power, in electricity and nuclear fuel production, that are worthy of continued investigation.

Fast-Fission Hybrids

Concepts

The early concept of the fast-fission hybrid was based on use of a subcritical plasma, in which the fusion reaction was not self-sustaining but was maintained through multiplication by the fusion process of an energy input supplied from an external source. The temperature and density of the plasma were to be low, such that the Lawson confinement parameter (the product of plasma density and energy confinement time) was well below its critical value for equality between energy deposited in the plasma and energy produced by fusion. The plasma power gain Q was to be low. Most of the thermal energy of the device was to be produced by fissions in a blanket fueled by a subcritical uranium assembly. The machine was to serve the dual purpose of generating about 1,000 MW of electricity and supplying surplus plutonium to approximately one LWR.

This version of the fast-fission hybrid was considered attractive because some researchers believed that it was technically achievable sooner than a pure fusion machine and would be realized as a way station on the path to a successful fusion reactor.

Cost was recognized as one difficulty. This early version of the fast-fission hybrid was likely to be expensive to construct and, perhaps, expensive to operate. It was to combine in one machine some of the more capital-intensive features of fusion reactors and liquid-metal fast reactors. It was, for instance, to have the magnetic fields, the plasma auxiliary heating systems, the ash removal system, and the first wall problems of the fusion reactor. At the same time it was to have the materials and handling problems that have been seen to elevate liquid-metal fast reactor costs.

A more recent version of this concept, the fast-fission fuel-producing hybrid, was described earlier in this chapter. It is clearly not meant to be a stepping stone to pure fusion machines. Instead, it is assumed to have commercial value in its own right. The authors of the design believe a fast-fission fuel-producing hybrid tokamak demonstration plant could be built to operate late in the 1990s and suggested a timetable for development of a commercial plant by the year 2006 (Jassby et al., 1986).

Discussion

First, although the fast-fission tokamak hybrid appears to be technically achievable without meeting intractable technical problems, some features of the technology require scaling up by very large factors. Some require further development, and some are not yet even under development. In addition to advances in physics, some of the required developments include plasma-support technologies to confine, heat, fuel, and remove impurities from the plasma; nuclear technology for tritium breeding, energy conversion, and radiation protection; and remote maintenance.

A second major question is whether the expectations for the neutronics of the fast-fission tokamak hybrid seem realizable. This review was necessarily done from a qualitative standpoint since detailed calculations of blanket performance are not available. A pertinent experiment was performed long ago by Snell (Snell, 1943; Argonne National Laboratory, 1963). This was a determination of fission multiplication in a large block of natural uranium metal. The estimate of a ten-to-one gain in power in the blanket of the fast-fission hybrid seems reasonable in light of the crude estimate provided by this experiment.

Third, breeding blanket development may be particularly difficult. Methods of loading and unloading must maintain removal of fission product heat. Remote methods will be needed because levels of radioactivity will be comparable to those in LWR spent fuel. A demonstration plant may demonstrate the principle of driving a fission blanket with a fusion plasma, but it is unlikely to contain the complexity of fuel handling of a commercial-sized machine. Substantial engineering development will be needed.

Fourth, experience in energy development, including fusion, does not support the rate of improvement and advance called for by the authors of the design. Even though the demands on fusion technology would be less than for a pure fusion machine, it appears that the added complexity of a fissioning blanket might well counterbalance this advantage in development requirements. Furthermore, the committee concluded from its analysis in Chapter 2 of the depletion of uranium resources that such rapid advance is unnecessary, so the overly optimistic schedule could slip without penalty.

A final point for consideration is fuel economy. Assume that the fresh fuel in the fast-fission hybrid blanket is depleted uranium left over from power reactor fuel enrichment. Assume that the exposure limit in the fast-fission hybrid tokamak blanket is about 30,000 MW-day/MT average. This corresponds to burnup of about 3 percent of the uranium. If LWRs at the same fuel exposure have been fed slightly enriched uranium from an isotope separation plant, about five-sixths of the initial natural uranium has been left at the separation plant as depleted uranium tails. Therefore the LWRs would burn only about one-sixth of the uranium entering isotope separation. So by burning depleted uranium the fast-fission hybrid would multiply the effective uranium resources by a factor of about six over what they would have been, assuming no reprocessing.

The Fission-Suppressed Hybrid

In more recent years it has been recognized that the fusion hybrid reactor should be regarded for cost purposes as part of a system including the LWRs that it would fuel. This realization led to a series of studies developing alternate design schemes that could take advantage of the ability to spread costs across a fuel cycle. The fission-suppressed blanket reduces the relative amount of energy generated by fission and increases the production of fissile material for LWR fuel. Therefore, a high capital cost of a fission-suppressed breeder could be spread over a number of satellite LWRs.

Discussion

The fission-suppressed hybrid concept has some disadvantages. First, the required plasma power gain Q is high, on the order of 10 or more. This gain is in the range contemplated for commercial fusion reactors. Therefore, if these designs are preferred, the notion of a fusion hybrid as a development less demanding than a fusion reactor has to be abandoned. It would take a development program approaching that for fusion reactors to achieve the fusion technology level required for this kind of fusion hybrid reactor.

The second area of added complexity is the use of the thorium fuel cycle. Conversion ratios in thermal reactors can be higher when the uranium-233 - thorium-232 cycle is used instead of the plutonium-239 - uranium-238 cycle. Thus, more uranium-233 fueled reactors can be served by a fusion-fission hybrid than plutonium-239 reactors. This would spread the high costs of the hybrid over more satellite reactors. This would also make it possible to reduce the fission rate in the blanket of the hybrid, taking advantage of the low fast-fission cross section of thorium. Although this feature is an important part of the strategy for suppressing fission, there are several disadvantages to the concept. It could require development of a totally new reprocessing cycle. Mainly because of the insolubility of thorium oxide, Thorex reprocessing (the aqueous process for thorium) is far more difficult and costly than the Purex process (the aqueous process to recover uranium and plutonium). Success of a commercial Thorex process is therefore more distant than that of commercial Purex processing. Mixed Thorex-Purex reprocessing is undeveloped and is expected to be even more expensive than Thorex reprocessing (Benedict et al., 1981).

Other disadvantages of the fission-suppressed concept include (1) frequent reprocessing of the blanket and (2) use of the same blanket region for fissile fuel production and tritium breeding, where the lithium cross-section can compete with and suppress fissions in bred uranium-233.

Schedule Considerations

The preceding section provides background for consideration of a reasonable development schedule for the fission-suppressed hybrid. Recall that development of the fission-suppressed hybrid concept preferred by the hybrid project might entail difficulty and expense comparable to that associated with the pure fusion reactor. The cost of the extensive fuel-cycle development will be high, as was the cost of the development of Purex technology for fast-breeder fuel, even though it was not a large extension from commercial Purex technology. The technological extensions for Thorex and Thorex-Purex or for new pyroprocessing are likely to be more demanding and more expensive. Technology for fabricating LWR fuel from recovered uranium-233 would have to be developed.

There now is essentially no dedication of technical resources in the United States to development of the fission-suppressed hybrid. The fusion program at its current level of funding is pointed toward commercial viability of a fusion reactor approximately in the period 2030 to 2050. Development of a hybrid would require additional resources. If hybrid development were to be added to the fusion program without increasing level of effort, the program would be extended by perhaps 20 years.

One might also ask what would be a reasonable period for development of the fission-suppressed hybrid under a heroic rate of effort. It is hard to believe that the basic rate of development of fusion technology can be increased by a large factor, since it depends on designing, constructing, and operating a series of test reactors to carry the technology to successively higher levels of achievement. The last stage would be a commercial-scale reactor, just preceded by a demonstration plant. Considering the newness of the technology and the many new technological problems whose answers will have to be found by simply operating over long periods of time, it is doubtful that the last two phases could consume less than about 20 years for construction and operation of two successive machines. Under the circumstances, it is unlikely that fusion reactors can be achieved on a commercial scale earlier than the 2030 to 2050 time frame. This is also true of fission-suppressed hybrids. To achieve commercial scale fission-suppressed hybrids in this period would require assigning substantial new resources to developing the proposed blanket technologies.

The following conclusion summarizes this discussion:

> The continuing development of fusion technology on its own merits will be the major impetus required to make fusion hybrid technology available as an alternative for fulfilling future energy needs.

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5

ECONOMIC AND SOCIAL ASPECTS

The preceding chapter assesses the technology required for fusion hybrid reactors. Of course, attaining technical feasibility alone is not the sole requirement for commercialization. Economic, safety, environmental, nonproliferation, and deployment aspects of the fusion hybrid must also be attractive. These matters are addressed in this chapter.

ECONOMIC RELATIONSHIPS

This section describes a possible economic climate in which the fusion hybrid could become a useful alternative nuclear source of electricity. The hybrid concept that generates electric power only is distinguished from that which produces both electric power and fissile fuel for light-water reactors (LWRs). The section is closely related to Chapter 2, which explores what rise in the price of U_3O_8 could result based on postulated future consumption of those resources. Detailed economic evaluation of the hybrid is not attempted because the costs of plant construction; fuel enrichment, fabrication, and reprocessing; waste disposal; and decommissioning are too uncertain for other than the identification of the essential features of the relationships. The following conclusion captures the essence of the full discussion:

> Fusion hybrid reactors could become economically viable, especially as a source of fissile fuel for light-water reactors, if the price of uranium oxide becomes high enough; however, this price can be estimated only roughly at present and may lie between $100 and $330 per pound.

Thus, a commercial benefit of introducing fuel from a fusion hybrid into the market could be to put a ceiling on the fuel-cost component of LWR electricity. Otherwise, that component would be vulnerable to further increases in the price of uranium oxide. Although significant aggregate savings could thereby be effected, these avoided costs would be small in a relative sense, since fuel cost is a minor fraction of the total cost of electricity generated by LWRs.

The Fast-Fission Power-Only Hybrid

If the fast-fission hybrid concept that aims only at electric power generation is to become economically competitive, the bus-bar cost of the electric energy so produced must be at least comparable to that of LWR-derived electricity; and it should preferably be even lower to justify the risks of investment in the new technology. Accordingly, fuel-cycle and capital costs for the two technologies should be compared to the extent possible.

This hybrid concept has the potential for lower fuel cost compared to the LWR. Its power-producing blanket does not require enriched uranium. If it can operate to the same fuel thermal exposure (that is, burnup) as fuel in a LWR, this concept will require about six times less uranium ore per unit of thermal energy produced (Chapter 4). Such a plant could even be fueled from stockpiled depleted uranium. Furthermore, the plant could operate without fuel reprocessing in the event that such a once-through fuel cycle is still the one in common use in the era when fusion technology is developed.

However, the capital cost of this fusion hybrid is likely to be more expensive per unit of rated electric power capacity than that of an LWR. Although any savings on fuel, appropriately discounted, could be used to offset excess capital cost, an upper limit on this offset, and hence on the allowable difference in capital cost, is the LWR fuel-cycle cost. That limit is currently only a few percent of the LWR capital cost. Hence the prospect for an economic advantage of the fast-fission power-only hybrid against the LWR alternative would be quite limited.

The Fission-Suppressed Hybrid and Light-Water Reactor Fuel

Fusion hybrid reactors and other means of extending fissile fuel supply, such as the liquid-metal fast reactor (LMFR), must compete economically with stand-alone LWRs, whose fuel source is natural uranium in the form of U_3O_8. To discuss the economic environment for fission-suppressed hybrids to fuel LWRs, it is assumed that LWRs are generating a significant fraction of the nation's electric energy, say one-fifth to one-third, and that spent LWR fuel is being reprocessed to recover uranium and plutonium for recycle to these LWRs. If such reprocessing technology is not available, acceptable, or economical at that time, it is unlikely that the fission-suppressed hybrid can be a viable option, because this hybrid application requires reprocessing at affordable cost (see Chapter 4).

Fissile fuel produced from the fission-suppressed hybrid can be substituted in LWRs for fuel derived from enriched or reprocessed uranium. Thus, the condition for economic viability of this hybrid is that LWR owners find it as cheap to buy fuel from the hybrid as to pay for the conventional fuel cycle. This condition will be satisfied at some point as the price of U_3O_8 rises. The following paragraphs develop this idea more fully.

Although the cost of LWR-derived electricity at the bus bar is composed of costs for capital, fuel cycle, operation and maintenance, waste storage and disposal, and decommissioning, LWR capital cost is the principal contributor. Hence, capital cost variability introduces considerable uncertainty into total cost. Estimates of future LWR capital costs (in constant 1986 dollars) range between $1,000/kWe to $1,500/kWe and the recently experienced amounts even greater than $3,000/kWe. The lower estimates may be achievable based on improvements in design, construction methods, and licensability. These values are widely regarded to be necessary before new LWR construction can commence. This wide range leads of course to a much greater uncertainty in bus-bar cost than the likely increment ascribable to higher U_3O_8 prices, discussed below.

A once-through fuel cycle incurs costs for uranium oxide, conversion, enrichment, and fabrication, as explained in Appendix C. For example, the bus-bar cost of electricity turns out to be about 60 mills/kWh for a once-through fuel cycle, assuming a LWR construction cost of $2,000/kWe, the current U_3O_8 price of about $20/lb, and current figures for the other cost components. This capital cost assumption is within the range estimated by Westinghouse Electric Corporation (1986) and Bechtel Power Corporation (1986).

The fuel cycle cost currently contributes a small fraction of the bus-bar cost of LWR-derived electric energy. Thus large increases in the price of natural uranium are necessary to cause a significant increase in the cost of electricity. In the example above, a rise in the price of U_3O_8 by tenfold, from $20/lb to $200/lb, would increase electrical generation costs to about 70 mills/kWh, a rise of only 17 percent. This dependence is qualitatively illustrated by the LWR line of small, positive slope in Figure 5-1, which plots the bus-bar cost of electricity as a function of the price of U_3O_8, for both an LWR and an illustrative hybrid design. The effect of reprocessing would be to raise the vertical intercept slightly and lower the slope slightly.

For the hybrid, the electricity cost decreases as the price of U_3O_8 increases. Although surprising at first glance, this result depends on the fact that the hybrid produces two marketable products, fissile fuel and electricity. Qualitatively, as the price of U_3O_8 increases, the revenues received from the sale of fissile fuel increase. These revenues can be viewed as offsetting total costs of plant and operation, thus lowering the effective cost of producing the second product, electricity.

Thus, for a fission-suppressed hybrid plant to become economically competitive, it must be able to sell fissile fuel (plutonium or uranium-233), to be mixed with natural or depleted uranium for LWR make-up fuel, at a price low enough that LWR owners would just as soon buy hybrid-produced fuel as continue to operate with a conventional fuel cycle. The market price of hybrid-produced fissile fuel will be

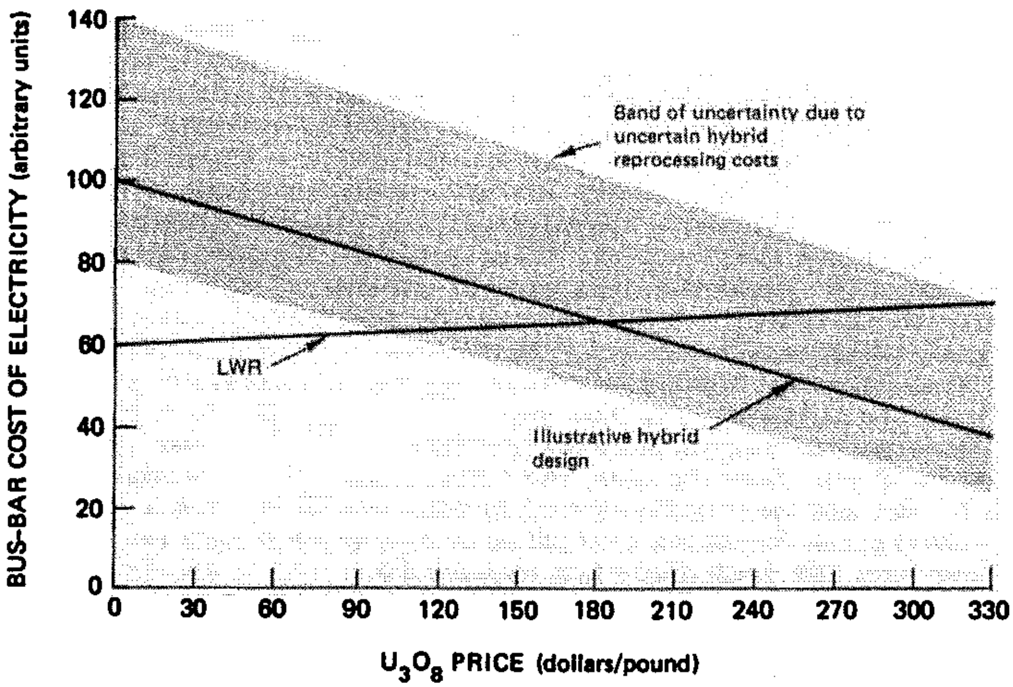

FIGURE 5-1 Illustrative relationship between electricity cost and U_3O_8 price.

determined by the "indifference price" of that fissile fuel to the LWR owners. The indifference price is that price of fissile fuel at which the cost of electric energy from LWRs is identical whether they are fueled with hybrid-produced fissile material or by means of a conventional fuel cycle. In estimating this indifference price, the energy cost using a conventional LWR fuel cycle must be estimated on the basis of reprocessing discharged fuel, with uranium and plutonium recycle, if the ore price is high enough to justify reprocessing. The indifference price of fissile material will thus depend on all of the parameters in the LWR fuel cycle, including reprocessing and fabrication of mixed-oxide fuel, and will increase with the price of uranium ore.

By estimating the indifference price of hybrid-produced fissile fuel as a function of ore price, one can calculate the net bus-bar cost of the electric energy generated by the hybrid as its second product, taking appropriate financial credit for the value of the fissile material produced by the hybrid. To arrive at this estimate requires assumptions of the future capital and operating costs of both hybrid and light-water reactors. In this way one may obtain an upward-sloping line for the stand-alone LWR and a downward-sloping line for the hybrid, similar to the lines qualitatively illustrated in Figure 5-1. The upward-sloping line shows that the cost of generating electricity by LWR increases with increase in U_3O_8 price, since purchases of U_3O_8 are required to operate the plant. The downward-sloping line shows that the cost of generating electricity by a fission-suppressed hybrid plant decreases as the price of U_3O_8 increases, since fissile fuel is a product whose market price will rise with that of U_3O_8. The intersection of the LWR line with the hybrid line, as illustrated in Figure 5-1, defines that particular indifference value of the bred fissile material at which the economics of the hybrid fuel cycle and of the conventional LWR fuel cycle are comparable.

Using an essentially equivalent methodology Delene (1985) estimates that the intersection, or break-even U_3O_8 price, occurs at $179/lb in constant (1983) dollars for a particular set of assumptions accepted by the committee as reasonable. These assumptions include capital investment cost of $1,390/kWe for LWRs and $3,810/kWe for a thorium-based hybrid concept designated as "OPT-Li," aqueous reprocessing, and industrial-rate financing.

In the region to the left of the intersection, where the calculated cost of electricity from the hybrid is greater than that for the LWR, there is no economic incentive to operate the hybrid. In particular, to recover costs in this region, the hybrid would have to charge more than the indifference price for the fissile fuel it produces to make up for its losses by having to sell electricity at the LWR market price. However, it would be unable to market its fuel, since LWRs could continue generating electric energy more cheaply using their conventional fuel cycles. In the region to the right of the intersection, the LWR plant burning natural uranium cannot compete with the hybrid in producing electricity. LWR demand for U_3O_8 then drops, and its price falls to that near the break-even point.

As ore prices increase from their value at the intersection, there will be a slight increase in the actual cost of electric energy generated by the hybrid-LWR system. The reason is that the bred material is not completely substitutable for natural uranium, so there remains a need for small makeup amounts of the latter. However, the hybrid's efficient production of fissile fuel directly from natural or depleted uranium or from natural thorium will effectively cap the cost of electric energy near the intersection value.

More realistically, the position of the hybrid line is uncertain within a band, as illustrated. Considerable uncertainties in the reprocessing costs, particularly for the thorium-blanketed concept advocated in recent hybrid designs, generate this band. For the thorium-based concept cited here, Delene (1985) estimates a U_3O_8 break-even price of $134/lb for pyrometallurgical reprocessing and utility-rate financing. Because this estimate is itself uncertain, we have rounded it to $100/lb for our purposes, to allow some optimism in the lower end of the break-even range. Using data from a more recent Oak Ridge National Laboratory study of aqueous reprocessing costs (Prince, 1986) and a sensitivity coefficient from Delene, as discussed in Chapter 4, the break-even price of mined U_3O_8 ore is estimated to lie in the range $260/lb to $330/lb for industrial-rate financing of fuel-cycle operations, at the capital costs assumed by Delene for the hybrid design. It is only at natural uranium prices within the band of uncertainty associated with the intersection that the hybrid line in Figure 5-1 begins to have real meaning, since only at higher uranium ore prices will operation of LWRs with hybrid-produced fuel be more economical.

With increasing values of the ratio of hybrid unit capital cost construction to that of LWRs, the intersection in Figure 5-1 will move to the right as the total costs to be recovered from the sale of fixed amounts of electricity and fissile fuel increase. However, these capital cost projections are so uncertain, particularly for the hybrid, that the actual values of the break-even price of U_3O_8 are correspondingly quite uncertain. This effect produces an even greater band of uncertainty than that shown in the figure. For the OPT-Li example, Delene (1985) calculates that a 50 percent increase in the capital cost of the hybrid would increase the break-even U_3O_8 price by about $60/lb.

For the hybrid to be introduced into a commercial energy system, this concept must offer utilities a clear cost advantage to compensate for the uncertainties and new institutional arrangements that will accompany commercial introduction of this new technology. Hence from a practical standpoint, the ore price that would encourage introduction of hybrids (or LMFRs, for that matter) must actually be somewhat greater than it is at the indifference price of fissile fuel (corresponding to the intersection in Figure 5-1) to make this substitution sufficiently attractive.

Economic Uncertainties

Other than capital cost, factors making it hard to predict the economics of hybrid reactors include reprocessing costs, tritium and fissile-fuel breeding efficiency, plant availability, and decommissioning costs. The fission-suppressed blanket designs that produce uranium-233 are particularly sensitive to breeding characteristics and to uncertainty in reprocessing and LWR fuel fabrication costs.

The fast-fission hybrid approach that produces fuel as well as power would use aqueous reprocessing of plutonium. This concept is subject to much less uncertainty in reprocessing cost than the fission-suppressed hybrid designed for a thorium fuel cycle. Moreover, it places lower demands on the fusion system. Accordingly, the fusion core for the fast-fission hybrid could be significantly less expensive than that for the fission-suppressed hybrid, since the fusion power level for a given amount of electricity production can be at least five times less (Jassby et al., 1986). In addition, the thermal and neutron load on the first wall can be significantly lower. These factors can have a beneficial effect on plant availability, since the life of the first wall could be significantly longer. Finally, prospects are improved for design features that increase plasma heating power, such as steady state current drive.

Moreover, if hybrid reactor costs can be reduced by improved fusion core designs suggested for pure fusion devices (Sheffield et al., 1986), it might be possible to achieve economic viability at a lower U_3O_8 price.

SAFETY AND ENVIRONMENT

The intrinsic safety characteristics of hybrid concepts, making them as safe or safer than LWRs, lead to the following conclusion:

> No significant changes in the overall nuclear safety and environmental characteristics that are then existing would result from the introduction of fusion hybrid reactors to generate electricity or to fuel light-water reactors.

Relative to a LWR, all three hybrid concepts have the potential safety advantage of lower power density and the impossibility of an accident due to a fission chain reaction. Tritium breeding and handling introduce additional safety requirements compared to LWRs, but the safety of these processes has been demonstrated in the production of tritium for nuclear weapons. However, the fast-fission hybrid will pose many of the other safety problems faced by fission. There would be need to dispose of high-level radioactive waste, as well as the large volume of low-level waste associated with all fusion devices. The blanket decay-heat load would also be considerably higher than it would be for a pure fusion device, requiring some sort of emergency blanket cooling system for protection during abnormal events. The fast-fission power-only hybrid is largely free of the need for reprocessing, a potential environmental advantage.

The lower decay heat, by a factor of 5 to 10, of the fission-suppressed hybrid would impose less demanding safety requirements than those for the fast-fission hybrid or an LWR. Thus, since the fission-suppressed hybrid has a safety advantage over the LWR, introduction of one or more such hybrids to fuel LWRs would not degrade the safety and environmental characteristics of the resulting system. Those characteristics would be dominated by those of the LWRs and of the reprocessing, fabrication, and transportation subsystems required to serve them. Hence, the safety of such a hybrid reactor-LWR system would remain comparable to that of a system of LWRs.

PROLIFERATION RESISTANCE

In this section, we examine whether hybrid technology offers any significant advantages or disadvantages with respect to proliferation resistance. That is, might a nuclear power system based on the hybrid make the diversion of fissile material to weapons purposes by a nation or a terrorist group significantly harder or easier compared to alternative nuclear power systems of similar magnitude?

In principle, the hybrid could have such an effect if it reduced (or increased) the potential for clandestine diversion of fissile materials readily fabricable into nuclear weapons. However, such a change effected by the hybrid would probably be small compared to other factors meanwhile affecting nuclear proliferation, especially given the long time period before hybrids could be deployed.

As a result of our examination, we believe that the following conclusion can be drawn:

> No significant arguments concerning the effect of fusion hybrid reactors on nuclear proliferation either support or oppose their introduction.

The Context

The impact of the hybrid on proliferation resistance will depend on the nuclear power system we assume it would supplement or replace. Roughly put, such a system would be predominantly based on one of three alternatives:

1. Thermal-neutron reactors, either current reactors or advanced converter reactors that are more uranium efficient, with once-through fuel cycles with no reprocessing of spent fuel and no recycling of fissile material.
2. Thermal-neutron reactors with substantial recycling of fissile material.
3. Liquid-metal fast reactors (LMFRs), possibly with reprocessing and fabrication plants colocated with the reactors.

Systems such as described in Alternative 2 above now appear to be emerging in most countries outside the United States. At present, 12 countries are either engaged in reprocessing spent fuel to extract plutonium for further burning, are constructing reprocessing facilities, or have declared an intention to do so soon. The list comprises most countries with substantial nuclear power programs, notable exceptions being the United States, Canada, and Sweden. At least seven countries have active programs to develop the plutonium-fueled LMFR and to pursue Alternative 3.

The amount of plutonium that is now planned for separation in commercial reprocessing plants over the next 15 years (to the end of the century) may soon exceed even the vast amounts of plutonium that are now in the arsenals of the nuclear weapon states. By the year 2000, the rate of separation of plutonium in commercial reprocessing in noncommunist countries could be nearly 30 metric tons per year, with much of this planned to be recycled into thermal-neutron reactors.

The Fast-Fission Power-Only Hybrid

As a reactor providing only electric power without reprocessing, the fast-fission power-only hybrid would have proliferation-resistant characteristics similar to those of the system contemplated in Alternative 1, and appears to be somewhat more proliferation resistant than the systems of Alternatives 2 or 3. Such a hybrid with a once-through fuel cycle would avoid commercial traffic in material readily used in weapons and, if the burnup in the blanket were very high, the bred plutonium could be further from ordinary weapons grade than is the case in today's reactor-grade fuel. On the other hand, the hybrid would probably produce more fissile material per unit of thermal power output than today's reactors, and this fissile material could be separated using readily available reprocessing technologies. These are differences in degree rather than in kind, and they are not strong arguments for or against the fast-fission power-only hybrid.

The Hybrid as a Fissile-Fuel Producer

A hybrid could, in principle, produce plutonium or uranium-233, which would then be separated, fabricated into fuel elements, and distributed to various LWRs. Such a system would generate much more traffic in weapons-usable material (plutonium or uranium-233) than that of Alternative 1 and, compared to this alternative, looks unattractive from the viewpoint of proliferation resistance. However, a system based on the hybrid fuel producer would not appear to be significantly less proliferation resistant than the systems of Alternatives 2 and 3, both of which require the separation and transport of fissile material.

A potential advantage that has been claimed for the hybrid system is that it could denature the fissile material leaving the reactor more easily than could alternative systems. This could be accomplished, for example, by spiking plutonium-239 with plutonium-238, whose greater radioactivity would make the plutonium difficult to handle. For the thorium cycle, the uranium-233 could be mixed with depleted or natural uranium, so that the isotopic mixture would be unsuited to weapons use. Such denaturing does not seem attractive for the following reasons:

o As discussed elsewhere in this report, the hybrid as a fuel producer appears uneconomic until at least the middle of the next century, and the cost of denaturing the fissile fuel would make this option even less economic. Spiking plutonium with plutonium-238 would require developing and constructing entirely new facilities for remote handling of the fissile material. The uranium-233 fuel cycle would require a considerable development program before it could be used on a commercial basis.

o Although denaturing would impede terrorist diversion of the fissile material, it would not greatly slow the acquisition of material by a nation that wished to do so. In fact, since the denaturing would presumably occur after the fissile material is produced in the blanket, a hybrid feeding even a denatured fuel cycle would allow the rapid acquisition by a nation of large amounts of high quality fissile material.

Hybrid Reactors and Spent Fuel Rods

It has been suggested that (1) a hybrid could be used to refresh spent fuel rods from converter reactors, so the rods could be reinserted into the reactor and (2) the rods could be burned further in the hybrid blanket to produce power. These prospects appear to be dubious for the following reasons. Handling of highly radioactive spent fuel is a process requiring use of heavy spent-fuel casks or remote manipulation under deep water. Shipping the fuel from the reactor to the hybrid, loading it into the hybrid, removing it at higher radioactivity levels from the hybrid, shipping it back to the reactor, and reloading it into the reactor would constitute a sequence of difficult operations with probable routine exposures of operating personnel to high radiation levels. Furthermore, the risk of physical damage to the fuel elements during the many complex handling steps could not be ignored. A fuel assembly that had been bent, that had fuel elements with scratched or dented cladding, or that had been injured in any of many conceivable ways could not be safely returned to the reactor or even to the hybrid where it was to be refreshed. Inspection for such damage would be hard at best, requiring remote methods in large hot cells. Even the inspection process could damage the fuel, and damage could be just as possible during complex handling after inspection had ended. The associated practical problems seem unsolvable.

Hybrid Reactors and Pure Fusion

Hybrid reactors are vulnerable to concerns about proliferation because they produce fissile material, which is meant for electric power production, but which is also suitable for use in some nuclear weapons.

By contrast, a pure fusion device would not constitute such a direct threat, since it does not produce fissile material. At present, fuels used for fusion could not be diverted to weapons application without the use of a fission trigger.

The totality of technology required for the development of pure (magnetic) fusion does not appear particularly applicable to the design of thermonuclear weapons. In contrast, some parts of inertially confined fusion systems might have such applications.

FUSION HYBRID DEPLOYMENT

If fusion hybrid reactors are to be deployed in the United States, electric utilities will need to become participants in that activity. Thus an important question is the evolving perception by the utilities of how such a plant would fit into their electricity generating plans. Succeeding sections deal in greater detail with certain aspects of the hybrid reactor that will be important to the utilities: technological requirements, cost estimates, and development paths that provide greater utility participation in the program. Those sections support the following conclusion:

> From the current perception of electric utilities as necessary partners in electricity supply, barriers to future hybrid deployment would have to be surmounted. These barriers stem from acceptability of complex new technology, uncertainty of capital costs of nuclear construction, and practicality of the development enterprise. The same caution would apply to any new nuclear technology, including liquid-metal fast reactors and pure fusion.

If fusion hybrid reactors are developed in special instances as fuel or nuclear material producing facilities only, electric utilities may not need to be involved. However, even in such circumstances, early participation by industry suppliers of equipment and engineering and construction services is essential.

Technological Requirements

A fusion hybrid plant, as currently envisioned, would introduce a number of technologies that are new both to utilities and to their traditional suppliers of equipment, engineering, and construction services. These technologies have contributed to a perception by the utility industry that the fusion hybrid reactor would be a more complicated and possibly less reliable means of generating electricity than current technologies. This perception, of course, was also true for fission in the early days; although at first the utilities largely overcame it. For example, technologies for the following systems typical of fusion hybrid reactor concepts will far exceed in novelty and complexity the utility power systems of today:

- Vacuum systems
- High-field magnet systems and associated cryogenics
- Radio-frequency generators and neutral-beam injectors
- Coolant systems
- Tritium-handling systems
- Computerized control systems
- Remote maintenance manipulators
- Reprocessing.

Utilities operating 30 to 50 years hence will have made much progress in liquid metals, helium, or molten salts as coolants; in computer-aided diagnosis and control; and in reprocessing. Nevertheless, the remaining items are unique to fusion technology, and hence will be unfamiliar to the operating utility. For example, large high-vacuum systems and high-power neutral beam apparatus are even more susceptible to technical problems than are cooling loops. The need for remote maintenance may diminish the attractiveness of fusion hybrid reactors. The remote-maintenance technologies will require a thorough demonstration of operational simplicity and reliability, including a firm understanding of the cost of remote maintenance requirements.

Just as some of the early fission plants suffered from low availability factors due in part to utility unfamiliarity with the technology, so the availability problem may arise for the fusion hybrid because of the complexity of its systems. These complexities are perceived by utilities as likely to cause increased operation and maintenance costs, including a higher level of education and training for its operators. Therefore, successful demonstration of the fusion hybrid reactor under conditions relevant to a utility environment will be essential.

Cost Estimates

The hybrid would have to compete on the basis of cost with natural uranium as a fuel for LWRs or with LWRs and LMFRs as an electricity supplier, in some future era of high uranium prices. While nuclear generation can still be less expensive than some non-nuclear alternatives, its financial risk has become large and experience has demonstrated a tremendous gap between early nuclear technology cost estimates and the ensuing reality. Consequently, utility executives and public utility commissioners, who were caught in the gap, have become especially sensitive to the accuracy of cost projections for new nuclear technology. In particular hybrid cost estimates are currently beset by many uncertainties.

Conceptual cost studies for the fusion hybrid have primarily been made to identify preferred design approaches from among candidate alternatives, identify cost drivers, and help define research and development needs. Accordingly, capital cost projections from such cost studies are not as realistic as those available for more mature power technologies like LWRs and LMFRs.

Similarly, hybrid designs have generally been carried only through preconceptual levels, and even then only major subsystems were addressed, leaving out many systems and components that support reactor operation. Moreover, these studies lack the extensive research, development, and detailed engineering required to develop new technologies.

The state of knowledge of the requisite fusion machine, consisting of fusion core, magnets, plasma heating systems, vacuum system, fission blankets, and associated auxiliaries, contributes to the uncertainties in the cost estimate. In view of today's limited understanding of the requisite technologies, there are also large uncertainties in the requirements of fabrication, materials, and support systems for these special components and related auxiliaries. The radiation effect of high-energy neutrons on materials is a significant source of uncertainty in selecting materials and determining their fabrication requirements. These uncertainties are compounded by the complex requirements of recovery of tritium from the blankets and the handling and management of tritium, which tends to migrate over large parts of the plant. The need for remote handling and storage of large activated components of the fusion reactor is another area of uncertainty that would have significant impact on building space requirements and therefore on plant cost.

Numerous other unresolved issues would significantly impact the actual cost: What kind of containment is required? Does the tritium fuel-cycle facility have to be at the same level of reliability as the primary system? What will be the licensing approach to safety? Will the concept of Operating Basis Earthquake be used, so all systems have to be designed to operate during and following an earthquake? What practice for in-service inspection will be followed? What redundancy and diversity requirements will be set? What replacement-maintenance concept will apply to the plant? What basic safety doctrine will govern the design? What are the costs of waste disposal and of decommissioning? The preliminary conceptual studies performed to date have not addressed these issues in enough depth to provide the required data.

In the same vein, the life expectancy of most of the components, which depends on the combined effects of radiation, magnetic fields, high temperature, and corrosion, needs to be determined. More analyses of failure modes and their effects are essential. The "design for safety" aspects need to be scoped. The problems of integrating the basic needs of the fusion plasma system with the licensing requirements of seismic design and safety design, together with the special provisions for remote maintenance and repair, are likely to pose complex requirements.

On the other hand, design and construction of the auxiliaries, connecting systems, support systems, and structures of the hybrid fusion facility are much more straightforward than design and fabrication of the special components of the fusion core and its fission blanket. There probably will be no unusual engineering problems in the engineering and construction of the conventional parts of the plant.

Until reliable cost estimates show large advantages, utilities are not likely to give the hybrid reactor serious consideration. Many of the foregoing considerations also apply to pure fusion as an alternative electricity generation option.

Development Paths

Before the hybrid can be considered as a commercial alternative by an electric utility or other investor, at least a demonstration plant, and probably a prototype, will have to be constructed and operated to prove costs, safety, and operating characteristics. However, the cost of demonstrations is so high and the probability of substantial economic benefit so small at this time that no utility, group of utilities, or other investor is likely to make more than a token contribution to hybrid development or construction. Thus, if the fusion hybrid reactor option is to be demonstrated, demonstration costs will probably have to be initially financed largely by the federal government or by a foreign government. The early deployment of LWRs was materially helped by the experience of the suppliers in the Nuclear Navy program and the availability of trained personnel from that program, but an analogous military development program relevant to the fusion hybrid reactor does not currently exist.

A possible development path that would allow sharing of costs, including those of a prototype plant and of a demonstration plant, is to develop a fusion hybrid technology as part of an international cooperative effort. The National Research Council (1984), for example, studied this issue for pure fusion, for which international collaboration is not new. International collaboration with the Soviet Union on fusion has been one recommendation emanating from recent political summit talks. The Soviet Union fusion program is currently placing great emphasis on developing hybrid reactors as fissile fuel producers. The United States, Japan, the European Community, and the Soviet Union have jointly been designing a next-step research reactor, known as the International Tokamak Reactor (INTOR). The high costs associated with the next generation of fusion experiments may keep alive the possibility of international cooperation.

The question then arises as to the optimum extent to which private industry should participate in the technical part of hybrid development, construction and operation. Even though industry is unlikely to be willing to finance more than a small part of the effort, its participation is necessary if fusion hybrids are to be deployed successfully. Manufacturers, constructors, and utilities need hands-on experience from the earliest stages. The number of suppliers for various components may be limited. This limitation, even now, continues to be a problem in the fission industry. No utility is likely to spend a few billion dollars buying something that has no established vendors to provide warranties. Thus it is highly desirable that industry take the lead in developing an infrastructure for hybrid fabrication technology.

From the standpoint of utilities, in some respects the fusion hybrid combines the worst features of both fission and fusion technologies. It has most of the complexity associated with fusion, along with the high-level radioactive waste and decay heat of fission. This mixture attaches an aura to the fusion hybrid that will need to be recognized and overcome. Furthermore, although they may represent a less formidable technological challenge than pure fusion, current fusion hybrid reactor concepts do not appear to be inherently attractive from the point of view of utility operations. The utility industry has developed a strong appreciation, through its experience with LWRs, for the practical advantages of simplicity and ease of operation of reactor systems. The apparent complexity of fusion hybrids runs contrary to this experience and will deter acceptance of this unfamiliar technology in the utility industry. To help overcome these barriers, technical participation by the utility industry is essential at an early stage.

One prerequisite to deployment, easily overlooked at a stage preoccupied with proof of concept, is the development of codes and standards appropriate to the fusion aspects of the hybrid. Many of the materials that will be required, along with the operating conditions under which these materials will be used, lie outside current codes and standards. Many of the fabrication procedures that will be required appear to fall outside currently certified processes. Thus, existing codes and standards will need to be modified and new ones devised. The process for achieving this evolution is notoriously prolonged, and it may delay deployment unless appropriate steps are taken well in advance.

Organizations or groups of utilities might be willing to operate the first and second hybrid units under favorable conditions, such as a national policy to encourage deployment and prior regulatory approval of the joint undertaking. Preferably, a consortium should be given the responsibility of designing, constructing, and operating a hybrid plant, so that it can also serve as a training ground for the design, construction, operation, and maintenance of succeeding hybrids. The possibility that public utility commissions might not permit utilities to charge consumers the full cost of fuel, should it prove to be higher than from an alternative source, might be a deterrent to this sort of arrangement.

External economic and political developments, both domestic and foreign, will be factors that influence the price of fossil and fissile fuels. Since the viability of fusion hybrids as an alternative source of fissile fuel depends on the competitive price of other fuels, these factors could change hybrid prospects for better or worse in major and unpredictable ways, even if demonstration and prototype plants were constructed and operated successfully and within predefined economic targets.

In any event, a significant change from the current climate of public opinion would be required before a national energy policy promoting the deployment of a new nuclear technology could be realized. Moreover, without such change there is also little chance that conventional LWR plants will grow to provide a major share of U.S. electrical capacity. Unless nuclear power experiences this sort of revival, the fusion hybrid will not be needed in the United States.

Many of the foregoing considerations also apply to the introduction of pure fusion.

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6

THE TRITIUM-BREEDING FUSION REACTOR

Tritium is a critical component in most nuclear weapons. Because of its half life of 12.6 years, tritium in existing weapons must be replaced periodically. Thus, a reliable source of tritium is critical to maintain the nation's nuclear stockpile. A tritium-breeding fusion reactor of specialized design, quite distinct from the pure fusion power reactor that also produces tritium, has been suggested to meet this need. The discussion in this chapter leads to the following conclusion and an associated recommendation:

> The concept of a tritium-breeding fusion reactor is not yet a realistic candidate for either near-term expansion or replacement of current U.S. tritium production facilities, because considerable fusion development and engineering, as well as much reliability testing, remain to be accomplished.

> Because the tritium-breeding fusion reactor offers promising features of yield, cost, and technology, officials in the U.S. Department of Energy concerned with the capability and security of tritium production should undertake a program that analyzes and periodically reassesses the concept, including design studies, experimentation, and evaluation, as fusion development proceeds.

UNIQUE FEATURES OF A FUSION REACTOR FOR TRITIUM PRODUCTION

A tritium-breeding fusion reactor has been proposed as a potentially attractive source of future U.S. tritium production, once certain aspects of practical and reliable fusion technology have been established. Tritium can be produced both from fission reactors and from appropriately designed fusion reactors, as shown in Table 6-1. Neutrons originate from the primary fission or fusion reactions. The fusion neutrons are multiplied by reaction with beryllium contained in a blanket. Some neutrons are lost by absorption and leakage; the rest react with lithium targets to product tritium. About 1.6 tritium

TABLE 6-1 Fusion and Fission Tritium-Breeding Reactions

Reactor	Reactions	
Fusion Tritium Breeder	D + T	→ n + ^{4}He + 17.6 MeV
	n + Be (multiple reactions)	→ 2.3 n - 0.7 n (absorption plus leakage) - 2.08 MeV
	1.6 n + Li (multiple reactions)	→ 1.6 T - 1 T (consumed by plasma) + 7.68 MeV
Net Reaction:	D + T + blanket	→ 0.6 T + ^{4}He + 23.2 MeV
Fission Tritium Producer	n + ^{235}U	→ 2.5 n - 0.7n (absorption plus leakage) - 1 n (fission) + fission products + 200 MeV
	0.8 n + Li (multiple reactions)	→ 0.8 T
Net Reaction:	n + ^{235}U + Li (target)	→ 0.8 T + fission products + 200 MeV

SOURCE: Adapted from Lokke and Fowler (1986).

nuclei are produced per fusion reaction, leaving 0.6 tritium nuclei as excess after one is returned to replenish the fusion plasma. About 0.8 tritium nuclei are produced per fission reaction, all of which are excess to the needs of the continuing fission process. Because the ratio of number of excess neutrons to thermal energy of reaction is much greater for fusion than fission, a tritium-breeding fusion reactor could produce tritium at about a sixfold greater rate than can a fission reactor of the same thermal power. For example, a 500-MWt tritium-breeding fusion reactor could produce about 10 kg/yr of tritium over and above that needed to fuel the fusion reaction, whereas about 3000 MWt of fission thermal power would be required to achieve the same tritium-production rate. This relationship is shown in Figure 6-1. If the dependence of capital costs on thermal power were about the same for fusion and fission reactors, the tritium-breeding fusion reactor would have the potential for producing tritium at lower cost than that of fission-derived tritium. This potential remains even if the capital cost of the tritium-breeding fusion reactor for a given thermal power is somewhat greater than that of the tritium-producing fission reactor.

Because of its large rate of tritium production per unit of thermal power, the tritium-breeding fusion reactor also offers the attractive possibility of tritium production facilities having wide ranges of output. In addition this fusion option could provide both technological and geographical diversity for the nation's tritium production.

REQUIRED TECHNOLOGICAL DEVELOPMENT

The tritium-breeding fusion reactor is technologically the least demanding of the fusion options studied here, largely because it requires a plasma power gain Q only slightly greater that that which can currently be attained in fusion. Moreover, it does not require a high temperature blanket for efficient conversion of heat to electricity--a further simplication because novel coolants, such as molten lithium, can be avoided. However, this concept will require significant development to increase the duration of the fusion plasma pulse. The plasma physics performance needed for this application could be demonstrated in the next generation of fusion experiments.

Conceptual designs proposed for both mirror and tokamak approaches to breeding tritium have blankets of neutron-multiplying beryllium blocks penetrated by aluminum tubes containing aluminum cans of lithium-aluminum alloy target material and water coolant (Moir, 1986; Neef and Jassby, 1986). These designs would employ the same lithium-target technology now used by tritium-producing fission reactors and would use similar water-cooling technology. The use of light water as a coolant tends to degrade the neutron energy, and results in extra neutron captures in the blanket, reducing the number of neutrons available for tritium production. It would also be possible to use heavy water, which does not appreciatively absorb neutrons and which is a weaker neutron moderator. The lithium targets can be processed in the same facilities now used to recover tritium

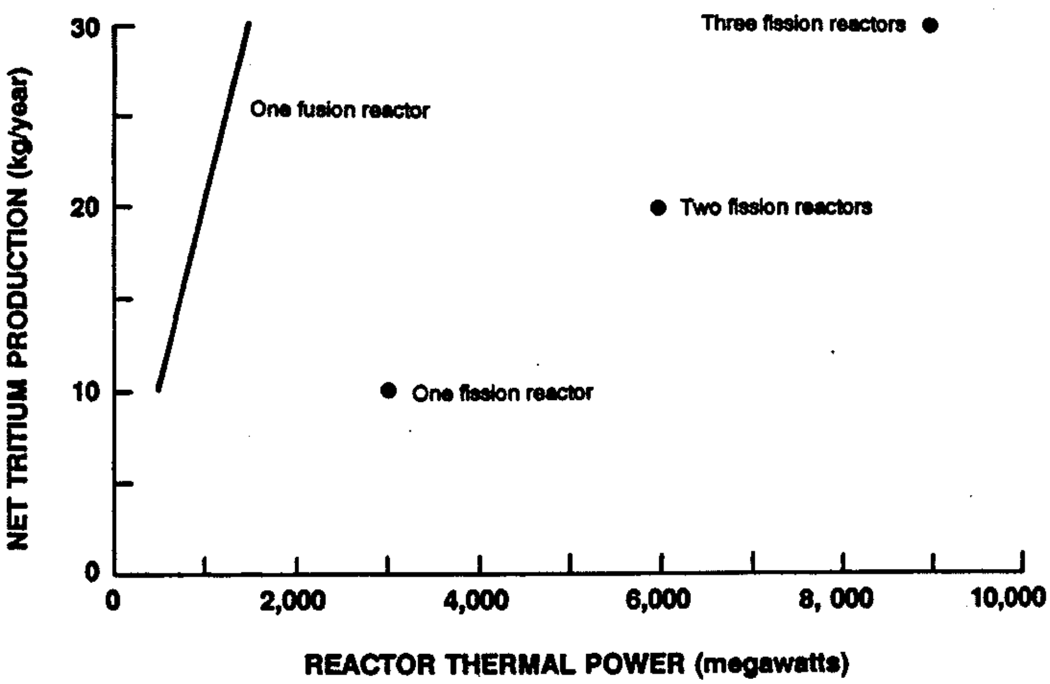

FIGURE 6-1 Net tritium production rate vs reactor thermal power for tritium-breeding fusion and fission reactors.

SOURCE: Adapted from Lokke and Fowler (1986).

from lithium targets irradiated in fission reactors. Consequently, the tritium-breeding fusion reactor requires less development of new technology for the fusion blanket and for external fuel-cycle operations than is required for any of the hybrid designs reviewed in this report. Nevertheless, some attention to blanket technology development will be appropriate as fusion technology advances. This work would probably include experiments on non-nuclear facilities, reactor test loops, and neutron sources, in addition to more specific design work on blanket concepts for tritium production than had been possible in the first, preliminary studies.

Some illustrative parameters of a possible tritium-breeding fusion reactor are shown in Table 6-2.

Generation of electricity from an energy-producing fusion hybrid blanket modified to operate at high temperature could be considered as a possible means of helping to recover tritium production costs. However, extensive previous design studies and evaluations (Glennan, 1982) of alternative fission reactors to produce tritium have emphasized the reliability available from low-temperature operation using lithium targets and from single-purpose tritium producers. Thus combined tritium and electric power production seems an undesirable compromise of reliability.

THE NEED FOR RELIABILITY

The requirement of well established and demonstrated reliability for U.S. tritium production counsels conservatism in projecting the time when the tritium-producing fusion reactor might be considered as a reasonable sole alternative when selecting a reactor concept for a new facility for tritium production. The point is especially cogent if the selected concept is expected to be ready for engineering design and construction. The first demonstration of fusion will be insufficient to establish such reliability, as will the first demonstration of a fusion technology system. Instead, significant prototype experience with a tritium-producing fusion reactor will be a necessity.

To substantiate this point, extensive reviews and evaluation of alternative fission reactor approaches for augmenting existing U.S. tritium production capability have downgraded at least two advanced fission reactor concepts, although there were at least two or more operating prototypes of each concept preceded by several successful demonstrations of fission reactor technology (Glennan, 1982). Each of these advanced concepts incorporated considerable new technology, and the prototype experience demonstrated that much of this new technology was insufficiently developed to meet the reliability criteria for tritium production.

Although the tritium-breeding fusion reactor is only a concept, it is an attractive one with considerable potential. This concept awaits further development of fusion technology well beyond the demonstration stage. Thus this concept is not yet a full-fledged candidate for near-term expansion or replacement of U.S. tritium production

TABLE 6-2 Parameters of a Possible Tritium-Breeding Fusion Reactor[a]

Parameter	Nominal Value
Total thermal power	500 MW
Total fusion power[b]	400 MW
Input power	100 MW (plasma heating)
Q (fusion gain)	4
Wall loading	1.5 MW/m^2
Breeding ratio	1.6
Tritium production	26 kg/yr
Tritium consumption	16 kg/yr
Net tritium production	10 kg/yr

[a] See, for example, Moir (1986) and Neef and Jassby (1986).
[b] Total fusion power is the energy per unit time generated from the fusion reaction, arising from the energy of the neutrons and recoil nuclei of the reaction.

facilities. Exactly when in the early part of the next century a tritium-breeding fusion reactor could be considered as a realistic alternative option for producing tritium for nuclear weapons will depend on the pace of fusion development.

Nevertheless, because the tritium-producing fusion reactor could eventually become a candidate to complement tritium production by fission reactors, and because it could eventually provide the nation with technological and geographical diversity for tritium production, this potential application of fusion should be established as one of the U.S. Department of Energy programs to enhance the capability and security of tritium production. Those government organizations concerned with defense programs and tritium production should include the tritium-breeding fusion reactor option in their plans, and should closely monitor the development of fusion technology related thereto. This would include analysis and periodic reassessment of this fusion application, including design studies, experimentation, and evaluation, as fusion development proceeds. National needs for tritium production and the unique features of the tritium-breeding fusion reactor lend support to the continued development of fusion, as long as it is realized that actual deployment of the tritium-producing fusion reactor is not likely to be attainable until at least early in the next century.

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APPENDIX A

STATEMENT OF TASK*

The committee will gather and summarize information on the technical status of the magnetically confined fusion hybrid reactor and its potential applications, addressing the following kinds of questions:

- What are future energy circumstances in which the hybrid might offer significant advantages?
- What is the status and what are the prospects of technology in the United States and elsewhere relevant to hybrids?
- What is the range of technical options for the hybrid application of fusion energy, and what are the economic and environmental risks and benefits of these options?
- What is a reasonable timetable for development and deployment of the hybrid?
- If the hybrid application appears to have merit in future U.S. energy circumstances, how might it best be approached?

The committee will hold four or five workshops over the nine-month period of the task. The workshops will include background briefings on the magnetic fusion program, future energy and electricity needs in the United States, and an overview of the hybrid. Presentations will also be given on the status and prospects of the hybrid technology in the United States and elsewhere.

*Excerpted largely from the Notice of Financial Assistance Award from the U.S. Department of Energy to the National Academy of Sciences-National Research Council.

APPENDIX B

LIST OF PRESENTATIONS TO THE COMMITTEE ON FUSION HYBRID REACTORS

December 16-17, 1985
National Research Council
Washington, D.C.

ALVIN W. TRIVELPIECE, U.S. Department of Energy
Perspective on Study Goals of the Committee on Fusion Hybrid Reactors

JOHN F. CLARKE, U.S. Department of Energy
The Department of Energy Magnetic Fusion Program: Motivation and Perspective on the Committee's Study Goals

ROBERT J. DOWLING, U.S. Department of Energy
The Department of Energy Magnetic Fusion Program: Background

T. KENNETH FOWLER, Lawrence Livermore National Laboratory
Introduction to Briefings and a Personal View of the Fusion Hybrid Reactor

RALPH W. MOIR, Lawrence Livermore National Laboratory
Motivation for Fusion Hybrid Reactors

JAMES A. MANISCALCO, TRW, Incorporated
Characterization of Fusion-Fission Hybrid Reactors

JOHN P. HOLDREN, University of California, Berkeley
Economic, Safety, and Environmental Aspects of Fusion Hybrid Reactors

ROBERT G. MILLS, Princeton University
Fusion Hybrid Reactors for Power

JERRY G. DELENE, Oak Ridge National Laboratory
Economic Analysis of Fusion Hybrid Reactors

THEODORE B. TAYLOR, Nova, Incorporated
Proliferation Aspects

HANS A. BETHE, Cornell University
Fusion Hybrid Reactors in Our Energy Future

February 20-21, 1986
Lawrence Livermore National Laboratory
Livermore, California

JOHN F. CLARKE, U.S. Department of Energy
Update from the Office of Fusion Energy

T. KENNETH FOWLER, Lawrence Livermore National Laboratory
Welcome to Livermore

WILLIAM A. LOKKE and T. KENNETH FOWLER, Lawrence Livermore National Laboratory
Stockpile Tritium Production from Fusion

MARY D. SCHROT, Lawrence Livermore National Laboratory
Reactor Products for the Twenty-First Century
RALPH W. MOIR et al., Lawrence Livermore National Laboratory
Fusion Technology for Tritium Production: Status and Development Requirements
JOHN J. TAYLOR, Electric Power Research Institute
The Role of the Fast Reactor in Meeting Future Energy Needs
ROBERT AVERY, Argonne National Laboratory
The Integral Fast Reactor System
J.S. ARMIJO, PHILIP R. PLUTA, and EDWARD A. AITKIN, General Electric Company
PRISM: Advanced Design and Its Associated Fuel Cycle
SIMCHA GOLAN, Bechtel Power Corporation
International Programs
JOHN SHEFFIELD, Oak Ridge National Laboratory
An Analysis of the Requirements for Economic Magnetic Fusion
GERALD L. KULCINSKI, University of Wisconsin
Status of Fusion Technology
DANIEL L. JASSBY, Princeton University
Tokamak Fusion Hybrids and Fast-Fission Blankets
DAVID BERWALD, TRW, Incorporated
Fission-Suppressed Hybrid Blanket Technology and Design Issues
B. GRANT LOGAN and J. D. LEE, Lawrence Livermore National Laboratory
Some Safety Considerations for Fusion and Fusion-Fission Hybrid Systems
RONALD C. DAVIDSON, Massachusetts Institute of Technology
Overview of Magnetic Fusion Advisory Committee (MFAC) Findings and Recommendations

April 8-9, 1986
Hilton Head, South Carolina

MICHAEL J. MONSLER, Satori Technologies
Competitive Prospects of Inertial Confinement Fusion

May 8-9, 1986
Bechtel Power Corporation
San Francisco, California

RALPH W. MOIR, Lawrence Livermore National Laboratory
Clarification of Committee Questions Relating to Fuel-Producing vs Power-Producing Hybrids
JOHN JERRIS AND FRANK SCOTT, Bechtel Power Corporation
Description and Demonstration of Bechtel's Three-Dimensional Computer-Aided-Design and Drafting System

July 21-23, 1986
National Research Council
Washington, D.C.

GERALD L. EPSTEIN, Office of Technology Assessment, U.S. Congress
Status of the Office of Technology Assessment's Study on the Department of Energy Magnetic Fusion Program
GREGORY M. HAAS, U.S. Department of Energy
Update from the Office of Fusion Energy

APPENDIX C

ALTERNATIVE PROJECTIONS OF URANIUM OXIDE USE

This appendix provides details of the scenarios summarized in Chapter 2. Those scenarios model the projected availability of uranium to fuel light-water reactors (LWRs). They utilize projections of future uranium oxide commitment and use under several plausible assumptions of available resources, electricity demand, and electricity supply. Explanations are provided here of the fuel-cost component of electrical energy cost, the parameters employed in the modeling, and the sensitivity of the projections to various assumptions. These explanations are followed by tabulations of the detailed projections for the various sets of parameters hypothesized. These tables are labeled according to the scenario designations referred to in the text of Chapter 2 and in this appendix.

THE FUEL-COST COMPONENT OF THE TOTAL COST OF ELECTRICITY FROM LIGHT-WATER REACTORS

The total cost of generating electricity by a given power plant is allocable to three cost components: fuel, capital, and operation/maintenance. One can arrive at the contribution of a given cost component to the total cost of generating electricity by converting the annual expense for that component to a cost per kilowatt-hour, as follows:

$$\text{cost (mills/kWh)} = \frac{\text{annual cost (millions of dollars)}}{\text{plant size (GWe)} \times 8.76 \times \text{capacity factor}}, \quad (1)$$

where the factor 8.76 corresponds to the 8,760 hours in a year.

The ongoing fuel-cost component of the cost of electricity from light-water reactors is comprised of two subcomponents: the cost of U_3O_8 and the cost of fuel processing (conversion, enrichment, and fabrication).

After its initial loading, a LWR generating 1,000 MWe (1 GWe) at a capacity factor of 80 percent is reloaded annually with a "reload core" that typically requires 189 standard tons of U_3O_8 having a tails assay of 0.2 percent (Westinghouse, 1986a). Assuming an eventual U_3O_8 cost of $200/lb, the annual cost of refueling comes to about $76 million. From equation (1), assuming an 80 percent plant capacity factor, the fuel-cost subcomponent corresponding to purchase of the ore required for refueling is projected to be about 10.8 mills/kWh.

As to the fuel-processing subcomponent of the fuel-cost component, the typical annual fuel-processing cost for a 1,000 MWe LWR, based on Westinghouse data (1986a), totalled $13.67 million. This total includes $9.37 million for enrichment, $3.55 million for fabrication, and $0.75 million for conversion. Using equation (1) with a capacity factor of 80 percent, the total fuel-processing cost of $13.67 million amounts to a fuel-processing sub-component cost of 2.0 mills/kWh. The total fuel-cost component is thus 10.8 + 2.0 = 12.8 mills/kWh.

The principal component of electrical energy cost results from amortizing the capital cost of the LWR. Included in capital cost is the initial core loading, typically requiring 373 standard tons per gigawatt of U_3O_8 having a tails assay of 0.2 percent. The amortization of capital cost can be accounted for as an annualized cost per kilowatt hour by using equation (1) and incorporating an annual capital cost given by the initial capital cost multiplied by the fixed-charge rate. Assuming a capital cost of $1,500/kW and a fixed-charge rate of 18 percent, this calculation yields an estimate of 38.5 mills/kWh. The remaining component of electrical energy cost is the cost of plant operation and maintenance (O&M). The annual O&M cost typically experienced (Westinghouse, 1986a) is about $35 million per year, or 5 mills/kWh. This cost component thus represents an annual operating expense of about two percent of plant capital cost.

Combining the three cost components incurred to operate a LWR for generating electricity results in a total cost estimate of about 12.8 + 38.5 + 5 = 56.3 mills/kWh, corresponding to an era when the cost of U_3O_8 has risen to $200/lb. At that price, fuel costs of 12.8 mills/kWh thus represent about 23 percent of the total cost of electricity and would have become far more significant than they are today. Currently, with U_3O_8 costing $17/lb and LWR capital costs considerably higher than $1500/kW, fuel costs amount to at most a few percent of the cost of LWR-derived electricity. The preceding cost estimates pertain to bus-bar costs; costs of electrical transmission and distribution are not included.

EFFECT OF PLUTONIUM AND URANIUM RECYCLING ON FUEL COST

If technologies for both fuel reprocessing and reprocessed fuel fabrication are developed and utilized, they can provide from plutonium and uranium recycling the equivalent of an estimated 46 standard tons of

U_3O_8 per 1,000 MWe reload (Westinghouse, 1986b). Effects of introducing reprocessing include increasing the fuel cost, increasing fuel transportation requirements, and reducing requirements for storage of radioactive wastes. Despite its increased cost, this source of fuel is potentially readily available. Reprocessing need not take place until such time as the cost of the refueling option becomes competitive with the increasing cost of uranium.

EXPLANATION OF THE PARAMETERS USED IN SCENARIO PROJECTIONS

Many of the input parameters utilized in projecting fissile fuel scenarios were described in Chapter 2. All input parameters and the various data derived from them are defined in Table C-1. Table C-2 contains definitions of the parameters derived using the committee's computer model.

An interesting datum derived from the uranium scenario projections is the net present value of the fuel-cost premiums paid during the period of the projection for not substituting hybrid-derived fuel that could have been produced at the breakeven cost (provided that the price of U_3O_8 equivalent exceeds that cost). This quantity is designated as EXTRA COST in the tabulations C-1A through C-18. The extra cost varies widely according to scenario, and for several scenarios reaches values of some tens of billions of dollars. Since this quantity rests on uncertain assumptions, no conclusions are drawn from it; it is provided for illustrative purposes only.

SENSITIVITY OF THE PROJECTIONS TO THE ASSUMPTIONS

This section explores how the conclusions of Chapter 2 are modified when the parameters and assumptions are varied. The strongest sensitivity is to the assumed growth rate of U.S. electric capacity. The effects of limitation on coal use, variations of tails assay, recycle of spent LWR fuel, LMFR deployment, nuclear growth as a fraction of total growth, nuclear capacity factor, and period of forward commitment to uranium are much more modest, amounting for each effect to a change of 5 years or less in the projected time of uranium resource exhaustion. Key parametric assumptions that were utilized in projecting these scenarios for fissile-fuel futures are summarized in Table 2-2 of Chapter 2 for eighteen cases applicable to a domestic U.S. fissile-fuel economy. Complete tabulations of input and output data for those cases are shown in tables in this appendix, numbered according to the scenario numbers shown in Table 2-2. Similarly, Table 2-4 summarizes the four international scenarios.

Effect of Assumed U.S. Electric Growth Rate

Figures C-1 and C-2 compare the cumulative U_3O_8 used, and used and committed, respectively, for the "fast" and "slow" U.S. electric growth

TABLE C-1 Input Parameters for Projecting Uranium Scenarios (page 1 of 4)

Input Parameter	Name	Definition	Range or Value	Input Data Source
EGR	Electrical growth rate 1986 to 2000	Annual percentage increase in U.S. generating capacity (It is assumed that load growth of 2.8%/yr reduces reserve margin to 20% by year 2000)	1.8%	Westinghouse (1985)
EGR1	Electrical growth rate 2000 to 2025	Same as above, except that there is a constant reserve margin of 20% (Both load and capacity grow at this rate, keeping their ratio constant)	1.0 to 2.5%	Committee assumption
EGR2	Electrical growth rate 2025 to 2065	Same as above	1.0 to 1.5%	Committee assumption
CGR	Coal growth rate 1986 to 2000	The percentage of new generating capacity added in year Y assumed to be coal	2.55%	Committee assumption
CGR1	Coal growth rate 2000 to 2025	The percentage of new generating capacity added in year Y assumed to be coal	EGR1	Committee assumption
CGR2	Coal growth rate 2025 to 2065	The percentage of new generating capacity added in year Y assumed to be coal	EGR2	Committee assumption

TABLE C-1 Input Parameters for Projecting Uranium Scenarios (page 2 of 4)

Input Parameter	Name	Definition	Range or Value	Input Data Source
NGR1	Nuclear percent of new generation, 2000 to 2025	The percentage of new generating capacity added in year Y assumed to be nuclear. (If coal use is unlimited, 30 or 40%; otherwise, 67%)	30 to 67%	Committee assumption
NGR2	Nuclear percent of new generation, 2025 to 2065	Same as above	30 to 67%	Committee assumption
UL	Uranium commitment years	Assumed number of years for which uranium ore is committed for each LWR in operation	30, 40, 60 years	Committee assumption
CF	Nuclear plant capacity factor	Nuclear plant operating time as a percentage of total elapsed time	70 or 80%	Westinghouse (1986c)
REPC	Replacement core	Annual tons of uranium ore required to fuel a 1 GWe LWR (for TAILS = 0.20% and CF = 80%, 189 tons)	153 to 189 tons	Westinghouse (1986a)
NC	New core	Tons of uranium ore required to start a new 1 GWe LWR (for above parameters, 373 tons)	302 to 373 tons	Westinghouse (1986a)
UNEEDED	Uranium needed for LMFR	Amount of uranium ore required to start a new 1 GWe LMFR	1136 or 1298 tons	Pigford & Yang (1981)

TABLE C-1 Input Parameters for Projecting Uranium Scenarios (page 3 of 4)

Input Parameter	Name	Definition	Range or Value	Input Data Source
PL	Economic plant life	Economic life of a light water reactor for which there is a forward commitment of uranium	30 or 60 years	Committee assumption
TAILS	Tails assay	Percentage of uranium-235 left in tailings of U_3O_8 ore after enrichment (0.08% for AVLIS; 0.20% for gaseous diffusion)	0.08 or 0.20%	Committee assumption
U3O8	Uranium ore resources	Inventory of uranium ore resource available for use or commitment at various forward costs and confidence levels (includes Reasonably Assured Reserves, Estimated Additional Resources, and Speculative Resources)	2.5 to 4.4 million tons[a]	U.S. Department of Energy (1983)

TABLE C-1 Input Parameters for Projecting Uranium Scenarios (page 4 of 4)

Input Parameter	Name	Definition	Range or Value	Input Data Source
FBR%	Fast Breeder rate	LMFR percentage of new nuclear capacity added in year Y	0 or 50%	Committee assumption
EQU308	Equivalent U308	Tons of uranium ore that could be saved annually per GW-year by recycling uranium and plutonium from spent LWR fuel	46 tons	Westinghouse (1986b)

[a]At a forward cost $100/lb of U_3O_8 for United States; 22.8 million tons for the world (outside centrally planned economies) (OECD-IAEA, 1983)

TABLE C-2 Data Derived from Uranium Scenario Projections (page 1 of 3)

Derived Datum	Definition
FUEL COST (MILLS/KWH)	Cost of fueling plant in mills per kilowatt hour of electric output (sum of costs of U_3O_8, conversion, enrichment, and fabrication)
COE LWRS	Cost of electric energy from LWRs in year Y (rate in mills/kWh; total cost in billions of dollars)
GWE	Total installed capacity, GWe
TOTAL GW N	Total installed capacity of LWRs and LMFRs, GWe
GW LWR	Installed capacity of LWRs, GWe
GW FBR	Installed capacity of LMFRs, GWe
GW COAL	Installed capacity of coal plants, GWe (for the remainder of this century, an assumed 2.55% annual increase in coal plants; after year 2000, 50% of annual increase in U.S. capacity is assumed to be coal plants if coal use is unlimited)
GW OTHER	Installed non-nuclear and non-coal electrical capacity
TOTAL % NUCLEAR	Percentage of nuclear capacity compared to total installed electric capacity. (includes both LWRs and LMFRs)
NUCLEAR GROWTH RATE	Annual percentage increase in nuclear capacity, including both LWRs and LMFRs

TABLE C-2 Data Derived from Uranium Scenario Projections (page 2 of 3)

Derived Datum	Definition
COAL BURNED Y	Amount of coal (in millions of tons) burned by utilities in the indicated year Y, assuming a heating value of coal of 12,000 Btu/lb, a heat rate of 9,355 Btu/kWh, and a capacity factor of 50%
U308 USED PERIOD	Amount of U_3O_8 inventory used during the period (14 year period from 1986 to 2000; 5 year period thereafter) in thousands of standard tons for new LMFRs and for LWR cores (new and reloads)
U308 USED CUM	Cumulative amount of U_3O_8 used since 1985, in thousands of standard tons
TOTAL U308 & EQUIV U UNCOM	Uncommitted amount of U_3O_8 resources available in year Y (original inventory plus present and future equivalent U_3O_8 in form of uranium and plutonium from recyle, less amounts used and committed)
U308 REMAINING	Amount of U_3O_8 resources not burned or in reactors, in thousands of standard tons
U308 COMMITTED	Amount of U_3O_8 resources committed, in thousands of standard tons. Derived from the LWR capacity in the indicated year times the U_3O_8 needed for a reload core times UL, plus that needed for LMFRs until 2065. All U_3O_8 for LMFRs is assumed to be committed the year of the first commercial LMFR. Each year thereafter the amount of ore actually used for LMFRs is subracted from the commitment.
U308 NEEDED FOR FBRS	The equivalent amount of U_3O_8 used in LMFRs in the five year period, in thousands of standard tons

TABLE C-2 Data Derived from Uranium Scenario Projections (page 3 of 3)

Derived Datum	Definition
PRESENT EQUIV U308 BY RECYCLE	The equivalent amount of U_3O_8 contained as uranium and plutonium in spent LWR fuel accumulated through year Y
FUTURE EQUIV U308 BY RECYCLE	The equivalent amount of U_3O_8 contained as uranium and plutonium in spent fuel committed to be burned in the future (during the economic life of existing LWRs), minus the "present equivalent U_3O_8 by recycle" defined above
COST OF RELOAD CORE	Cost of LWR core replacement (total cost of U_3O_8, conversion, enrichment, and fabrication for one year) in millions of dollars
PRICE U308	Price of U_3O_8 in dollars per lb, determined according to Figure 2-2 for the United States, or by its analogue for the international market
EXTRA COST	Net present value of fuel-cost premiums paid in period for not substituting hybrid-derived fuel that could have been produced at the breakeven cost (if the price of U_3O_8 exceeds that cost) in billions of dollars. Discount rate is assumed to be 4%; breakeven cost for hybrid is assumed to be \$180/lb U_3O_8.

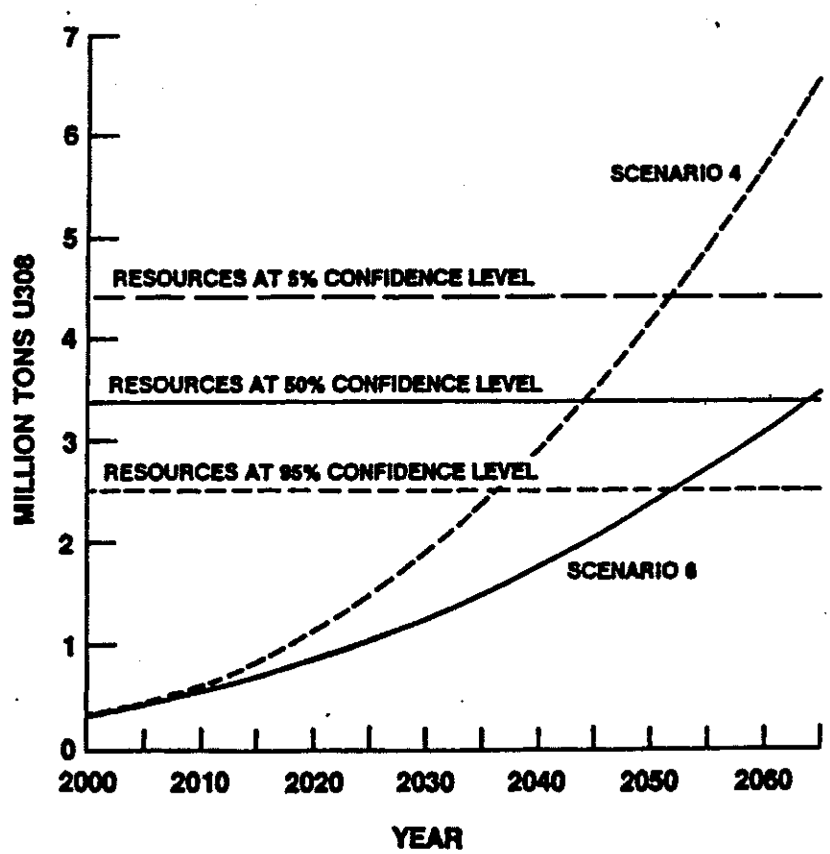


FIGURE C-1 Cumulative U.S. U_3O_8 used in LWRs, for Scenarios 4 and 6 at the assumed "fast" and "slow" U.S. electric growth rates respectively, 2000 through 2065, for estimates of domestic ore resources at various confidence levels. LMFRs are assumed not to have been introduced.

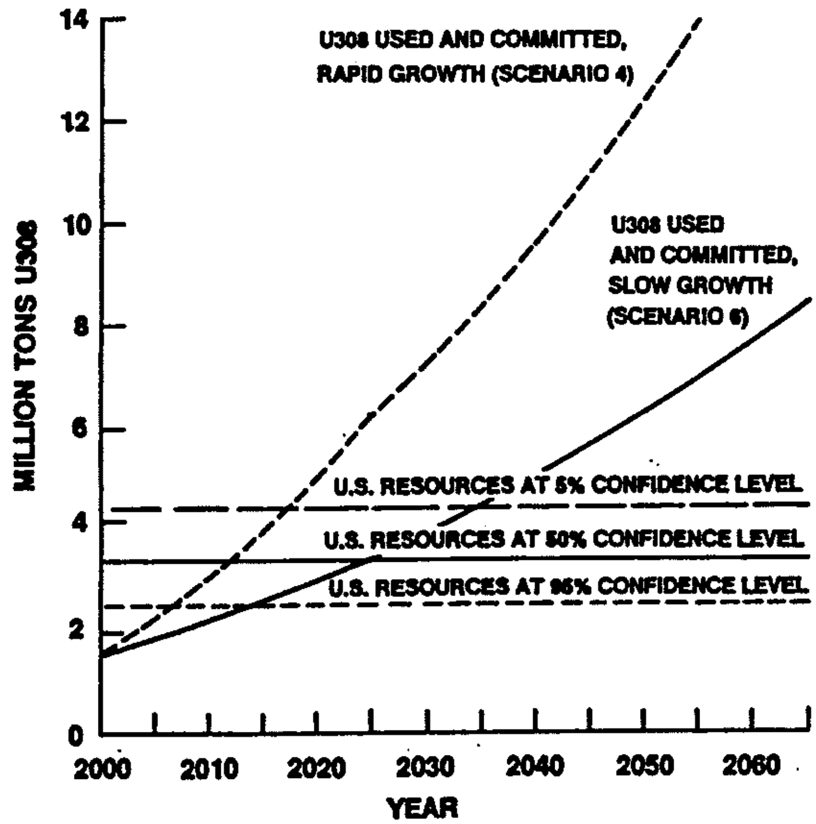


FIGURE C-2 Cumulative U.S. U_3O_8 used and committed for use in LWRs, at various confidence levels, 2000 through 2065. LMFRs are assumed not to have been introduced.

rates. Recall that in this report, "fast" growth corresponds to 2.5 percent per year between 2000 and 2025, and 1.5 percent per year thereafter; "slow" growth is a flat 1 percent per year between 2000 and 2065. The change from "fast" to "slow" growth (scenarios 4 and 6, respectively) delays the date of uranium resource exhaustion through use by about 20 years, and the date of exhaustion through use and commitment by about 12 years. Figure C-3 shows the effect of the change in growth rate on the rise in uranium price. The change from "slow" to "fast" growth shortens by about 15 years the time required for a rise in price to $100/lb, and by about 20 years the time required for a rise in price to $200/lb.

Effect of Limitation on Coal Use

In the scenarios presented here, only the rate of LWR deployment has a direct influence on uranium use and price, which in turn determines when fusion hybrids or other nuclear-fuel producers may be needed. Since coal and nuclear power appear to be the two most important candidates for baseload electric capacity growth in the next 75 years, there is a complementarity between these two sources: if for some reason one of them cannot be deployed quickly enough, an increasing electric demand may have to be satisfied by more rapid development of the other. If the current slowdown in the U.S. nuclear industry continues, the direction of this tradeoff will be that more new coal plants will be installed than would otherwise have been the case. Since this alternative results in no projected need for the fusion hybrid or other fissile-fuel producer, the committee did not consider it further.

On the other hand, there is also the possibility that the growth of coal-derived power will be limited at some time in the next century by environmental problems, such as acid precipitation or accumulation of atmospheric carbon dioxide. In some scenarios, the committee attempted to model this potential constraint by imposing a limitation on U.S. coal use for power generation; namely, a ceiling equal to three times the amount consumed in 1986. The resulting limit is 1.6 billion tons of coal burned per year for electrical generation. The effect of imposing this limit on coal use starting in 2035 is shown in Figure C-4, where the curve labelled "rapid growth, limited coal" flattens out to a constant value after that year. Thereafter, nuclear power is allowed to increase faster than for unlimited coal use, so as to compensate for the shortfall in total electric capacity.

Without the effect of coal limitation, Figure C-4 shows a range of projected coal use between 1.5 and 3 billion tons per year in 2065, corresponding to installed coal-fired generation capacities of 750 and 1,525 GWe, respectively, at a capacity factor of 50 percent. If coal use is limited in the manner described above, the maximum amount projected to be burned per year by 2065 remains at 1.6 billion tons rather than rising to 3 billion tons. The presumed result of this limitation on coal use is an increased deployment of LWRs. The resulting ramifications for the fusion hybrid include the following basic result: because the limitation on coal use does not come into

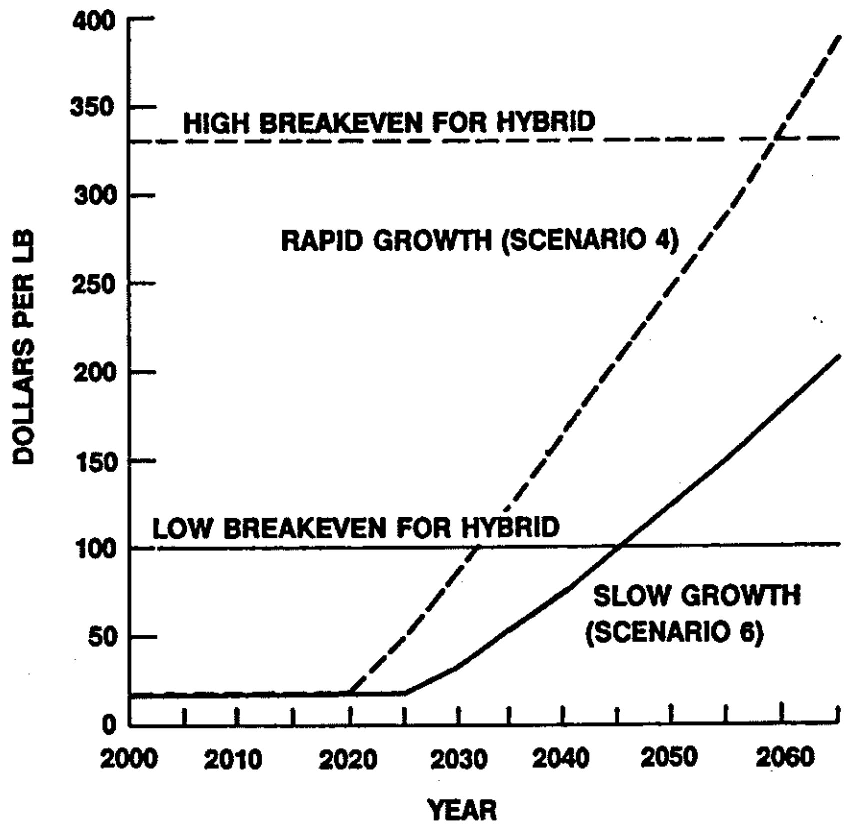
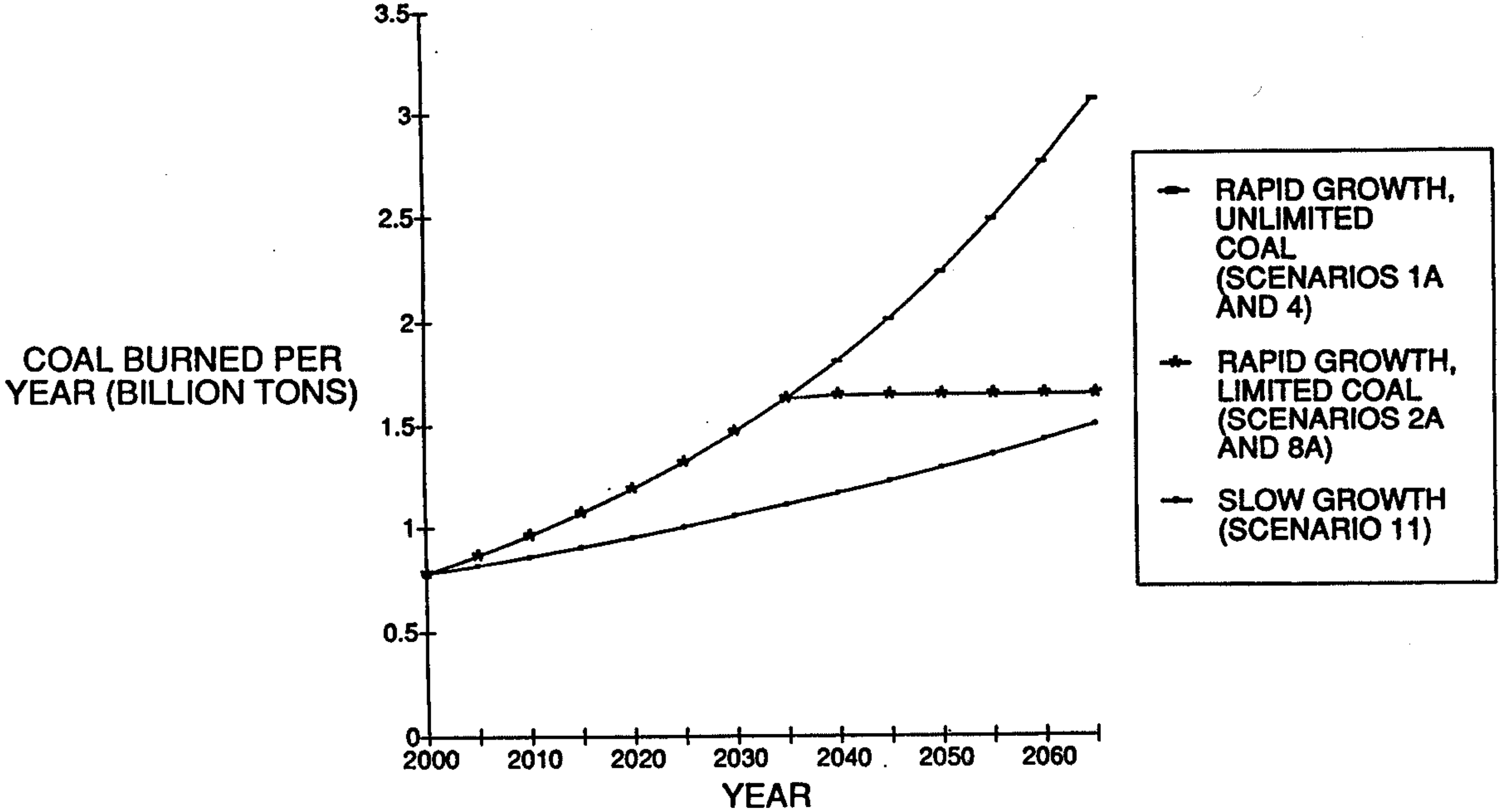


FIGURE C-3 Projected price rise of U.S. U_3O_8 for the period 2000 through 2065. LMFRs are assumed not to have been introduced.



'IGURE C-4 Comparison of coal burned per year under different assumptions, 2000 through 2065.

play until 2035 or later in our scenarios, its effect is to hasten the date of U_3O_8 exhaustion by only 2 or 3 years. On the other hand, if limitations on increased coal use came into play sooner than 2035 (especially during the period 2000 to 2025), there could be a significant enhancement of LWR deployment. For the fast growth scenario, this could hasten U_3O_8 exhaustion by some 10 to 15 years.

Figure C-4 shows the variation in coal use that is postulated when the annual limit of coal burned for electricity production is assumed to be 1.6 billion standard tons. The gap in electrical production resulting from a limit on coal use will presumably be made up by a faster growth of LWR capacity. This is illustrated in the top two pairs of curves in Figure C-5. However, the coal-burning limitation assumed here is too little and too late to have substantial impact on the time of uranium resource exhaustion; Figure C-6 shows that exhaustion is hastened by only 2 or 3 years when coal use is limited.

Effect of Assumed Tails Assay

Figure C-7 compares the cumulative U_3O_8 used and committed for two different tails assays, 0.2 and 0.08 percent. Refining uranium ore more efficiently, by decreasing the tails assay from 0.2 to 0.08 percent, delays the date of uranium resource exhaustion by only about 5 years in these models.

Effect of Uranium and Plutonium Recycle

The scenarios detailed here calculate the amount of U_3O_8 that would be saved by the recycle of uranium and plutonium from spent LWR fuel.* This added recycle would delay the date when \$100/lb U_3O_8 is used and committed. The delay ranges from 4 to 8 years in the scenarios. The mean delay is approximately 5 years.

Effect of LMFR Commercial Deployment

If uranium use has been high enough that the fusion hybrid application becomes viable, then LMFRs will also be a market option for relieving the shortage of fissile fuel. This study did not perform a detailed analysis of the LMFR option. However it did include LMFRs in the uranium use scenarios. Two LMFR commercial deployment alternatives were considered: An "early" one, where deployment begins in 2020, and a "late" one, where it begins in 2035. In both cases, it is assumed that once LMFR deployment has begun, LMFRs will constitute 50 percent of each new generation of nuclear power (the other half being LWRs).

*Denoted by "Equivalent U_3O_8 by Recycle" in Tables C-1A through C-33.

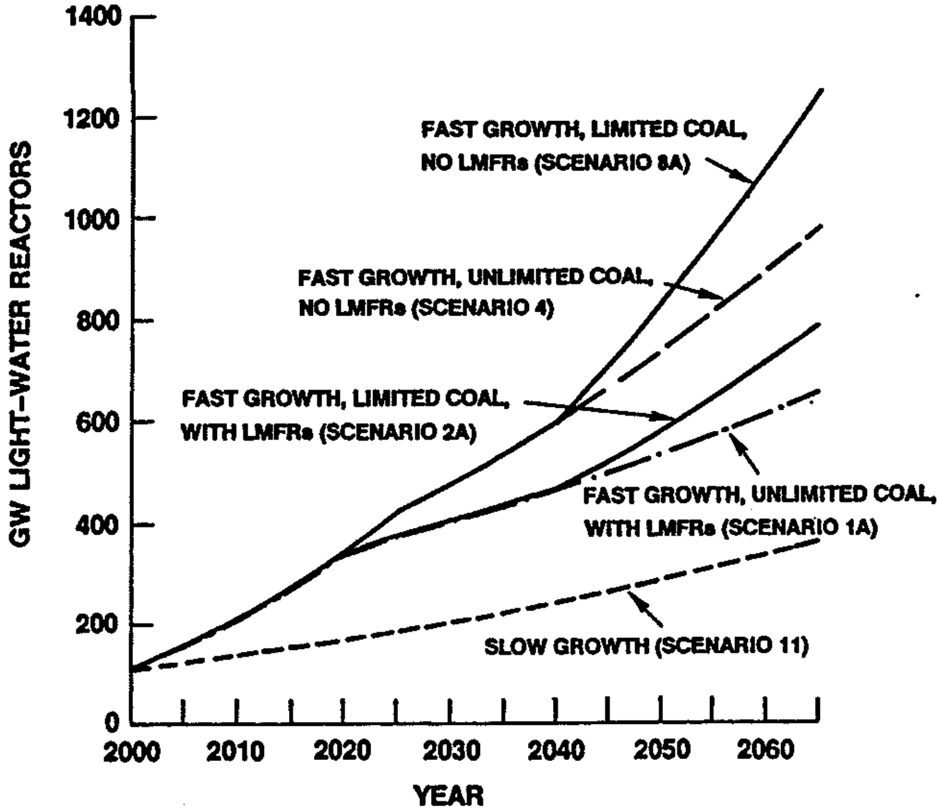


FIGURE C-5 Projected installed capacity of LWRs, 2000 through 2065.

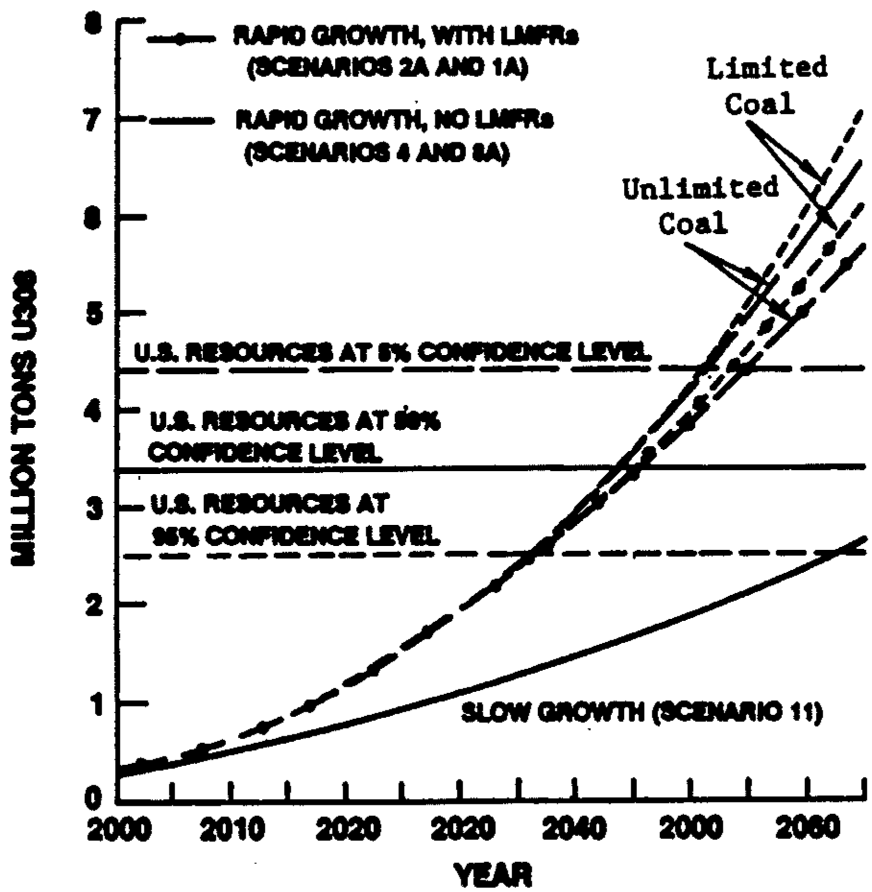


FIGURE C-6 Comparison of the cumulative amounts of U.S. U_3O_8 used and committed for use in LWRs for the various deployment scenarios shown in Figure C-5.

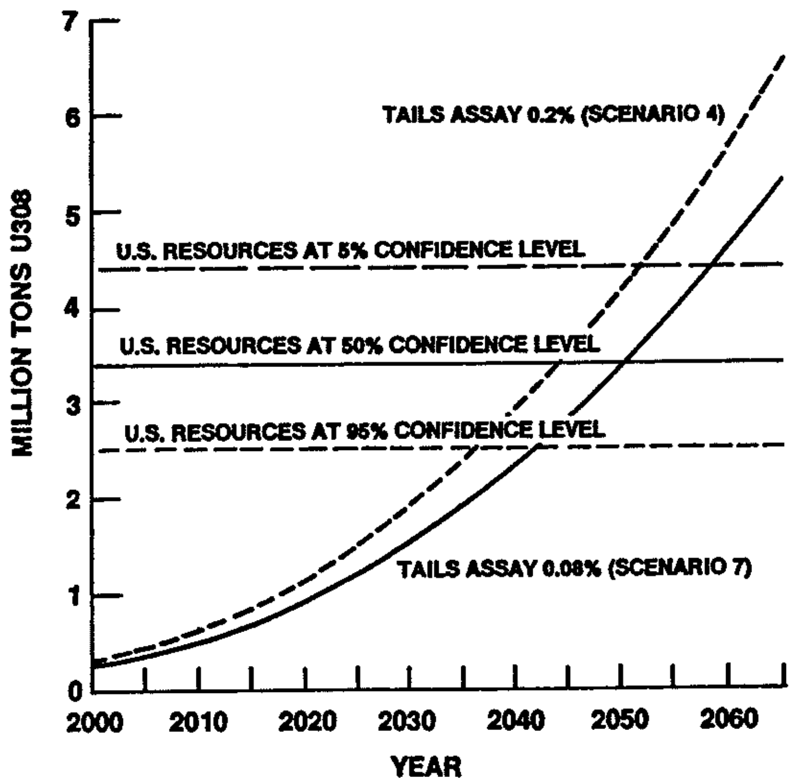


FIGURE C-7 Effect of tails assay on cumulative U.S. U_3O_8 used and committed for use in LWRs, at various confidence levels, 2000 through 2065. LMFRs are assumed not to have been introduced.

Figure C-8 shows the possible evolution of LMFR installed capacity resulting from "early" LMFR deployment, and compares it with the installed capacity of LWRs. By 2065, LMFRs constitute about 33 percent of total nuclear capacity, with LWRs making up the remainder. Yet Figure C-9 shows that even for this "early" deployment scenario, LMFRs have relatively little impact on the time of uranium resource exhaustion; namely, their introduction delays that event by less than 5 years. The reason for this minimal impact is that subsequent to LMFR deployment there is inadequate time for fissile-fuel conservation by LMFRs to have much effect on the date of uranium exhaustion. Likewise, early deployment of LMFRs delays by less than 5 years the date when the uranium forward cost reaches $100/lb.

Effect of Nuclear Growth as a Fraction of Total Growth

The scenarios developed by the committee parameterize the growth rate of nuclear power (LWRs plus LMFRs) by the quantity "NGR", the percentage of new generation capacity each year contributed by nuclear energy. This fraction was varied from 30 to 40 percent (for example in scenarios 4 and 9). Figure C-10 shows the resulting change of installed LWR capacity. This change produces a variation of about 5 years in the time when U.S. uranium resources are exhausted through use, or through use and committment, as illustrated in Figure C-11.

Effect of Capacity Factor for Nuclear Plants

The scenarios in this report used capacity factors of 70 and 80 percent for LWRs. This range brackets the median value of 77 percent achieved by all U.S. Westinghouse reactors in 1985 (Westinghouse, 1986c). Figure C-12 illustrates that this variation in capacity factor results in delaying by less than 5 years the time of $100/lb uranium resource exhaustion.

Effect of Period of Forward Commitment for Uranium

The projection of uranium used and committed assumes that when a LWR is commissioned the operating utility contracts for enough fuel to keep the reactor in service for a considerable portion of its economic life. In the scenarios developed in this report, commitment durations of 30, 40, and 60 years were assumed. Figure C-13 illustrates the effect of this plant-life variation on the U_3O_8 used and committed. A change of forward commitment time from 60 to 30 years delays by about 15 years the time of total use and commitment of U.S. uranium ore resources.

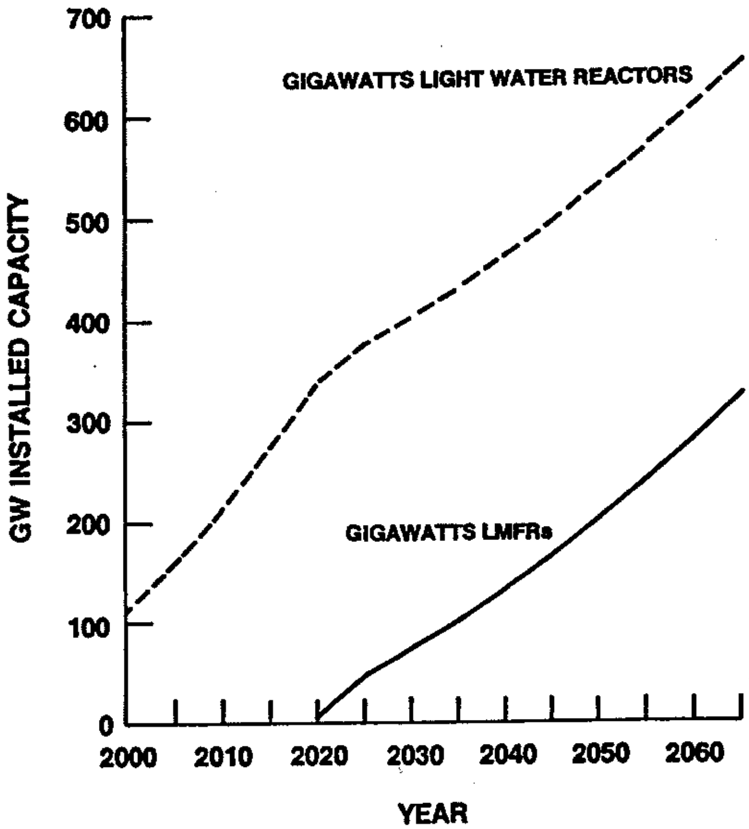


FIGURE C-8 Projected "early" LMFR deployment compared to the deployment of LWRs, 2000 through 2065, based on Scenario 1A.

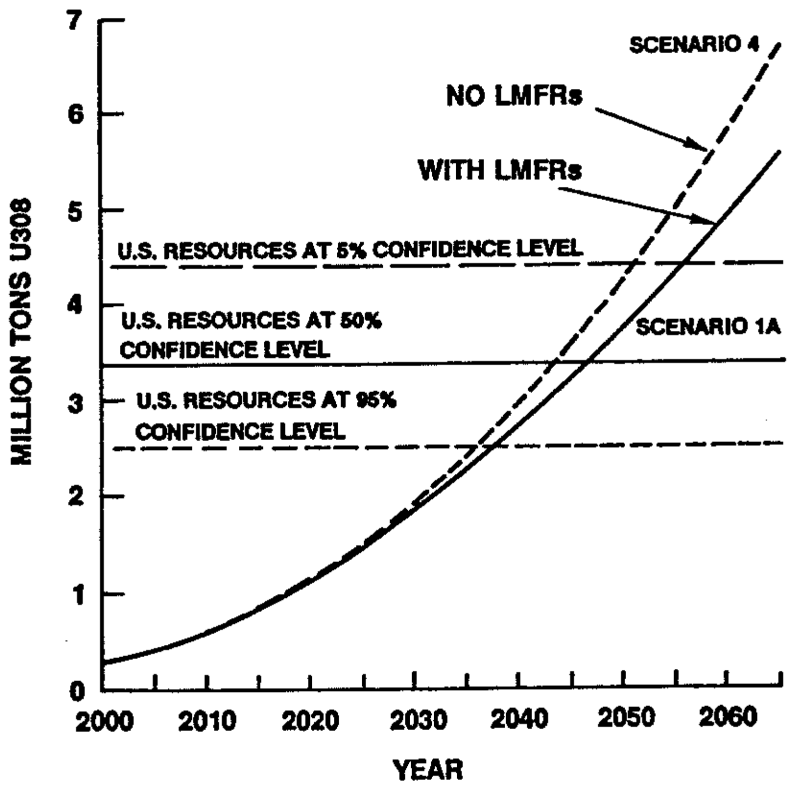


FIGURE C-9 Comparison of the cumulative amounts of U.S. U_3O_8 used and committed for use in LWRs, at various confidence levels, 2000 through 2065.

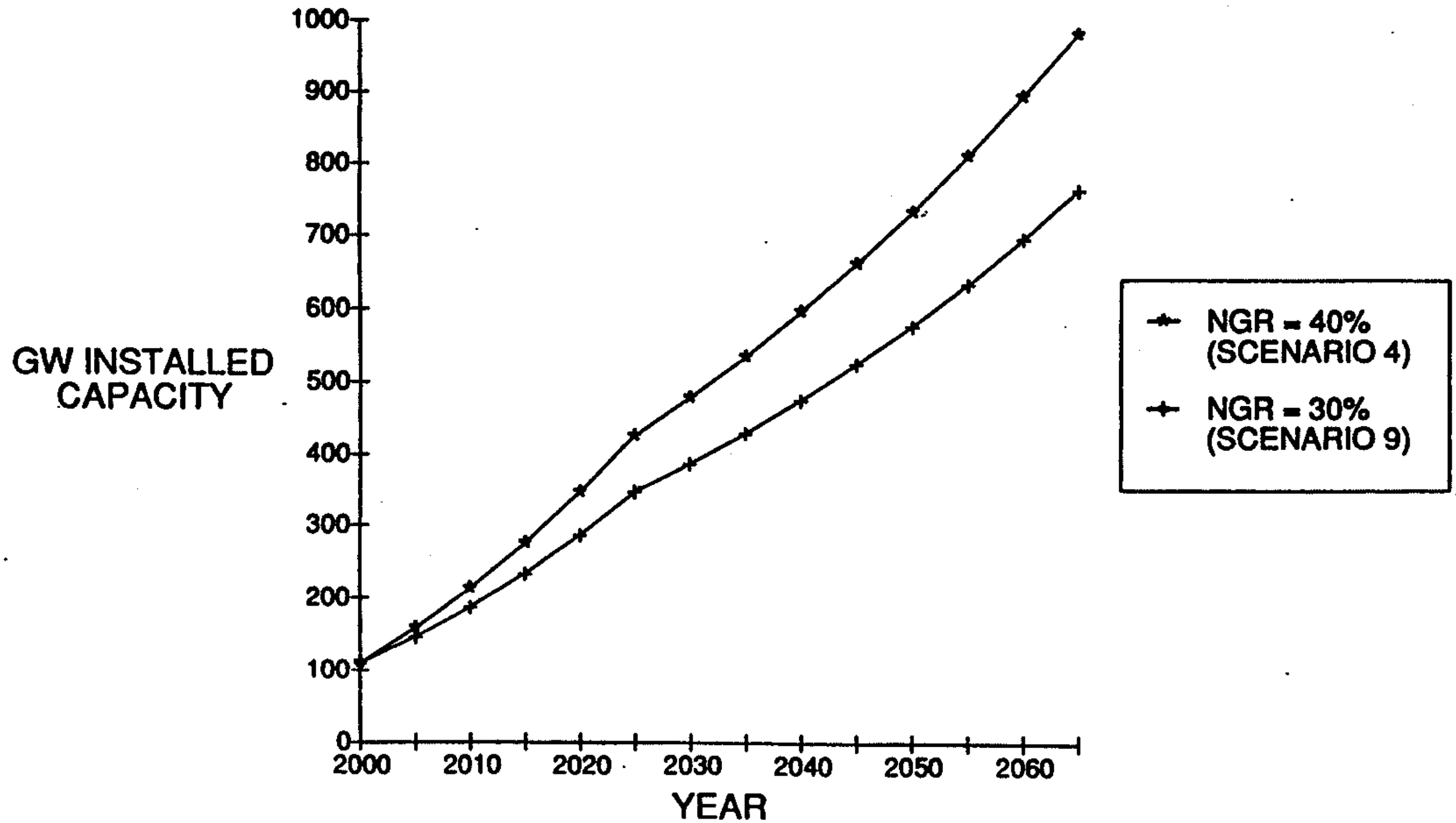


FIGURE C-10 Possible evolution of the LWR component of U.S. electric capacity at several nuclear percentages of new generation (NGR), for "fast" U.S. electric growth, 2000 through 2065.

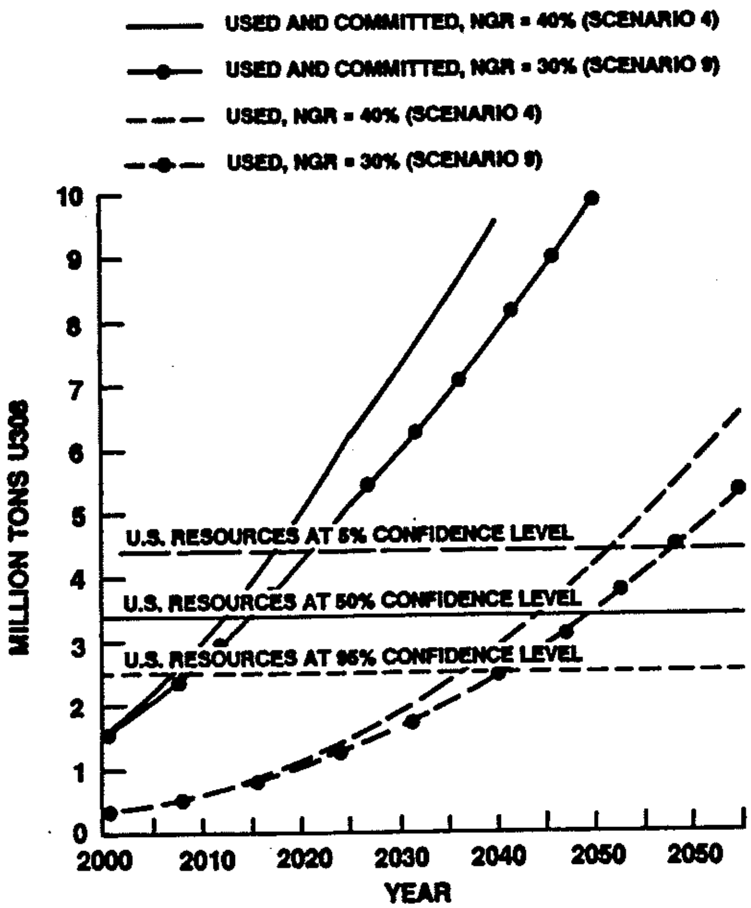


FIGURE C-11 Comparison of the cumulative amounts of U.S. U_3O_8 used and committed for use in LWRs for several nuclear percentages of new generation for "fast" U.S. electric growth and without the LMFR option at several confidence levels, 2000 through 2065.

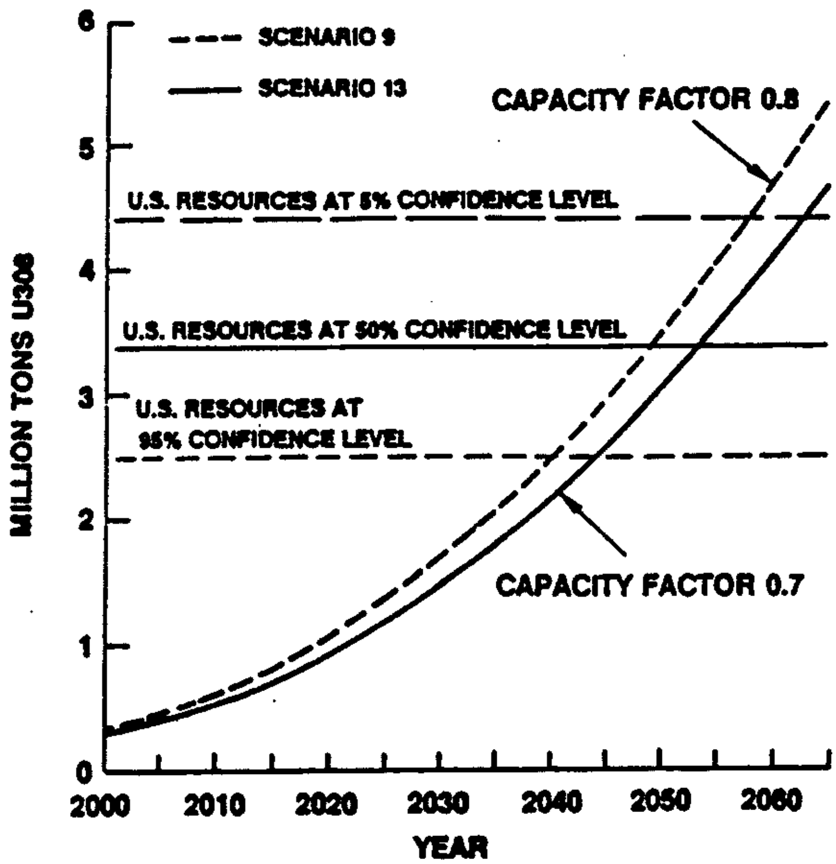


FIGURE C-12 Sensitivity of the cumulative amounts of U.S. U_3O_8 used in LWRs, for several LWR capacity factors, for "fast" U.S. electric growth and without the LMFR option at various confidence levels, 2000 through 2065.

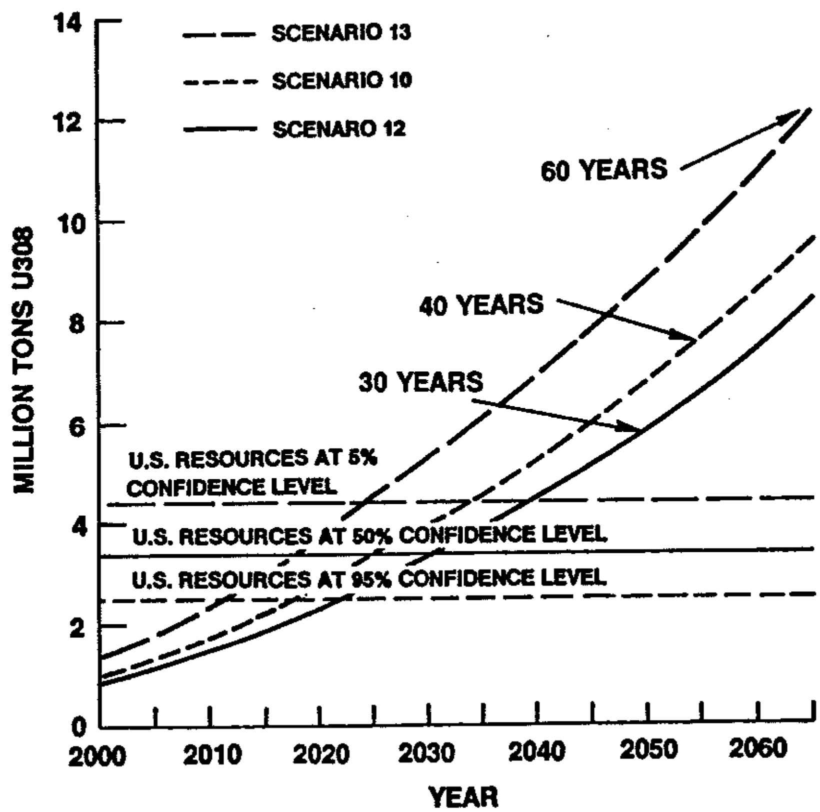


FIGURE C-13 Sensitivity of the cumulative amounts of U_3O_8 used in LWRs to the duration of fuel-commitment periods for "fast" U.S. electric growth and without the LMFR option at various confidence levels, 2000 through 2065.

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TABLE C-1A Projections Calculated for Domestic Scenario 1A Using the Stated Assumptions

PSHEET1A SCENARIO NO. 1A REVISED 10/10/86

ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.5% 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% 2025-2065 ----------> 2.1%
NUCLEAR % NEW GEN.2000-2025(NGR1)---> 40% 2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.1% 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U308 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U308 FOR NEW CORE (NC) ------------> 373 STD TONS CAPACITY FACTOR -----> 80%
ANNUAL U308 PER 1000 MW (REPC) ----> 189 STD TONS TAILS ASSAY --------> 0.20%
U308 RESOURCES (U308) ------------------------------> 3381 STD.TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> FAST FIRST COMMERCIAL LMFR IN -----> 2020
IF LMFR DEPLOYMENT IS FAST ENTER 1 -------> 1
U308 NEEDED TO START 1000MW LMFR (NEEDED) 1298 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL 2065 IN YEAR 2020
NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP -> 2032
YEAR ALL U308 < $100/LB USED UP-> 2046
YEAR ALL U308 < $100/LB COMMITTED 2012
YEAR ALL U308+EQU308 COMMITTED -> 2016
CAPITAL COST OF LWR PER KW -----> $1500
CAPITAL COST OF LWR MILLS/KWH---> 28.5
U308 RESOURCES BELOW $100/LB ---> 3381 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $13.67 MILLIONS
COST OF U308 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 50%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST 27.0 BILLION DOLLARS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	548	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	780	17	20	3	46	36
2005	1029	158	433	437	158	0	15%	122	452	2218	1600	0	135	302	2929	1766	866	17	20	3	46	51
2010	1164	213	481	472	213	0	18%	170	623	3000	970	0	171	417	2758	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	224	0	220	539	2533	3069	1069	17	20	3	46	89
2020	1497	346	594	558	339	7	23%	293	1141	4916	-601	9	284	651	2240	3775	1187	18	21	3	46	110
2025	1696	425	659	612	378	47	25%	387	1528	5748	-1322	52	362	683	1863	4220	1319	52	33	5	48	128
2030	1828	478	732	618	405	73	26%	402	1929	6444	-1946	34	449	669	1452	4515	1465	88	47	7	50	142
2035	1971	535	813	622	433	102	27%	430	2360	7192	-2615	37	542	654	1021	4832	1627	122	60	9	52	158
2040	2124	597	903	624	464	133	28%	461	2821	7995	-3334	40	641	639	560	5175	1807	157	73	10	54	176
2045	2290	663	1003	624	497	166	29%	494	3315	8858	-4105	43	748	624	66	5544	2007	195	87	12	56	195
2050	2468	734	1114	620	533	201	30%	530	3844	9786	-4934	46	862	608	-463	5941	2229	227	100	14	58	216
2055	2660	811	1238	612	571	240	30%	568	4412	10782	-5875	50	985	592	-1031	6370	2476	261	112	16	60	238
2060	2868	894	1375	599	613	281	31%	609	5022	11854	-6782	54	1116	575	-1641	6832	2750	297	126	18	62	264
2065	3091	983	1527	581	657	326	32%	654	5675	13006	-7810	58	1257	557	-2294	7330	3084	336	141	20	64	298
										TOTAL U308 USED FOR LMFRs->		423										

TABLE C-1B Projections Calculated for Domestic Scenario 1B Using the Stated Assumptions

PSREET1B SCENARIO NO. 1B REVISED 10/10/86
ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.5% | 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% | 2025-2065 ----------> 2.1%
NUCLEAR % NEW GEN.2000-2025(NGR1)--> 40% | 2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.1% | 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U3O8 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U3O8 FOR NEW CORE (NC) ------------> 373 STD TONS | CAPACITY FACTOR ----> 80%
ANNUAL U3O8 PER 1000 MW (PEPC) ----> 189 STD TONS | TAILS ASSAY --------> 0.20%
U3O8 RESOURCES (U3O8) -----------------------> 4403 STD.TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> FAST | FIRST COMMERCIAL LMFR IN ----> 2020
IF LMFR DEPLOYMENT IS FAST ENTER 1-----> 1
U3O8 NEEDED TO START 1000MW LMFR(NEEDED) 1298 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL 2055 IN YEAR 2020

U3O8 RESOURCES ARE AT 5% CONFIDENCE LEVEL
YEAR ALL U3O8 < $50/LB USED UP -> 2039
YEAR ALL U3O8 < $100/LB USED UP-> 2055
YEAR ALL U3O8 < $100/LB COMMITTED 2017
YEAR ALL U3O8+EQU3O8 COMMITTED -> 2023
CAPITAL COST OF LWR PER KW ------> $ 1500
CAPITAL COST OF LWR MILLS/KWH --> 38.5
U3O8 RESOURCES BELOW $100/LB ---> 4403 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB ----> 2748 THOUSAND STD TONS
U3O8 RESOURCES BELOW $30/LB ----> 1556 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $13.67 MILLIONS
COST OF U3O8 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 50%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U3O8 @ 180 9.7 MILLS/KWH
PREMIUM FOR U3O8 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST 8.9 BILLION DOLLARS

NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT. EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	3716	0	91	130	4387	892	548	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	3150	0	110	194	4073	1227	780	17	20	3	46	36
2005	1029	158	433	437	158	0	15%	122	452	2718	2622	0	135	302	3951	1766	866	17	20	3	46	51
2010	1166	213	481	472	213	0	15%	170	623	3000	1992	0	171	417	3780	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	1246	0	230	539	3555	3069	1069	17	20	3	46	89
2020	1497	346	594	558	339	7	23%	293	1141	4916	421	9	284	651	3262	3775	1187	17	20	3	46	110
2025	1696	425	659	612	378	47	25%	387	1528	5748	-300	52	362	683	2875	4220	1319	17	20	3	46	123
2030	1828	478	732	618	405	73	26%	402	1929	6444	-924	34	449	669	2474	4515	1465	43	30	4	48	136
2035	1971	535	813	622	433	102	27%	430	2360	7192	-1593	37	542	654	2043	4832	1627	73	41	6	49	150
2040	2124	597	903	624	464	133	28%	461	2821	7995	-2312	40	641	639	1582	5175	1807	104	53	8	51	166
2045	2290	663	1003	624	497	166	29%	494	3315	8958	-3083	43	748	624	1088	5544	2007	134	64	9	53	184
2050	2468	734	1114	620	533	201	30%	530	3844	9786	-3912	46	862	608	559	5941	2229	166	77	11	54	203
2055	2660	811	1238	612	571	240	30%	558	4412	10782	4103	50	995	592	-9	6370	2476	200	89	13	56	225
2060	2848	894	1375	579	613	281	31%	609	5022	11854	-5760	54	1116	575	-619	6832	2750	228	100	14	58	248
2065	3091	983	1527	581	657	326	32%	654	5675	13006	-6788	58	1257	557	-1272	7330	3054	258	111	16	59	274
									TOTAL U3O8 USED FOR LMFRs ->			423										

TABLE C-1C Projections Calculated for Domestic Scenario 1C Using the Stated Assumptions

PSHEETIC SCENARIO NO. 1C REVISED 10/10/86
ELEC. GROWTH RATE 2000-2025 (EGR1) -> 2.5% 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% 2025-2065 ----------> 2.1%
NUCLEAR % NEW GEN. 2000-2025(NGR1)--> 40% 2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.1% 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U308 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U308 FOR NEW CORE (NC) ------------> 373 STD TONS CAPACITY FACTOR ----> 80%
ANNUAL U308 PER 1000 MW (REPC) ---> 189 STD TONS TAILS ASSAY --------> 0.20%
U308 RESOURCES (U308) ------------------------------> 2502 STD. TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFRDEPLOYMENT SCENARIO-> FAST FIRST COMMERCIAL LMFR IN ---> 2020
IF LMFRDEPLOYMENT IS FAST ENTER 1-----> 1
U308 NEEDED TO START 1000MWLMFR(NEEDED) 1290 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL 2025 IN YEAR 2020
NOTE: ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

U308 RESOURCES ARE AT 95% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP -> 2025
YEAR ALL U308 < $100/LB USED UP-> 2037
YEAR ALL U308 < $100/LB COMMITTED 2007
YEAR ALL U308+EQU308 COMMITTED -> 2011
CAPITAL COST OF LWR PER KW -----> $1500
CAPITAL COST OF LWR MILLS/KWH --> 30.5
U308 RESOURCES BELOW $100/LB ---> 2502 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ----> 1502 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ----> 791 THOUSAND STD TONS
CONV., ENRICH, FAB/GW BELOW ----> $13.67 MILLIONS
COST OF U308 PER POUND (NOW)---> $ 17

LMFR % OF NEW NUCLEAR GENERATION 90%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 100 PER LB:
DISCOUNT RATE 4%
EXTRA COST 64.5 BILLION DOLLARS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL. TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	1815	0	91	130	2486	892	540	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	1249	0	110	194	2172	1227	780	17	20	3	46	36
2005	1029	158	433	437	158	0	15%	122	452	2210	721	0	135	302	2050	1766	866	17	20	3	46	51
2010	1166	213	481	472	213	0	18%	170	623	3000	91	0	171	417	1879	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	-655	0	220	539	1654	3069	1069	24	23	3	47	90
2020	1497	346	594	558	359	7	23%	293	1141	4916	-1480	9	284	651	1361	3775	1187	98	36	5	49	115
2025	1696	425	659	612	378	47	25%	387	1520	5748	-2201	52	362	683	974	4228	1319	103	52	7	51	135
2030	1828	478	732	618	405	73	26%	402	1929	6444	-2825	34	449	669	573	4515	1465	143	68	10	53	151
2035	1971	535	813	622	433	102	27%	430	2360	7192	-3494	37	542	654	142	4832	1627	186	84	12	55	169
2040	2124	597	903	624	464	133	28%	461	2821	7995	-4213	46	641	639	-319	5175	1807	225	99	14	58	187
2045	2290	663	1003	624	497	166	29%	494	3315	8858	-4984	43	748	624	-813	5544	2007	265	114	16	60	208
2050	2468	734	1114	620	533	201	30%	530	3844	9786	-5813	46	862	608	-1342	5941	2229	307	130	19	62	232
2055	2660	811	1238	612	571	240	30%	568	4412	10782	-6704	50	985	592	-1910	6370	2476	353	147	21	65	258
2060	2868	894	1375	599	613	281	31%	609	5022	11854	-7661	54	1116	575	-2528	6832	2738	401	165	24	67	288
2065	3091	983	1527	581	657	326	32%	654	5675	13006	-8689	59	1257	557	-3173	7330	3054	454	185	26	70	322
									TOTAL U308 USED FOR LMFRs->			423										

TABLE C-2A Projections Calculated for Domestic Scenario 2A Using the Stated Assumptions

PSHEET.M SCENARIO NO. 2A REVISED 10/10/86

ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.5% 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% 2025-2065 ----------> 2.7%
NUCLEAR % NEW GEN.2000-2025(NGR1)--> 40% 2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 ---> 300%COAL LIMITED,ENTER NUCLEAR % NEW GEN 67%
COAL GROWTH RATE (CGR1) -----------> 2.1% 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U3O8 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U3O8 FOR NEW CORE (NC) ------------> 373 STD TONS CAPACITY FACTOR ----> 80%
ANNUAL U3O8 PER 1000 MW (PEPC) ----> 189 STD TONS TAILS ASSAY ---------> 0.20%
U3O8 RESOURCES (U3O8) ------------------------------------> 3381 STD.TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> FAST FIRST COMMERCIAL LMFR IN ----> 2020
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U3O8 NEEDED TO START 1000MW LMFR (NEEDED) 1298 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL 2065 IN YEAR 2020

U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U3O8 < $50/LB USED UP -> 2032
YEAR ALL U3O8 < $100/LB USED UP-> 2045
YEAR ALL U3O8 < $100/LB COMMITTED 2012
YEAR ALL U3O8+EQU3O8 COMMITTED -> 2016
CAPITAL COST OF LWR PER KW -----> $ 1500
CAPITAL COST OF LWR MILLS/KWH --> 38.5
U3O8 RESOURCES BELOW $100/LB ---> 3291 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB ----> 2056 THOUSAND STD TONS
U3O8 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS
COST OF U3O8 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 50%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U3O8 $ 180 9.7 MILLS/KWH

PREMIUM FOR U3O8 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST 36.5 BILLION DOLLARS

NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8† NEEDED FOR LMFRs† IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	548	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	780	17	20	3	46	36
2005	1029	158	433	437	159	0	15%	122	452	2218	1600	0	135	302	2929	1766	866	17	20	3	46	51
2010	1166	213	481	472	213	0	18%	170	623	3000	970	0	171	417	2758	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	224	0	220	539	2533	3069	1069	17	20	3	46	89
2020	1497	346	594	558	339	7	23%	293	1141	4916	-601	9	284	651	2240	3775	1187	18	21	3	46	110
2025	1696	425	659	612	378	47	25%	387	1528	5748	-1322	52	362	683	1853	4220	1319	52	33	5	48	128
2030	1840	478	732	618	405	73	26%	402	1929	6444	-1946	34	449	669	1452	4515	1465	88	47	7	50	142
2035	1971	535	813	622	433	102	27%	430	2360	7192	-2615	37	542	654	1021	4832	1627	122	60	9	52	158
2040	2124	597	822	706	464	133	28%	461	2821	7995	-3334	40	641	639	560	5175	1644	157	73	10	54	176
2045	2290	707	822	761	519	188	31%	531	3352	9141	-4327	72	748	685	29	5790	1644	198	88	13	56	204
2050	2468	826	822	820	579	247	33%	590	3942	10395	-5417	77	868	730	-561	6453	1644	239	102	15	58	235
2055	2660	954	822	885	643	311	36%	654	4596	11763	-6609	83	1001	773	-1215	7167	1644	272	116	17	60	271
2060	2868	1092	822	954	712	380	38%	723	5319	13257	-7911	90	1148	816	-1938	7937	1644	315	133	19	62	312
2065	3091	1241	822	1028	786	455	40%	797	6117	14884	-9333	97	1312	850	-2736	8767	1644	362	150	21	65	358

TOTAL U3O8 USED FOR LMFRs-> 590

TABLE C-3 Projections Calculated for Domestic Scenario 3 Using the Stated Assumptions

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PSHEET3                                     SCENARIO NO. 3           REVISED    10/10/86                 U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL
ELEC.GROWTH RATE 2000-2025 (EGR1) ->           2.5%                  2025-2065 (EGR2) --->   1.5%                                                         OPERATING & MAINTENANCE              5 MILLS/KWH
NUCLEAR GROWTH RATE 2000-2025 ------>          5.6%                  2025-2065 ----------->  2.1%    YEAR ALL U3O8 < $50/LB USED UP ->        2032        FUEL COST, U3O8 @      100         9.7 MILLS/KWH
NUCLEAR % NEW GEN.2000-2025(NGR1)-->            40%                  2025-2065 (NGR2) ---> 40.0%     YEAR ALL U3O8 < $100/LB USED UP->        2044
COAL USE PERMITTED AS % OF 1986 --->          2500%                                                  YEAR ALL U3O8 < $100/LB COMMITTED        2012        PREMIUM FOR U3O8 >          $  100 PER LB:
COAL GROWTH RATE (CGR1) ----------->           2.1%                  2025-2065 (CGR2) --->   2.1%    YEAR ALL U3O8+EQU3O8 COMMITTED ->        2016        DISCOUNT RATE                      4%
COMMITMENT OF U3O8 FOR (UL) ------->             60 YEARS INTO THE FUTURE                            CAPITAL COST OF LWR PER KW ----->      $ 1300        EXTRA COST                 37.0 BILLION DOLLARS
U3O8 FOR NEW CORE (NC) ------------>            373 STD TONS         CAPACITY FACTOR ---->    80%    CAPITAL COST OF LWR MILLS/KWH --->       30.5
ANNUAL U3O8 PER 1000 MW (REPC) ---->            189 STD TONS         TAILS ASSAY --------->  0.20%   U3O8 RESOURCES BELOW $100/LB --->        3381 THOUSAND STD TONS
U3O8 RESOURCES (U3O8) ------------------------------------->  3381   STD.TONS                        U3O8 RESOURCES BELOW $50/LB ---->        2066 THOUSAND STD TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8)               46  STD TONS                        U3O8 RESOURCES BELOW $30/LB ---->        1127 THOUSAND STD TONS
LMFR DEPLOYMENT SCENARIO-> SLOW          FIRST COMMERCIAL LMFR IN ---->           2035               CONV.,ENRICH, FAB/KW RECORD --->     $13.67 MILLIONS
IFLMFRDEPLOYMENT IS FAST ENTER 1------->       0                                                     COST OF U3O8 PER POUND (NOW)--->     $    17
U3O8 NEEDED TO START 1000MWLMFR(NEEDED)    1290 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL  2065      IN YEAR      2035                                      LMFR % OF NEW NUCLEAR GENERATION          50%
                                    NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS
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YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL. TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	540	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	700	17	20	3	46	36
2005	1029	158	433	437	158	0	15%	122	452	2218	1600	0	135	302	2929	1766	866	17	20	3	46	51
2010	1166	213	481	472	213	0	18%	170	623	3000	970	0	171	417	2758	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	224	0	228	539	2533	3069	1069	17	20	3	46	89
2020	1497	346	594	558	346	0	23%	287	1134	4988	-653	0	294	670	2247	3854	1187	18	20	3	46	112
2025	1696	425	659	612	425	0	25%	357	1491	6234	-1679	0	363	811	1890	4743	1319	49	32	5	48	143
2030	1820	478	732	610	478	0	26%	422	1913	7245	-2545	0	461	859	1468	5332	1465	86	46	7	50	160
2035	1971	535	813	622	507	28	27%	500	2413	8063	-3283	37	571	827	968	5650	1627	126	61	9	52	186
2040	2124	597	903	624	537	59	28%	530	2943	8935	-4071	40	687	796	438	5992	1807	167	77	11	54	208
2045	2290	663	1003	624	570	92	29%	563	3506	9867	-4912	43	811	763	-125	6361	2007	207	92	13	57	227
2050	2468	734	1114	620	606	128	30%	599	4105	10864	-5810	46	942	731	-724	6759	2229	248	105	15	59	249
2055	2660	811	1238	612	645	166	30%	637	4742	11930	-6770	50	1082	697	-1361	7186	2476	281	120	17	61	274
2060	2868	894	1375	599	686	208	31%	679	5421	13071	-7796	54	1230	663	-2040	7650	2750	321	135	19	63	302
2065	3091	983	1527	581	731	252	32%	723	6144	14292	-8894	58	1388	629	-2763	8148	3054	363	151	22	65	330
									TOTAL U3O8 USED FOR LMFRs->			328										

TABLE C-4 Projections Calculated for Domestic Scenario 4 Using the Stated Assumptions

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PSHEET4                                    SCENARIO NO. 4              REVISED   10/10/86
ELEC.GROWTH RATE 2000-2025 (EGR1) ->           2.5%                    2025-2065 (EGR2) --->   1.5%
NUCLEAR GROWTH RATE 2000-2025 ----->           5.6%                    2025-2065 ---------->   2.1%
NUCLEAR % NEW GEN.2000-2025(NGR1)-->            40%                    2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 --->          2500%
COAL GROWTH RATE (CGR1) - --------->           2.1%                    2025-2065 (CGR2) --->   2.1%
COMMITMENT OF U3O8 FOR (UL) ------->             60 YEARS INTO THE FUTURE
U3O8 FOR NEW CORE (NC) ------------>            373 STD TONS           CAPACITY FACTOR ---->   80%
ANNUAL U3O8 PER 1000 MW (REPC) -- ->            189 STD TONS           TAILS ASSAY -------->  0.20%
U3O8 RESOURCES (U3O8) ----------- ----------------->    3381   STD.TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8)          46 STD TONS
LMFR DEPLOYMENT SCENARIO->  NO LMFRs
IF FBR DEPLOYMENT IS FAST ENTER 1- ---->      1
U3O8 NEEDED TO START 1000MWLMFR(NEEDED)   1298 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL   NO LMFRs
                                          NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL
YEAR ALL U3O8 < $50/LB USED UP ->          2032
YEAR ALL U3O8 < $100/LB USED UP->          2044
YEAR ALL U3O8 < $100/LB COMMITTED          2012
YEAR ALL U3O8+EQU3O8 COMMITTED ->          2016
CAPITAL COST OF LWR PER KW ----->         $1500
CAPITAL COST OF LWR MILLS/KWH---->         38.5
U3O8 RESOURCES BELOW $100/LB --->          3381 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB ---->          2066 THOUSAND STD TONS
U3O8 RESOURCES BELOW $30/LB ---->          1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ---->        $13.67 MILLIONS
COST OF U3O8 PER POUND (NOW)---->        $   17

LMFR % OF NEW NUCLEAR GENERATION            0%

OPERATING & MAINTENANCE                              5 MILLS/KWH
FUEL COST, U3O8 @      180                         9.7 MILLS/KWH

PREMIUM FOR U3O8 >          $  180 PER LB:
DISCOUNT RATE                    4%
EXTRA COST                    47.8 BILLION DOLLARS
```

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	548	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	780	17	20	3	46	36
2005	1029	158	433	437	158	0	15%	122	452	2218	1600	0	135	302	2929	1766	866	17	20	3	46	51
2010	1166	213	481	472	213	0	18%	170	623	3000	970	0	171	417	2758	2377	962	17	20	3	46	69
2015	1321	275	534	511	275	0	21%	225	848	3917	224	0	220	539	2533	3069	1069	17	20	3	46	89
2020	1497	346	594	558	346	0	23%	287	1134	4988	-653	0	284	670	2247	3854	1187	18	20	3	46	112
2025	1696	425	659	612	425	0	25%	357	1491	6234	-1679	0	363	811	1890	4743	1319	49	32	5	48	143
2030	1829	478	732	618	478	0	26%	422	1913	7245	-2545	0	461	859	1468	5332	1465	86	46	7	50	168
2035	1971	535	813	622	535	0	27%	473	2386	8354	-3496	0	571	906	995	5968	1627	124	61	9	52	196
2040	2124	597	903	624	597	0	28%	529	2915	9568	-4540	0	694	952	466	6652	1807	165	76	11	54	227
2045	2290	663	1003	624	663	0	29%	589	3504	10894	-5684	0	831	998	-123	7390	2007	207	92	13	57	263
2050	2468	734	1114	620	734	0	30%	653	4157	12343	-6936	0	984	1042	-776	8186	2229	246	107	15	59	302
2055	2660	811	1238	612	811	0	30%	723	4880	13923	-8304	0	1153	1086	-1499	9043	2476	289	123	18	61	347
2060	2868	894	1375	599	894	0	31%	798	5678	15645	-9797	0	1339	1128	-2297	9967	2759	336	141	20	64	398
2065	3091	983	1527	581	983	0	32%	878	6556	17520	-11425	0	1545	1169	-3175	10964	3054	388	160	23	66	457
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-6 Projections Calculated for Domestic Scenario 6 Using the Stated Assumptions

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PSHEET6                                  SCENARIO NO. 6          REVISED   10/10/86                      U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL
ELEC.GROWTH RATE 2000-2025 (EGR1) ->         1.0%               2025-2065 (EGR2) --->   1.0%                                                            OPERATING & MAINTENANCE              5 MILLS/KWH
NUCLEAR GROWTH RATE 2000-2025 ----->         2.7%               2025-2065 ----------->  1.8%    YEAR ALL U308 < $50/LB USED UP ->     2045     FUEL COST, U308 @     100          9.7 MILLS/KWH
NUCLEAR % NEW GEN.2000-2025(NGR1)-->          40%               2025-2065 (NGR2) ---> 40.0%    YEAR ALL U308 < $100/LB USED UP->     2064
COAL USE PERMITTED AS % OF 1986 --->        2500%                                               YEAR ALL U308 < $100/LB COMMITTED     2024     PREMIUM FOR U308 >       $  100 PER LB:
COAL GROWTH RATE (CGR1) ----------->         1.0%               2025-2065 (CGR2) --->   1.0%    YEAR ALL U308+EQU308 COMMITTED ->     2031     DISCOUNT RATE               4%
COMMITMENT OF U308 FOR (UL) ------->          60 YEARS INTO THE FUTURE                          CAPITAL COST OF LWR PER KW ----->   $ 1500     EXTRA COST               0.00 BILLION DOLLARS
U308 FOR NEW CORE (NC) ------------>         373 STD TONS       CAPACITY FACTOR ---->    80%    CAPITAL COST OF LWR MILLS/KWH--->     38.5
ANNUAL U308 PER 1000 MW (REPC) ---->         189 STD TONS       TAILS ASSAY -------->  0.20%    U308 RESOURCES BELOW $100/LB --->     3381 THOUSAND STD TONS
U308 RESOURCES (U308) ------------------------------------>  3381   STD.TONS                    U308 RESOURCES BELOW $50/LB ---->     2066 THOUSAND STD TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308)             46 STD TONS                      U308 RESOURCES BELOW $30/LB ---->     1127 THOUSAND STD TONS
LMFR DEPLOYMENT SCENARIO->  NO LMFRs                                                            CONV.,ENRICH, FAB/GW RELOAD ---->   $ 13.67 MILLIONS
 IF LMFR DEPLOYMENT IS FAST ENTER 1------->       1                                             COST OF U308 PER POUND (NOW)---->   $   17
U308 NEEDED TO START 1000MW LMFR(NEEDED)   1298 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL  NO LMFRs                                                    LMFR % OF NEW NUCLEAR GENERATION      0%
                                      NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS
```

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE.	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	548	17	20	3	46	26
2000	909	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	780	17	20	3	46	36
2005	955	129	410	416	129	0	13%	111	441	1875	1861	0	135	220	2940	1434	820	17	20	3	46	42
2010	1003	148	431	424	148	0	15%	129	570	2223	1567	0	164	245	2811	1653	862	17	20	3	46	48
2015	1055	169	453	433	169	0	16%	140	710	2600	1247	0	199	267	2663	1882	906	17	20	3	46	55
2020	1109	190	476	442	190	0	17%	168	886	3009	898	0	237	288	2495	2123	953	17	20	3	46	62
2025	1166	213	501	452	213	0	18%	189	1074	3451	518	0	281	307	2307	2377	1002	17	20	3	46	69
2030	1226	237	526	462	237	0	19%	210	1285	3928	107	0	330	324	2096	2644	1053	31	25	4	47	78
2035	1289	262	553	473	262	0	20%	234	1518	4442	-337	0	385	339	1863	2924	1107	52	33	5	48	89
2040	1355	289	582	484	289	0	21%	258	1776	4994	-817	0	445	352	1605	3219	1164	74	42	6	49	100
2045	1424	316	612	496	316	0	22%	283	2059	5587	-1333	0	511	362	1322	3538	1223	99	51	7	51	113
2050	1497	346	643	508	346	0	23%	310	2369	6223	-1888	0	584	370	1012	3854	1286	123	60	9	52	126
2055	1574	376	676	522	376	0	24%	338	2707	6904	-2484	0	664	375	674	4196	1352	149	70	10	54	141
2060	1654	409	711	535	409	0	25%	368	3075	7631	-3123	0	750	377	306	4556	1421	177	80	11	55	158
2065	1739	443	747	550	443	0	25%	399	3474	8409	-3806	0	844	377	-93	4935	1494	206	91	13	57	175
									TOTAL U308 USED FOR LMFRs->			0										

TABLE C-7 Projections Calculated for Domestic Scenario 7 Using the Stated Assumptions

PSHEET7 SCENARIO NO. 7 REVISED 10/10/86

ELEC. GROWTH RATE 2000-2025 (EGR1) -> 2.5% — 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% — 2025-2065 ----------> 2.1%
NUCLEAR % NEW GEN. 2000-2025(NGR1)--> 40% — 2025-2065 (NGR2) ---> 40.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.1% — 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U3O8 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U3O8 FOR NEW CORE (NC) -----------> 302 STD TONS — CAPACITY FACTOR ----> 80%
ANNUAL U3O8 PER 1000 MW (REPC) ----> 153 STD TONS — TAILS ASSAY --------> 0.08%
U3O8 RESOURCES (U3O8) -----------------------------> 3381 STD. TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> NO LMFRs
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U3O8 NEEDED TO START 1000MWLMFR(NEEDED) 1298 STD TONS
U3O8 COMMITTED FOR ALLLMFRsUNTIL NO LMFRs

U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U3O8 < $50/LB USED UP -> 2037
YEAR ALL U3O8 < $100/LB USED UP-> 2050
YEAR ALL U3O8 < $100/LB COMMITTED 2016
YEAR ALL U3O8+EQU3O8 COMMITTED -> 2022
CAPITAL COST OF LWR PER KW -----> $ 1500
CAPITAL COST OF LWR MILLS/KWH---> 38.5
U3O8 RESOURCES BELOW $100/LB ---> 3381 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS
U3O8 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS
COST OF U3O8 PER POUND (NOW)----> $ 17

LMFR% OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U3O8 @ 180 9.7 MILLS/KWH

PREMIUM FOR U3O8 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST 19.9 BILLION DOLLARS

NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL. TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	738	2863	0	91	130	3365	722	548	17	19	3	46	26
2000	918	110	390	408	110	0	12%	254	270	1263	2421	0	110	194	3111	993	780	17	19	3	46	36
2005	1029	158	433	437	158	0	15%	99	369	1799	2019	0	135	302	3012	1430	866	17	19	3	46	51
2010	1166	213	481	472	213	0	18%	138	507	2431	1538	0	171	417	2874	1924	962	17	19	3	46	69
2015	1321	275	534	511	275	0	21%	182	689	3174	967	0	220	539	2692	2485	1069	17	19	3	46	89
2020	1497	346	594	558	345	0	23%	232	921	4041	294	0	284	670	2460	3120	1187	17	19	3	46	112
2025	1696	425	659	612	425	0	25%	289	1210	5050	-495	0	363	811	2171	3840	1319	24	21	3	47	139
2030	1828	478	732	618	479	0	26%	342	1552	5868	-1168	0	461	859	1829	4317	1465	55	30	4	48	160
2035	1971	535	813	622	535	0	27%	383	1935	6766	-1908	0	571	906	1446	4831	1627	88	41	6	49	185
2040	2124	597	903	624	597	0	28%	428	2363	7748	-2721	0	694	952	1010	5385	1807	123	51	7	51	213
2045	2290	663	1003	624	663	0	29%	477	2840	8822	-3612	0	831	998	541	5983	2007	159	62	9	52	243
2050	2468	734	1114	620	734	0	30%	529	3369	9995	-4588	0	984	1042	12	6627	2229	199	75	11	54	279
2055	2660	811	1238	612	811	0	30%	585	3954	11274	-5655	0	1153	1086	-573	7321	2476	234	85	12	56	317
2060	2868	894	1375	599	894	0	31%	646	4599	12668	-6820	0	1339	1128	-1218	8069	2750	272	97	14	57	359
2065	3091	983	1527	581	983	0	32%	711	5311	14186	-8091	0	1545	1169	-1930	8875	3054	314	110	16	59	408
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-8A Projections Calculated for Domestic Scenario 8A Using the Stated Assumptions

PSHEET8A SCENARIO NO. 8A REVISED 10/10/86

ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.5% 2025-2065 (EGR2) ---> 1.5%

NUCLEAR GROWTH RATE 2000-2025 -----> 5.6% 2025-2065 ----------> 2.7%

NUCLEAR % NEW GEN.2000-2025(NGR1)--> 40% 2025-2065 (NGR2) ---> 40.0%

COAL USE PERMITTED AS % OF 1986 ---> 300%COAL LIMITED,ENTER NUCLEAR % NEW GEN 67%

COAL GROWTH RATE (CGR1) ----------> 2.1% 2025-2065 (CGR2) ---> 2.1%

COMMITMENT OF U308 FOR (UL) -------> 60 YEARS INTO THE FUTURE

U308 FOR NEW CORE (NC) ------------> 373 STD TONS CAPACITY FACTOR ----> 80%

ANNUAL U308 PER 1000 MW (REPC) ----> 189 STD TONS TAILS ASSAY --------> 0.20%

U308 RESOURCES (U308) ---------------------------------> 3381 STD.TONS

TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS

LMFR DEPLOYMENT SCENARIO-> NO LMFRs

IF LMFR DEPLOYMENT IS FAST ENTER 1-----> 1

U308 NEEDED TO START 1000MWLMFR:UNEEDED) 1298 STD TONS

U308 COMMITTED FOR ALLLMFRsUNTIL NO LMFRs

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP -> 2032

YEAR ALL U308 < $100/LB USED UP-> 2044

YEAR ALL U308 < $100/LB COMMITTED 2012

YEAR ALL U308+EQU308 COMMITTED -> 2016

CAPITAL COST OF LWR PER KW -----> $1500

CAPITAL COST OF LWR MILLS/KWH---> 38.5

U308 RESOURCES BELOW $100/LB ---> 3381 THOUSAND STD TONS

U308 RESOURCES BELOW $50/LB ---> 2066 THOUSAND STD TONS

U308 RESOURCES BELOW $30/LB ---> 1127 THOUSAND STD TONS

CONV.,ENRICH, FAB/GW RELOAD ---> $13.67 MILLIONS

COST OF U308 PER POUND (NOW) ---> $ 17

LMFR % OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 5 MILLS/KWH

FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 180 PER LB:

DISCOUNT RATE 4%

EXTRA COST 62.9 BILLION DOLLARS

NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.
1986	705	80	274	351	80	0	11%	16	16	908	2694
2000	908	110	390	408	110	0	12%	314	330	1557	2128
2005	1029	158	433	437	158	0	15%	122	452	2218	1600
2010	1166	213	481	472	213	0	18%	170	623	3000	970
2015	1321	275	534	511	275	0	21%	225	848	3917	224
2020	1497	346	594	558	346	0	23%	287	1134	4988	-653
2025	1696	425	659	612	425	0	25%	357	1491	6234	-1679
2030	1828	478	732	618	478	0	26%	422	1913	7245	-2545
2035	1971	535	813	622	535	0	27%	473	2386	8354	-3496
2040	2124	597	822	706	597	0	28%	529	2915	9560	-4540
2045	2290	707	822	761	707	0	31%	605	3521	11403	-6071
2050	2468	826	822	820	826	0	33%	713	4234	13442	-7782
2055	2660	954	822	885	954	0	36%	829	5063	15700	-9686
2060	2868	1092	822	954	1092	0	38%	954	6016	18194	-11799
2065	3091	1241	822	1028	1241	0	40%	1088	7104	20942	-14136

YEAR	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS /KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	0	91	130	3365	892	548	17	20	3	46	26
2000	0	110	194	3051	1227	780	17	20	3	46	36
2005	0	135	302	2929	1766	866	17	20	3	46	51
2010	0	171	417	2758	2377	962	17	20	3	46	69
2015	0	220	539	2533	3069	1069	17	20	3	46	89
2020	0	284	670	2247	3854	1187	18	20	3	46	112
2025	0	363	811	1890	4743	1319	49	32	5	48	143
2030	0	461	859	1460	5332	1465	86	46	7	50	168
2035	0	571	906	995	5968	1627	124	61	9	52	196
2040	0	694	952	466	6652	1644	165	76	11	54	227
2045	0	831	1120	-140	7082	1644	208	92	13	57	281
2050	0	994	1285	-853	9208	1644	250	108	15	59	341
2055	0	1184	1449	-1682	10637	1644	299	127	18	62	412
2060	0	1403	1611	-2635	12177	1644	356	148	21	65	495
2065	0	1654	1771	-3723	13838	1644	420	173	25	68	593

TOTAL U308 USED FOR LMFRs-> 0

TABLE C-9 Projections Calculated for Domestic Scenario 9 Using the Stated Assumptions

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PSHEET9                                        SCENARIO NO. 9          REVISED    10/10/86                 U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL
ELEC.GROWTH RATE 2000-2025 (EGR1) ->               2.5%                2025-2065 (EGR2) --->    1.5%                                                           OPERATING & MAINTENANCE               5 MILLS/KWH
NUCLEAR GROWTH RATE 2000-2025 ----->               4.7%                2025-2065 ----------->   2.0%   YEAR ALL U3O8 < $50/LB USED UP ->      2035     FUEL COST, U3O8 @     180            9.7 MILLS/KWH
NUCLEAR % NEW GEN.2000-2025(NGR1)-->                30%                2025-2065 (NGR2) --->   30.0%   YEAR ALL U3O8 < $100/LB USED UP->      2049
COAL USE PERMITTED AS % OF 1986 --->              2500%                                                YEAR ALL U3O8 < $100/LB COMMITTED      2015     PREMIUM FOR U3O8 >       $ 180 PER LB:
COAL GROWTH RATE (CGR1) ------------>              2.1%                2025-2065 (CGR2) --->    2.1%   YEAR ALL U3O8+EQU3O8 COMMITTED ->      2020     DISCOUNT RATE                4%
COMMITMENT OF U3O8 FOR (UL) ------->                 60 YEARS INTO THE FUTURE                          CAPITAL COST OF LWR PER KW ----->     $1500     EXTRA COST            20.2 BILLION DOLLARS
U3O8 FOR NEW CORE (NC) ------------>                373 STD TONS       CAPACITY FACTOR ---->     80%   CAPITAL COST OF LWR MILLS/KWH--->      38.5
ANNUAL U3O8 PER 1000 MW (REPC) ---->                189 STD TONS       TAILS ASSAY -------->   0.20%   U3O8 RESOURCES BELOW $100/LB --->      3381 THOUSAND STD TONS
U3O8 RESOURCES (U3O8) ------------------------------>       3381       STD.TONS                        U3O8 RESOURCES BELOW $50/LB ---->      2066 THOUSAND STD TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8)                46   STD TONS                        U3O8 RESOURCES BELOW $30/LB ---->      1127 THOUSAND STD TONS
LMFR DEPLOYMENT SCENARIO-> NO LMFRs                                                                    CONV.,ENRICH, FAB/GW RELOAD ---->    $13.67 MILLIONS
IF LMFR DEPLOYMENT IS FAST ENTER 1------>      1                                                       COST OF U3O8 PER POUND (NOW)---->    $   17
U3O8 NEEDED TO START 1000MW LMFR(UNEEDED)   1290 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL  NO LMFRs                                                           LMFR % OF NEW NUCLEAR GENERATION        0%
                                      NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS
```

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	908	2694	0	91	130	3365	892	548	17	20	3	46	26
2000	908	110	390	408	110	0	12%	314	330	1557	2128	0	110	194	3051	1227	780	17	20	3	46	36
2005	1029	146	433	449	146	0	14%	118	448	2079	1706	0	135	269	2933	1631	866	17	20	3	46	48
2010	1166	187	481	497	187	0	16%	154	602	2691	1207	0	169	349	2779	2089	962	17	20	3	46	61
2015	1321	234	534	553	234	0	18%	195	796	3405	622	0	212	434	2585	2609	1069	17	20	3	46	76
2020	1497	297	594	617	297	0	19%	241	1037	4234	-42	0	265	526	2344	3197	1187	17	20	3	46	93
2025	1696	347	659	691	347	0	20%	294	1331	5195	-857	0	331	625	2050	3864	1319	35	27	4	47	115
2030	1828	386	732	710	386	0	21%	342	1673	5979	-1532	0	411	655	1708	4306	1465	65	38	5	49	123
2035	1971	429	813	729	429	0	22%	381	2054	6837	-2272	0	500	684	1327	4782	1627	99	51	7	51	153
2040	2124	475	903	746	475	0	22%	423	2477	7773	-3081	0	599	712	904	5296	1807	131	63	9	53	175
2045	2290	525	1003	762	525	0	23%	468	2945	8794	-3565	0	708	740	436	5849	2007	167	77	11	54	200
2050	2468	578	1114	776	578	0	23%	516	3460	9906	-4930	0	828	767	-79	6446	2229	205	91	13	57	229
2055	2660	636	1239	787	636	0	24%	568	4029	11118	-5992	0	961	793	-648	7089	2476	238	104	15	58	260
2060	2848	698	1375	795	698	0	24%	624	4653	12435	-7128	0	1108	819	-1272	7782	2750	275	118	17	60	295
2065	3091	765	1527	799	765	0	25%	685	5338	13867	-8375	0	1260	843	-1957	8529	3054	316	133	19	63	335
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-10 Projections Calculated for Domestic Scenario 10 Using the Stated Assumptions

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PSHEET10                                   SCENARIO NO. 10        REVISED   10/10/86                U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL
ELEC.GROWTH RATE 2000-2025 (EGR1) ->            2.5%               2025-2065 (EGR2) --->   1.5%                                                           OPERATING & MAINTENANCE                  5 MILLS/KWH
NUCLEAR GROWTH RATE 2000-2025 ----->            4.7%               2025-2065 ----------->   2.0%   YEAR ALL U3O8 < $50/LB USED UP ->       2039   FUEL COST, U3O8 @     180                 9.7 MILLS/KWH
NUCLEAR % NEW GEN.2000-2025(NGR1)-->             30%               2025-2065 (NGR2) --->  30.0%   YEAR ALL U3O8 < $100/LB USED UP->       2054
COAL USE PERMITTED AS % OF 1986 --->           2500%                                               YEAR ALL U3O8 < $100/LB COMMITTED       2025   PREMIUM FOR U3O8 >       $ 180 PER LB:
COAL GROWTH RATE (CGR1) ----------->            2.1%               2025-2065 (CGR2) --->   2.1%   YEAR ALL U3O8+EQU3O8 COMMITTED ->       2031   DISCOUNT RATE                4%
COMMITMENT OF U3O8 FOR (UL) ------->              40 YEARS INTO THE FUTURE                         CAPITAL COST OF LWR PER KW ------>    $1500   EXTRA COST               10.2 BILLION DOLLARS
U3O8 FOR NEW CORE (NC) ------------>             336 STD TONS      CAPACITY FACTOR ---->    70%   CAPITAL COST OF LWR MILLS/KWH --->      44.0
ANNUAL U3O8 PER 1000 MW (REPC) ---->             165 STD TONS      TAILS ASSAY --------->  0.20%   U3O8 RESOURCES BELOW $100/LB --->       3381 THOUSAND STD TONS
U3O8 RESOURCES (U3O8) ------------------------------->   3381     STD.TONS                         U3O8 RESOURCES BELOW $50/LB ---->       2066 THOUSAND STD TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8)            46  STD TONS                         U3O8 RESOURCES BELOW $30/LB ---->       1127 THOUSAND STD TONS
LMFR DEPLOYMENT SCENARIO->  NO LMFRs                                                               CONV.,ENRICH, FAB/GW RELOAD ---->   $ 13.67 MILLIONS
IF LMFR DEPLOYMENT IS FAST ENTER 1------>         1                                                COST OF U3O8 PER POUND (NOW)---->   $    17
U3O8 NEEDED TO START 1000MWLMFR(UNEEDED)    1136 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL  NO LMFRs                                                       LMFR % OF NEW NUCLEAR GENERATION         0%
                                  NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS
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YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	532	2996	0	91	96	3365	516	540	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	1000	2583	0	110	93	3090	709	780	17	19	3	52	36
2005	1029	146	433	449	146	0	14%	103	394	1337	2313	0	135	134	2987	943	866	17	19	3	52	47
2010	1166	187	481	497	187	0	16%	135	529	1737	1989	0	169	176	2853	1208	962	17	19	3	52	60
2015	1321	234	534	553	234	0	18%	170	699	2208	1604	0	212	219	2682	1509	1069	17	19	3	52	75
2020	1497	287	594	617	287	0	19%	211	910	2759	1150	0	265	262	2471	1849	1187	17	19	3	52	92
2025	1696	347	659	691	347	0	20%	257	1166	3401	617	0	331	306	2215	2235	1319	20	20	3	52	111
2030	1828	396	732	710	396	0	21%	300	1466	3957	135	0	411	299	1915	2490	1465	47	29	5	54	127
2035	1971	429	813	729	429	0	22%	333	1799	4566	-395	0	500	289	1582	2766	1627	76	39	6	56	146
2040	2124	475	903	746	475	0	22%	370	2169	5232	-978	0	599	275	1212	3063	1807	108	49	8	57	166
2045	2290	525	1003	762	525	0	23%	409	2578	5962	-1615	0	708	257	803	3383	2007	139	60	10	59	189
2050	2468	578	1114	776	578	0	23%	451	3030	6758	-2314	0	828	235	351	3728	2229	173	71	12	61	215
2055	2660	636	1238	787	636	0	24%	497	3527	7627	-3076	0	961	208	-146	4100	2476	209	83	13	63	244
2060	2868	698	1375	795	698	0	24%	546	4073	8574	-3909	0	1108	177	-692	4501	2790	241	93	15	64	278
2065	3091	765	1527	799	765	0	25%	599	4672	9606	-4817	0	1268	139	-1291	4933	3054	276	105	17	66	310
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-11 Projections Calculated for Domestic Scenario 11 Using the Stated Assumptions

PERFET11	SCENARIO NO. 11	REVISED 10/10/86		
ELEC.GROWTH RATE 2000-2025 (EGR1) ->	1.0%	2025-2065 (EGR2) --->	1.0%	
NUCLEAR GROWTH RATE 2000-2025 ----->	2.2%	2025-2065 ---------->	1.6%	
NUCLEAR % NEW GEN.2000-2025(NGR1)-->	33%	2025-2065 (NGR2) --->	30.0%	
COAL USE PERMITTED AS % OF 1986 --->	2500%			
COAL GROWTH RATE (CGR1) ----------->	1.0%	2025-2065 (CGR2) --->	1.0%	
COMMITMENT OF U308 FOR (UL) ------->	40 YEARS INTO THE FUTURE			
U308 FOR NEW CORE (NC) ------------>	326 STD TONS	CAPACITY FACTOR ---->	70%	
ANNUAL U308 PER 1000 MW (REPC) ---->	165 STD TONS	TAILS ASSAY -------->	0.20%	
U308 RESOURCES (U308) ------------------------------>	3381	STD.TONS		
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308)	46	STD TONS		
MFR DEPLOYMENT SCENARIO-> NO LMFRs				
IF LMFR DEPLOYMENT IS FAST ENTER 1 ----->	1			
U308 NEEDED TO START 1000MWLMFR(UNEEDED)	1136 STD TONS			
U308 COMMITTED FOR ALL LMFRs UNTIL	NO LMFRs			

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP ->	2054
YEAR ALL U308 < $100/LB USED UP->AFTER	2070
YEAR ALL U308 < $100/LB COMMITTED	2046
YEAR ALL U308+EQU308 COMMITTED ->	2053
CAPITAL COST OF LWR PER KW ----->	$ 1500
CAPITAL COST OF LWR MILLS/KWH -->	44.0
U308 RESOURCES BELOW $100/LB --->	3381 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ---->	2066 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ---->	1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ---->	$13.67 MILLIONS
COST OF U308 PER POUND (NOW)---->	$ 17
LMFR % OF NEW NUCLEAR GENERATION	0%

OPERATING & MAINTENANCE	5 MILLS/KWH
FUEL COST, U308 @ 180	9.7 MILLS/KWH
PREMIUM FOR U308 >	$ 180 PER LB:
DISCOUNT RATE	4%
EXTRA COST IN 2065:	1.5 BILLION DOLLARS

NOTE: ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1996	705	80	274	351	80	0	11%	16	16	532	2996	0	91	56	3365	516	548	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	1000	2583	0	110	93	3090	709	780	17	19	3	52	35
2005	955	124	410	421	124	0	13%	96	386	1186	2423	0	135	93	2995	800	820	17	19	3	52	40
2010	1003	139	431	434	139	0	14%	107	494	1388	2248	0	163	92	2887	894	862	17	19	3	52	44
2015	1055	154	453	448	154	0	15%	120	614	1607	2057	0	195	88	2767	994	906	17	19	3	52	49
2020	1109	170	476	462	170	0	15%	133	746	1845	1850	0	231	83	2635	1098	953	17	19	3	52	54
2025	1166	187	501	478	187	0	16%	146	893	2101	1625	0	270	75	2488	1208	1002	17	19	3	52	60
2030	1226	205	526	494	205	0	17%	161	1054	2378	1391	0	313	65	2327	1324	1053	17	19	3	52	66
2035	1289	224	553	511	224	0	17%	176	1230	2675	1118	0	360	52	2151	1446	1107	26	22	4	53	72
2040	1355	244	582	529	244	0	18%	192	1422	2995	835	0	412	37	1959	1574	1164	43	28	5	54	80
2045	1424	265	612	548	265	0	19%	209	1630	3338	530	0	468	19	1751	1708	1223	61	34	6	55	89
2050	1497	287	643	567	287	0	19%	226	1856	3706	203	0	529	-1	1525	1849	1286	81	41	7	56	98
2055	1574	310	676	588	310	0	20%	245	2101	4099	-148	0	595	-25	1280	1998	1352	103	48	8	57	109
2060	1654	334	711	610	334	0	20%	264	2365	4519	-524	0	666	-52	1016	2154	1421	123	54	9	58	119
2065	1739	359	747	633	359	0	21%	285	2650	4968	-925	0	743	-82	731	2318	1494	144	61	10	59	130
2070	1828	386	785	657	386	0	21%	306	2956	5446	-1355	0	825	-115	425	2490	1571	168	69	11	60	143
									TOTAL U308 USED FOR LMFRs->			0										

TABLE C-12 Projections Calculated for Domestic Scenario 12 Using the Stated Assumptions

PSHEET12 SCENARIO NO. 12 REVISED 10/10/86

ELEC GROWTH RATE 2000-2025 (EGR1) -> 2.5% 2025 2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 4.7% 2025-2065 ----------> 2.0%
NUCLEAR % NEW GEN. 2000-2025(NGR1)--> 30% 2025-2065 (NGR2) ---> 30.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.1% 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U308 FOR (UL) -------> 30 YEARS INTO THE FUTURE
U308 FOR NEW CORE (NC) ------------> 326 STD TONS CAPACITY FACTOR ----> 70%
ANNUAL U308 PER 1000 MW (REPC) ----> 165 STD TONS TAILS ASSAY --------> 0.20 %
U308 RESOURCES (U308) ------------------------------> 3381 STD. TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFRDEPLOYMENT SCENARIO-> NO LMFRs
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U308 NEEDED TO START 1000MWLMFR(UNEEDED) 1136 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL NO LMFRs

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP -> 2039
YEAR ALL U308 < $100/LB USED UP-> 2054
YEAR ALL U308 < $100/LB COMMITTED 2031
YEAR ALL U308+EQU308 COMMITTED -> 2036
CAPITAL COST OF LWR PER KW -----> $1500
CAPITAL COST OF LWR MILLS/KWH --> 44.0
U308 RESOURCES BELOW $100/LB ---> 3381 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $13.67 MILLIONS
COST OF U308 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTCN COST 10.2 BILLION DOLLARS

NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	400	3092	0	91	19	3365	304	540	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	818	2714	0	110	42	3090	520	780	17	19	3	52	35
2005	1029	146	433	449	146	0	14%	103	394	1095	2488	0	135	67	2987	701	866	17	19	3	52	47
2010	1166	187	481	497	187	0	16%	135	528	1427	2213	0	169	90	2853	899	962	17	19	3	52	60
2015	1321	234	534	553	234	0	18%	170	699	1821	1883	0	212	111	2682	1122	1069	17	19	3	52	75
2020	1497	297	594	617	287	0	19%	211	910	2285	1492	0	265	130	2471	1375	1187	17	19	3	52	92
2025	1696	347	659	691	347	0	20%	257	1166	2828	1031	0	331	147	2215	1662	1319	20	20	3	52	111
2030	1828	386	732	710	386	0	21%	300	1466	3318	596	0	411	122	1915	1852	1465	47	29	5	54	127
2035	1971	429	813	729	429	0	22%	333	1799	3856	117	0	500	92	1582	2057	1627	76	39	6	55	146
2040	2124	475	903	746	475	0	22%	370	2169	4447	-411	0	599	57	1212	2270	1807	108	49	8	57	166
2045	2290	525	1003	762	525	0	23%	409	2578	5094	-989	0	708	16	803	2516	2007	139	60	10	59	189
2050	2468	578	1114	776	578	0	23%	451	3030	5802	-1623	0	828	-31	351	2772	2229	173	71	12	61	215
2055	2660	636	1238	787	636	0	24%	497	3527	6576	-2318	0	961	-84	-146	3049	2476	209	83	13	63	244
2060	2868	698	1375	795	698	0	24%	546	4073	7420	-3076	0	1108	-144	-692	3347	2750	241	93	15	64	275
2065	3091	765	1527	799	765	0	25%	599	4672	8341	-3904	0	1268	-213	-1291	3668	3054	276	105	17	66	310

TOTAL U308 USED FOR LMFRs-> 0

TABLE C-13 Projections Calculated for Domestic Scenario 13 Using the Stated Assumptions

PSHEET13 SCENARIO NO. 13 REVISED 10/10/86

ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.5% | 2025-2065 (EGR2) ---> 1.5%
NUCLEAR GROWTH RATE 2000-2025 -----> 4.7% | 2025-2065 ----------> 2.0%
NUCLEAR % NEW GEN.2000-2025(NGR1)--> 30% | 2025-2065 (NGR2) ---> 30.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) ----------> 2.1% | 2025-2065 (CGR2) ---> 2.1%
COMMITMENT OF U308 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U308 FOR NEW CORE (NC) -----------> 326 STD TONS | CAPACITY FACTOR ----> 70%
ANNUAL U308 PER 1000 MW (REPC) ---> 165 STD TONS | TAILS ASSAY --------> 0.20%
U308 RESOURCES (U308) ---------------------------> 3301 STD.TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> NO LMFRs
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U308 NEEDED TO START 1000MWLMFR(UNEEDED) 1136 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL NO LMFRs

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP -> 2039
YEAR ALL U308 < $100/LB USED UP-> 2054
YEAR ALL U308 < $100/LB COMMITTED 2018
YEAR ALL U308+EQU308 COMMITTED -> 2023
CAPITAL COST OF LWR PER KW -----> $ 1500
CAPITAL COST OF LWR MILLS/KWH---> 44.0
U308 RESOURCES BELOW $100/LB ---> 3301 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS
COST OF U308 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST 10.2 BILLION DOLLARS

NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	797	2805	0	91	130	3365	781	540	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	1364	2320	0	110	194	3090	1073	780	17	19	3	52	35
2005	1029	146	433	449	146	0	14%	103	394	1821	1964	0	135	269	2987	1427	866	17	19	3	52	47
2010	1166	187	481	497	187	0	16%	135	528	2357	1542	0	169	349	2853	1828	962	17	19	3	52	60
2015	1321	234	534	553	234	0	18%	170	699	2981	1045	0	212	434	2682	2283	1069	17	19	3	52	75
2020	1497	287	594	617	287	0	19%	211	910	3707	465	0	265	526	2471	2797	1187	17	19	3	52	92
2025	1696	347	659	691	347	0	20%	257	1166	4547	-210	0	331	625	2215	3301	1319	20	20	3	52	111
2030	1828	386	732	710	386	0	21%	300	1466	5234	-787	0	411	655	1915	3768	1465	47	29	5	54	127
2035	1971	429	813	729	429	0	22%	333	1799	5994	-1419	0	500	684	1502	4185	1627	76	39	6	55	146
2040	2124	475	903	746	475	0	22%	370	2169	6803	-2111	0	599	712	1212	4634	1807	108	49	8	57	166
2045	2290	525	1003	762	525	0	23%	409	2578	7697	-2868	0	708	740	803	5110	2007	139	60	10	59	189
2050	2468	578	1114	776	578	0	23%	451	3030	8670	-3694	0	828	767	351	5640	2229	173	71	12	61	215
2055	2660	636	1238	787	636	0	24%	497	3527	9730	-4594	0	961	793	-146	6203	2476	209	83	13	63	244
2060	2868	698	1375	795	698	0	24%	546	4073	10883	-5575	0	1108	819	-692	6809	2750	241	93	15	64	275
2065	3091	765	1527	799	765	0	25%	599	4672	12136	-6643	0	1268	843	-1291	7463	3054	276	105	17	66	310

TOTAL U308 USED FOR LMFRs-> 0

TABLE C-14 Projections Calculated for Domestic Scenario 14 Using the Stated Assumptions

PSHEET14 SCENARIO NO. 14 REVISED 10/10/86

ELEC.GROWTH RATE 2000-2025 (EGR1) ->	2.0%	2025-2065 (EGR2) --->	1.0%
NUCLEAR GROWTH RATE 2000-2025 ----->	3.9%	2025-2065 ---------->	1.4%
NUCLEAR % NEW GEN.2000-2025(NGR1)-->	30%	2025-2065 (NGR2) --->	30.0%
COAL USE PERMITTED AS % OF 1986 --->	2500%		
COAL GROWTH RATE (CGR1) ----------->	2.0%	2025-2065 (CGR2) --->	1.0%
COMMITMENT OF U308 FOR (UL) ------->	40 YEARS INTO THE FUTURE		
U308 FOR NEW CORE (NC) ------------>	326 STD TONS	CAPACITY FACTOR ---->	70%
ANNUAL U308 PER 1000 MW (PEPC) ---->	165 STD TONS	TAILS ASSAY -------->	0.20 %

U308 RESOURCES (U308) ------------------------------> 3381 STD.TONS
TONS U308 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> FAST FIRST COMMERCIAL LMFR IN ----> 2020
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U308 NEEDED TO START 1000MW LMFR(NEEDED) 1136 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL 2065 IN YEAR 2020

U308 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U308 < $50/LB USED UP ->	2045
YEAR ALL U308 < $100/LB USED UP->	2067
YEAR ALL U308 < $100/LB COMMITTED	2035
YEAR ALL U308+EQU308 COMMITTED ->	2043
CAPITAL COST OF LWR PER KW ----->	$ 1500
CAPITAL COST OF LWR MILLS/KWH -->	44.0
U308 RESOURCES BELOW $100/LB --->	3381 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB ---->	2066 THOUSAND STD TONS
U308 RESOURCES BELOW $30/LB ---->	1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ---->	$ 13.67 MILLIONS
COST OF U308 PER POUND (NOW)---->	$ 17

LMFR % OF NEW NUCLEAR GENERATION 50%

OPERATING & MAINTENANCE 5 MILLS/KWH
FUEL COST, U308 @ 180 9.7 MILLS/KWH

PREMIUM FOR U308 > $ 180 PER LB:
DISCOUNT RATE 4%
EXTRA COST IN 2065: 1.5 BILLION DOLLARS

NOTE:ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U308 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1995	705	80	274	351	80	0	11%	16	16	532	2996	0	91	56	3365	516	548	17	19	3	52	26
2000	909	110	390	408	110	0	12%	275	291	1000	2583	0	110	93	3090	709	780	17	19	3	52	35
2005	1003	139	431	434	139	0	14%	100	391	1206	2351	0	135	130	2990	894	862	17	19	3	52	44
2010	1109	170	476	462	170	0	15%	125	516	1615	2080	0	167	147	2865	1098	953	17	19	3	52	54
2015	1225	205	526	494	205	0	17%	152	669	1993	1766	0	206	172	2712	1324	1053	17	19	3	52	66
2020	1255	244	582	529	240	4	18%	186	854	2403	1420	4	253	189	2527	1549	1164	17	19	3	52	77
2025	1497	287	643	567	261	25	19%	230	1084	2771	1091	24	308	173	2297	1686	1286	17	19	3	52	84
2030	1574	310	676	588	273	37	20%	233	1317	3078	805	13	369	134	2064	1761	1352	34	25	4	53	89
2035	1654	334	711	610	285	49	20%	243	1561	3400	906	14	431	93	1820	1839	1421	55	32	5	54	95
2040	1739	359	747	633	298	62	21%	254	1815	3736	193	14	497	51	1566	1921	1494	78	39	6	55	101
2045	1823	386	785	657	311	75	21%	266	2081	4088	-135	15	565	7	1300	2007	1571	101	47	8	57	109
2050	1922	414	826	682	325	89	22%	278	2359	4457	-477	16	637	-39	1022	2098	1651	122	54	9	58	115
2055	2021	444	868	709	340	104	22%	291	2650	4843	-836	17	712	-86	731	2193	1736	144	61	10	59	123
2060	2124	475	912	737	356	119	22%	304	2954	5247	-1212	18	790	-136	427	2293	1825	168	69	11	60	131
2065	2233	508	959	766	372	136	23%	318	3272	5670	-1605	19	872	-187	109	2399	1918	192	77	13	62	140
2070	2348	542	1008	797	389	153	23%	333	3604	6114	-2017	20	957	-241	-223	2510	2017	213	84	14	63	150
									TOTAL U308 USED FOR LMFRs-->			174										

TABLE C-15A Projections Calculated for Domestic Scenario 15A Using the Stated Assumptions

PSWEE115A	SCENARIO NO. 15A	REVISED 10/10/86		U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL		
ELEC.GROWTH RATE 2000-2025 (EGR1) ->	2.0%	2025-2065 (EGR2) --->	1.0%		OPERATING & MAINTENANCE	5 MILLS/KWH
NUCLEAR GROWTH RATE 2000-2025 ----->	3.9%	2025-2065 ---------->	2.0%	YEAR ALL U3O8 < $50/LB USED UP -> 2045	FUEL COST, U3O8 @ 180	9.7 MILLS/KWH
NUCLEAR % NEW GEN.2000-2025(NGR1)-->	30%	2025-2065 (NGR2) --->	30.0%	YEAR ALL U3O8 < $100/LB USED UP-> 2065		
COAL USE PERMITTED AS % OF 1986 --->	300%COAL LIMITED,ENTER NUCLEAR % NEW GEN		67%	YEAR ALL U3O8 < $100/LB COMMITTED 2035	PREMIUM FOR U3O8 >	$ 180 PER LB:
COAL GROWTH RATE (CGR1) ----------->	2.0%	2025-2065 (CGR2) --->	1.0%	YEAR ALL U3O8+EQU3O8 COMMITTED -> 2043	DISCOUNT RATE	4%
COMMITMENT OF U3O8 FOR (UL) ------->	40 YEARS INTO THE FUTURE			CAPITAL COST OF LWR PER KW -----> $ 1500	EXTRA COST	1.5 BILLION DOLLARS
U3O8 FOR NEW CORE (NC) ----------->	326 STD TONS	CAPACITY FACTOR ---->	70%	CAPITAL COST OF LWR MILLS/KWH --> 44.0		
ANNUAL U3O8 PER 1000 MW (PEPC) ---->	165 STD TONS	TAILS ASSAY --------->	0.20 %	U3O8 RESOURCES BELOW $100/LB ---> 3381 THOUSAND STD TONS		
U3O8 RESOURCES (U3U8) ---------------------------------->	3381	STD.TONS		U3O8 RESOURCES BELOW $50/LB ---> 2066 THOUSAND STD TONS		
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8)	46	STD TONS		U3O8 RESOURCES BELOW $30/LB ---> 1127 THOUSAND STD TONS		
LMFR DEPLOYMENT SCENARIO-> FAST	FIRST COMMERCIAL LMFR IN ---->	2020		CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS		
IF LMFR DEPLOYMENT IS FAST ENTER 1------>	1			COST OF U3O8 PER POUND (NOW)----> $ 17		
U3O8 NEEDED TO START 1000MW LMFR(NEEDED)	1136 STD TONS					
U3O8 COMMITTED FOR ALL LMFRs UNTIL 2065	IN YEAR	2020		LMFR % OF NEW NUCLEAR GENERATION 50%		

NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	15	532	2996	0	91	56	3365	516	548	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	1000	2583	0	110	93	3090	709	780	17	19	3	52	35
2005	1003	139	431	434	139	0	14%	100	391	1286	2351	0	135	120	2990	894	862	17	19	3	52	44
2010	1109	170	476	462	170	0	15%	125	516	1615	2080	0	167	147	2865	1098	953	17	19	3	52	54
2015	1226	205	526	494	205	0	17%	152	669	1993	1766	0	206	172	2712	1324	1053	17	19	3	52	66
2020	1355	244	582	529	240	4	18%	186	854	2403	1420	4	253	189	2527	1549	1164	17	19	3	52	77
2025	1497	287	643	567	261	25	19%	230	1064	2771	1091	24	308	173	2297	1686	1286	17	19	3	52	84
2030	1574	310	676	588	273	37	20%	233	1317	3078	805	13	369	134	2064	1761	1352	34	25	4	53	89
2035	1654	334	711	610	285	49	20%	243	1561	3400	506	14	431	93	1820	1839	1421	55	32	5	54	95
2040	1739	359	747	633	298	62	21%	254	1815	3735	193	14	497	51	1566	1921	1494	78	39	6	55	101
2045	1828	386	785	657	311	75	21%	266	2081	4088	-135	15	565	7	1300	2007	1571	101	47	8	57	108
2050	1922	414	822	686	325	89	22%	278	2359	4457	-477	16	637	-39	1022	2098	1644	122	54	9	58	115
2055	2021	480	822	719	358	122	24%	317	2676	4986	-946	37	712	-53	705	2310	1644	146	62	10	59	130
2060	2124	549	822	753	393	156	26%	347	3023	5555	-1452	39	794	-72	358	2532	1644	173	71	12	61	146
2065	2233	622	822	790	429	193	28%	378	3401	6167	-1997	41	884	-95	-20	2767	1644	201	80	13	62	163
									TOTAL U3O8 USED FOR LMFRs->			219										

TABLE C-17 Projections Calculated for Domestic Scenario 17 Using the Stated Assumptions

PSHEET17 SCENARIO NO. 17 REVISED 10/10/86

ELEC. GROWTH RATE 2000-2025 (EGR1) -> 2.0% 2025-2065 (EGR2) ---> 1.0%
NUCLEAR GROWTH RATE 2000-2025 -----> 3.9% 2025-2065 -----------> 1.4%
NUCLEAR % NEW GEN. 2000-2025(NGR1)--> 30% 2025-2065 (NGR2) ---> 30.0%
COAL USE PERMITTED AS % OF 1986 ---> 2500%
COAL GROWTH RATE (CGR1) -----------> 2.0% 2025-2065 (CGR2) ---> 1.0%
COMMITMENT OF U3O8 FOR (UL) -------> 60 YEARS INTO THE FUTURE
U3O8 FOR NEW CORE (NC) ------------> 326 STD TONS CAPACITY FACTOR ----> 70%
ANNUAL U3O8 PER 1000 MW (REPC) ----> 165 STD TONS TAILS ASSAY --------> 0.20%
U3O8 RESOURCES (U309) ------------------------------> 3381 STD. TONS
TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU308) 46 STD TONS
LMFR DEPLOYMENT SCENARIO-> NO LMFRs
IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1
U3O8 NEEDED TO START 1000MW LMFR(LNEEDED) 1136 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL NO LMFRs

U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL
YEAR ALL U3O8 < $50/LB USED UP -> 2043
YEAR ALL U3O8 < $100/LB USED UP-> 2062
YEAR ALL U3O8 < $100/LB COMMITTED 2021
YEAR ALL U3O8+EQU308 COMMITTED -> 2029
CAPITAL COST OF LWR PER KW -----> $ 1500
CAPITAL COST OF LWR MILLS/KWH ---> 44.0
U3O8 RESOURCES BELOW $100/LB ----> 3381 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS
U3O8 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS
CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS
COST OF U3O8 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 8 MILLS/KWH
FUEL COST, U3O8 @ 180 9.7 MILLS/KWH

PREMIUM FOR U3O8 > $ 100 PER LB:
DISCOUNT RATE 4%
EXTRA COST 1.5 BILLION DOLLARS

NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU308 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL. TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS/KWH	C.O.E. / LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	797	2805	0	91	130	3365	781	548	17	19	3	52	26
2000	908	110	390	408	110	0	12%	275	291	1364	2320	0	110	194	3090	1073	780	17	19	3	52	35
2005	1003	139	431	434	139	0	14%	100	391	1744	2020	0	135	248	2990	1353	862	17	19	3	52	44
2010	1109	170	476	462	170	0	15%	125	516	2178	1673	0	167	303	2865	1642	953	17	19	3	52	54
2015	1226	205	526	494	205	0	17%	152	669	2672	1276	0	206	361	2712	2003	1053	17	19	5	52	66
2020	1355	244	582	529	244	0	18%	183	851	3232	823	0	253	420	2530	2380	1164	17	19	3	52	78
2025	1497	287	643	567	287	0	19%	216	1067	3865	308	0	329	482	2314	2797	1286	17	19	3	52	92
2030	1574	310	676	588	310	0	20%	245	1312	4334	-99	0	375	480	2069	3022	1352	39	25	4	53	101
2035	1654	334	711	610	334	0	22%	264	1576	4834	-532	0	446	475	1805	3258	1421	57	32	5	54	111
2040	1739	359	747	633	359	0	21%	285	1861	5367	-994	0	523	469	1520	3507	1494	82	41	7	56	123
2045	1828	386	785	657	386	0	21%	306	2167	5934	-1488	0	636	460	1214	3768	1571	108	49	8	57	135
2050	1922	414	826	682	414	0	22%	329	2495	6537	-2013	0	695	449	886	4042	1651	133	58	9	58	148
2055	2021	444	868	709	444	0	22%	352	2848	7178	-2572	0	790	435	533	4331	1736	159	66	11	60	163
2060	2124	475	912	737	475	0	22%	377	3225	7859	-3167	0	832	419	156	4634	1825	188	76	12	61	179
2065	2233	508	959	764	508	0	23%	404	3628	8581	-3799	0	1001	400	-247	4953	1918	218	85	14	63	196
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-18 Projections Calculated for Domestic Scenario 18 Using the Stated Assumptions

PSHEET18 SCENARIO NO. 18

ELEC.GROWTH RATE 2000-2025 (EGR1) -> 2.0%

NUCLEAR GROWTH RATE 2000-2025 ----> 3.9%

NUCLEAR % NEW GEN.2000-2025(NGR1)--> 30%

COAL USE PERMITTED AS % OF 1986 ---> 2500%

COAL GROWTH RATE (CGR1) ----------> 2.0%

COMMITMENT OF U3O8 FOR (UL) -------> 40 YEARS INTO THE FUTURE

U3O8 FOR NEW CORE (NC) ------------> 326 STD TONS

ANNUAL U3O8 PER 1000 MW (REPC) ----> 165 STD TONS

U3O8 RESOURCES (U3O8) ------------------------------> 3301 STD.TONS

TONS U3O8 SAVED PER YEAR BY U & Pu RECYCLE(EQU3O8) 46 STD TONS

LMFR DEPLOYMENT SCENARIO-> NO LMFRs

IF LMFR DEPLOYMENT IS FAST ENTER 1------> 1

U3O8 NEEDED TO START 1000MW LMFR (NEEDED) 1136 STD TONS

U3O8 COMMITTED FOR ALL LMFRs UNTIL NO LMFRs

REVISED 10/10/86

2025-2065 (EGR2) ---> 1.0%

2025-2065 ----------> 1.4%

2025-2065 (NGR2) ---> 30.0%

2025-2065 (CGR2) ---> 1.0%

CAPACITY FACTOR ---> 70%

TAILS ASSAY --------> 0.20 %

U3O8 RESOURCES ARE AT 50% CONFIDENCE LEVEL

YEAR ALL U3O8 < $50/LB USED UP -> 2043

YEAR ALL U3O8 < $100/LB USED UP-> 2062

YEAR ALL U3O8 < $100/LB COMMITTED 2031

YEAR ALL U3O8+EQU3O8 COMMITTED -> 2030

CAPITAL COST OF LWR PER KW -----> $ 1500

CAPITAL COST OF LWR MILLS/KWH--> 44.0

U3O8 RESOURCES BELOW $100/LB ---> 3301 THOUSAND STD TONS

U3O8 RESOURCES BELOW $50/LB ----> 2066 THOUSAND STD TONS

U3O8 RESOURCES BELOW $30/LB ----> 1127 THOUSAND STD TONS

CONV.,ENRICH, FAB/GW RELOAD ----> $ 13.67 MILLIONS

COST OF U3O8 PER POUND (NOW)----> $ 17

LMFR % OF NEW NUCLEAR GENERATION 0%

OPERATING & MAINTENANCE 5 MILLS/KWH

FUEL COST, U3O8 @ 180 9.7 MILLS/KWH

PREMIUM FOR U3O8 > $ 100 PER LB:

DISCOUNT RATE 4%

EXTRA COST 1.5 BILLION DOLLARS

NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GWe	GW NUCLEAR	GW COAL	GW OTHER	GW LWR	GW LMFR	TOTAL % N	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs IN PERIOD	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	COAL BURNED PER YEAR MIL.TONS	PRICE U3O8 $/LB	COST REPL. CORE MILLIONS	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	705	80	274	351	80	0	11%	16	16	532	2996	0	91	56	3365	516	540	17	19	3	52	36
2000	908	110	390	408	110	0	12%	275	291	1000	2583	0	110	93	3090	709	700	17	19	3	52	35
2005	1003	139	431	434	139	0	14%	100	391	1286	2351	0	135	120	2990	894	862	17	19	3	52	44
2010	1109	170	476	462	170	0	15%	125	516	1615	2080	0	167	147	2865	1090	953	17	19	3	52	54
2015	1226	205	526	494	205	0	17%	152	669	1993	1766	0	206	172	2712	1324	1053	17	19	3	52	66
2020	1355	244	582	529	244	0	18%	183	851	2425	1405	0	253	196	2530	1574	1164	17	19	3	52	78
2025	1497	287	643	567	287	0	19%	216	1067	2916	992	0	309	218	2314	1849	1286	17	19	3	52	92
2030	1574	310	676	580	310	0	20%	245	1312	3310	641	0	375	196	2069	1990	1352	33	25	4	53	101
2035	1654	334	711	610	334	0	20%	264	1576	3730	266	0	446	160	1805	2154	1421	57	32	5	54	111
2040	1739	359	747	633	359	0	21%	285	1861	4179	-136	0	523	138	1520	2318	1494	82	41	7	56	129
2045	1828	386	786	657	386	0	21%	306	2167	4657	-566	0	606	105	1214	2490	1571	108	49	8	57	135
2050	1922	414	826	682	414	0	22%	329	2495	5167	-1024	0	695	67	886	2672	1651	133	58	9	58	148
2055	2021	444	868	705	444	0	22%	352	2848	5710	-1512	0	790	27	538	2863	1736	159	66	11	60	163
2060	2124	475	912	737	475	0	22%	377	3225	6208	-2033	0	892	-18	156	3063	1825	188	76	12	61	179
2065	2233	508	959	766	508	0	23%	404	3620	6902	-2587	0	1001	-67	-247	3274	1918	215	85	14	63	196
									TOTAL U3O8 USED FOR LMFRs->			0										

TABLE C-30 Projections Calculated for International Scenario 30 Using the Stated Assumptions

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PSHEET30                                     SCENARIO NO.   30      REVISED   10/26/86           U3O8 RESOURCES ARE AT MEAN (MOST LIKELY) IMEA LEVEL
U.S. NUCLEAR GROWTH RATE (N.G.R.), 2000-2025:      2.7%     2025-2100 ----------->   1.8%
N.G.R., WORLD - CENT. PLANNED EC.'S, 2000-2025:    2.7%     2025-2100 ----------->   1.8%    YEAR ALL U3O8 <$50/LB USED :            2086
WORLD LESS U.S.& CENTRALLY PLANNED ECONOMIES:      2.7%     2025-2100 ----------->   1.8%    YEAR ALL U3O8 <$100/LB USED:            2092
U.S.ELECTRIC GROWTH RATE 2000-2025 (EGR1):         1.0%     2025-2100 (EGR2) --->    1.0%    YEAR ALL U3O8 <$100/LB COMM.:           2052
                                                                                             YEAR $100/LB U3O8+EDU3O8 COMM.:         2059
PERIOD OF COMMITMENT FOR U3O8 (UL):                 60 YEARS                                 CAPITAL COST OF LWR PER KW :           $1800
U3O8 FOR NEW CORE (NC):                            373 TONS     CAPACITY FACTOR --->  80%    CAPITAL COST OF LWR(MILLS/KWH) :          39
ANNUAL U3O8 RELOAD PER 1000 MW (REPC):             189 TONS     TAILS ASSAY ------>  0.20%   U3O8 RESOURCES BELOW $100/LB :        22800 THOUSAND STD TONS
U3O8 SAVED/YR BY U & Pu RECYCLE (EDU3O8):           46 STD TONS/GW                           U3O8 RESOURCES BELOW $50/LB :         19800 THOUSAND STD TONS
ENTER 1 IF LMFR DEPLOYMENT IS FAST:                  0                                       CONV,ENRICH,FAB COST/GW RELOAD :      $13.7 MILLIONS
LMFR DEPLOYMENT SCENARIO:                      (NO LMFRs),                                   COST OF U3O8 PER POUND (NOW) :          $17
YEAR OF FIRST COMMERCIAL LMFR:                 (NO LMFRs)                                    OPERATING AND MAINTENANCE COST:            5 MILLS/KWH
U3O8 NEEDED TO START 1000MW LMFR:                 1298 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL:            (NO LMFRs)
LMFR PERCENT OF NEW NUCLEAR GENERATION:             0%
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NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GW NUCLEAR U.S.	GW NUCLEAR OUTSIDE U.S.	GW NUCLEAR TOTAL	GW LWR	GW LMFR	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EDU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs CUM.	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	PRICE U3O8 DOLLARS PER LB	COST REPL. CORE (MILLIONS)	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	80	147	227	227	0	43	43	2574	20852	0	182	445	22757	2531	17	20	3	46	74
2000	110	288	398	398	0	842	884	5321	18577	0	234	864	21916	4436	17	20	3	46	129
2005	129	329	458	458	0	404	1289	6397	17667	0	326	939	21511	5108	17	20	3	46	149
2010	148	377	525	525	0	465	1753	7611	16639	0	431	1019	21047	5857	17	20	3	46	171
2015	169	432	600	600	0	532	2285	8980	15477	0	552	1105	20515	6694	17	20	3	46	195
2020	190	494	684	684	0	607	2892	10524	14165	0	690	1199	19908	7631	17	20	3	46	223
2025	213	565	779	779	0	691	3584	12265	12684	0	847	1304	19216	8681	17	20	3	46	253
2030	237	619	856	856	0	772	4356	13897	11265	0	1026	1336	18444	9541	17	20	3	46	278
2035	262	677	939	939	0	848	5204	15675	9717	0	1223	1369	17596	10471	17	20	3	46	305
2040	289	741	1029	1029	0	930	6134	17610	8030	0	1439	1401	16666	11477	17	20	3	46	335
2045	316	810	1127	1127	0	1019	7152	19717	6193	0	1676	1434	15648	12564	20	21	3	47	368
2050	346	887	1232	1232	0	1115	8267	22008	4193	0	1936	1466	14533	13741	27	24	3	47	406
2055	376	970	1346	1346	0	1218	9485	24500	2016	0	2218	1498	13315	15014	35	27	4	47	447
2060	409	1061	1470	1470	0	1331	10816	27209	-352	0	2528	1529	11984	16398	44	30	4	48	493
2065	443	1161	1604	1604	0	1452	12269	30155	-2928	0	2866	1561	10531	17886	53	34	5	48	543
2070	485	1271	1756	1756	0	1588	13856	33438	-5792	0	3235	1612	8944	19582	63	37	5	49	601
2075	532	1391	1923	1923	0	1738	15595	37033	-8927	0	3639	1667	7208	21439	74	41	6	49	666
2080	583	1521	2105	2105	0	1903	17498	40969	-12360	0	4081	1728	5302	23472	86	46	7	50	739
2085	640	1665	2305	2305	0	2083	19581	45279	-16118	0	4568	1798	3219	25698	99	51	7	51	820
2090	702	1822	2523	2523	0	2281	21862	49996	-20233	0	5096	1868	938	28134	169	77	11	55	968
2095	769	1993	2762	2762	0	2497	24359	55162	-24738	0	5676	1948	-1599	30802	214	94	13	57	1108
2100	843	2181	3024	3024	0	2734	27093	60817	-29670	0	6311	2036	-4298	33729	238	104	15	58	1236

TABLE C-31 Projections Calculated for International Scenario 31 Using the Stated Assumptions

PSHEET31	SCENARIO NO. 31	REVISED 10/26/86		U3O8 RESOURCES ARE AT MEAN (MOST LIKELY) IAEA LEVEL	
U.S. NUCLEAR GROWTH RATE (N.G.R.), 2000-2025:	2.7%	2025-2100 ------------>	1.8%		
N.G.R., WORLD - CENT. PLANNED EC.'S, 2000-2025:	5.1%	2025-2100 ------------>	2.6%	YEAR ALL U3O8 <$50/LB USED :	2060
WORLD LESS U.S.& CENTRALLY PLANNED ECONOMIES:	5.6%	2025-2100 ------------>	2.7%	YEAR ALL U3O8 <$100/LB USED:	2065
U.S.ELECTRIC GROWTH RATE 2000-2025 (EGR1):	1.0%	2025-2100 (EGR2) --->	1.0%	YEAR ALL U3O8 <$100/LB COMM.:	2029
				YEAR $100/LB U3O8+EQU3O8 COMM.:	2035
PERIOD OF COMMITMENT FOR U3O8 (UL):	60 YEARS			CAPITAL COST OF LWR PER KW :	$1500
U3O8 FOR NEW CORE (NC):	373 TONS	CAPACITY FACTOR ---->	80%	CAPITAL COST OF LWR (MILLS/KWH):	39
ANNUAL U3O8 RELOAD PER 1000 MW (REPC):	189 TONS	TAILS ASSAY ------------>	0.20%	U3O8 RESOURCES BELOW $100/LB :	22800 THOUSAND STD TONS
U3O8 SAVED/YR BY U & Pu RECYCLE (EQU3O8):	46 STD TONS/GW			U3O8 RESOURCES BELOW $50/LB :	19800 THOUSAND STD TONS
ENTER 1 IF LMFR DEPLOYMENT IS FAST:	0			CONV,ENRICH,FAB COST/GW RELOAD :	$13.7 MILLIONS
LMFR DEPLOYMENT SCENARIO:	(NO LMFRs)			COST OF U3O8 PER POUND (NOW) :	$17
YEAR OF FIRST COMMERCIAL LMFR:	(NO LMFRs)			OPERATING AND MAINTENANCE COST:	5 MILLS/KWH
U3O8 NEEDED TO START 1000MW LMFR:	1298 STD TONS				
U3O8 COMMITTED FOR ALL LMFRs UNTIL:	(NO LMFRs)				
LMFR PERCENT OF NEW NUCLEAR GENERATION:	0%				

NOTE:ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GW NUCLEAR U.S.	GW NUCLEAR OUTSIDE U.S.	GW NUCLEAR TOTAL	GW LWR	GW LMFR	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs CUM.	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	PRICE U3O8 DOLLARS PER LB	COST REPL. CORE (MILLIONS)	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	80	147	227	227	0	43	43	2574	20852	0	182	445	22757	2531	17	20	3	46	74
2000	110	288	398	398	0	842	884	5321	18577	0	234	864	21916	4436	17	20	3	46	129
2005	129	381	509	509	0	429	1313	6994	17212	0	326	1080	21487	5601	17	20	3	46	166
2010	148	504	652	652	0	549	1862	9134	15466	0	443	1357	20938	7272	17	20	3	46	212
2015	169	667	836	836	0	703	2565	11882	13224	0	593	1713	20235	9317	17	20	3	46	272
2020	190	882	1073	1073	0	902	3467	15427	10333	0	785	2175	19333	11961	17	20	3	46	349
2025	213	1167	1380	1380	0	1159	4626	20019	6591	0	1032	2778	18174	15393	17	20	3	46	449
2030	237	1336	1573	1573	0	1396	6021	23562	3579	0	1349	2992	16779	17541	17	20	3	46	511
2035	262	1529	1791	1791	0	1590	7611	27586	158	0	1711	3233	15109	19975	30	25	4	47	891
2040	289	1750	2039	2039	0	1810	9420	32154	-3728	0	2123	3504	13880	22734	52	34	5	48	690
2045	316	2003	2319	2319	0	2059	11480	37344	-8142	0	2592	3810	11320	25864	48	32	5	48	781
2050	346	2293	2638	2638	0	2342	13822	43241	-13159	0	3125	4156	8978	29419	62	37	5	49	903
2055	376	2624	3000	3000	0	2664	16486	49942	-18862	0	3732	4548	6314	33496	79	44	6	50	1046
2060	409	3003	3412	3412	0	3030	19516	57561	-25344	0	4422	4994	3284	38045	98	51	7	51	1214
2065	443	3437	3880	3880	0	3445	22961	66225	-32717	0	5207	5501	-161	43264	201	90	13	56	1532
2070	485	3934	4419	4419	0	3921	26883	76163	-41165	0	6099	6098	-4083	49280	236	103	15	58	1802
2075	532	4503	5035	5035	0	4467	31350	87493	-50797	0	7116	6780	-8850	56143	275	118	17	60	2128
2080	583	5154	5737	5737	0	5090	36439	100412	-61778	0	8274	7560	-13639	63973	320	134	19	63	2522
2085	640	5898	6538	6538	0	5800	42239	115146	-74301	0	9593	8452	-19439	72907	371	154	22	65	2999
2090	702	6751	7452	7452	0	6611	48850	131952	-88583	0	11097	9472	-26050	83102	429	176	25	69	3582
2095	769	7727	8496	8496	0	7536	56385	151123	-104874	0	12811	10638	-33585	94738	495	201	29	72	4296
2100	843	8843	9687	9687	0	8591	64977	172996	-123460	0	14765	11971	-42177	108019	570	229	33	76	6174

TABLE C-32 Projections Calculated for International Scenario 32 Using the Stated Assumptions

PSHEET32 SCENARIO NO. 32 REVISED 10/26/86

U308 RESOURCES ARE AT MEAN (MOST LIKELY) IAEA LEVEL

U.S. NUCLEAR GROWTH RATE (N.G.R.), 2000-2025: 5.6% 2025-2100 ----------> 2.7%
N.G.R., WORLD - CENT. PLANNED EC.'S, 2000-2025: 5.7% 2025-2100 ----------> 2.7%
WORLD LESS U.S.& CENTRALLY PLANNED ECONOMIES: 5.6% 2025-2100 ----------> 2.7%
U.S.ELECTRIC GROWTH RATE 2000-2025 (EGR1): 2.5% 2025-2100 (EGR2) ---> 1.5%

PERIOD OF COMMITMENT FOR U308 (LE): 60 YEARS
U308 FOR NEW CORE (NC): 373 TONS CAPACITY FACTOR ----> 80%
ANNUAL U308 RELOAD PER 1000 MW (REPC): 189 TONS TAILS ASSAY --------> 0.20 %
U308 SAVED/YR BY U & Pu RECYCLE (EQU308): 46 STD TONS/GW
ENTER 1 IF LMFR DEPLOYMENT IS FAST: 0
LMFR DEPLOYMENT SCENARIO: (NO LMFRs)
YEAR OF FIRST COMMERCIAL LMFR: (NO LMFRs)
U308 NEEDED TO START 1000MW LMFR: 1298 STD TONS
U308 COMMITTED FOR ALL LMFRs UNTIL: (NO LMFRs)
LMFR PERCENT OF NEW NUCLEAR GENERATION: 0%

YEAR ALL U308 <$50/LB USED : 2086
YEAR ALL U308 <$100/LB USED: 2060
YEAR ALL U308 <$100/LB COMM.: 2025
YEAR $100/LB U308+EQU308 COMM.: 2031
CAPITAL COST OF LWR PER KW : $1500
CAPITAL COST OF LWR (MILLS/KWH): 39
U308 RESOURCES BELOW $100/LB : 22800 THOUSAND STD TONS
U308 RESOURCES BELOW $50/LB : 19800 THOUSAND STD TONS
CONV,ENRICH,FAB COST/GW RELOAD : $13.7 MILLIONS
COST OF U308 PER POUND (NOW) : $17
OPERATING AND MAINTENANCE COST: 5 MILLS/KWH

NOTE: ALL U308 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GW NUCLEAR U.S.	GW NUCLEAR OUTSIDE U.S.	GW NUCLEAR TOTAL	GW LWR	GW LMFR	U308 USED PERIOD	U308 USED CUM.	U308 USED AND COMMITTED	TOTAL U308 & EQU308 UNCOM.	U308 NEEDED FOR BREEDERS CUM.	PRESENT EQUIVALENT U308 BY RECYCLE	FUTURE EQUIVALENT U308 BY RECYCLE	U308 REMAINING	U308 COMMITTED END OF YEAR	PRICE U308 DOLLARS PER LB	COST REPL. CORE (MILLIONS)	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1996	80	147	227	227	0	43	43	2574	20852	0	182	445	22757	2581	17	20	3	46	74
2000	110	288	398	398	0	842	884	5321	18577	0	234	864	21916	4436	17	20	3	46	129
2005	150	381	539	539	0	443	1327	7336	16951	0	326	1162	21473	6009	17	20	3	46	175
2010	213	504	717	717	0	593	1920	9915	14864	0	430	1529	20888	7994	17	20	3	46	238
2015	275	667	942	942	0	784	2704	13206	12194	0	615	1906	20896	10902	17	20	3	46	306
2020	346	882	1228	1228	0	1025	3729	17425	8765	0	884	2599	19071	13696	17	20	3	46	399
2025	425	1167	1592	1592	0	1333	5062	22818	4377	0	1114	3281	17738	17756	17	28	3	46	518
2030	478	1336	1814	1814	0	1609	6672	26899	907	0	1480	3827	16128	20228	18	20	3	46	598
2035	535	1529	2064	2064	0	1832	8504	31521	-3024	0	1897	3800	14296	23017	41	29	4	48	698
2040	597	1750	2347	2347	0	2084	10588	36761	-7488	0	2372	4186	12212	26173	67	39	6	49	688
2045	707	2003	2710	2710	0	2390	12978	43198	-12910	0	2912	4568	9822	30220	57	35	5	49	922
2050	826	2293	3119	3119	0	2754	15732	50507	-19100	0	3536	5072	7068	34775	74	42	6	49	1082
2055	954	2624	3578	3578	0	3164	18896	58794	-26110	0	4252	5623	3904	39858	94	49	7	51	1268
2060	1092	3003	4095	4098	0	3626	22521	68187	-34084	0	5075	6228	279	45666	191	86	12	56	1608
2065	1241	3437	4678	4678	0	4145	26667	78834	-43122	0	6017	6895	-3867	52167	234	102	15	58	1908
2070	1421	3934	5356	5356	0	4741	31408	91127	-53546	0	7098	7688	-8608	59719	276	118	17	60	2268
2075	1628	4503	6131	6131	0	5427	36835	105200	-65479	0	8325	8896	-14038	68365	323	136	19	63	2708
2080	1865	5154	7018	7018	0	6213	43048	121310	-79139	0	9738	9636	-20248	78262	378	156	22	66	3239
2085	2136	5898	8034	8034	0	7112	50161	139752	-94777	0	11349	10826	-27361	89092	440	180	26	69	3857
2090	2447	6751	9198	9190	0	8142	58303	160864	-112679	0	13157	12188	-35503	102862	511	207	30	73	4709
2095	2802	7727	10529	10529	0	9321	67624	185032	-133179	0	15313	13740	-44824	117459	598	238	34	77	5717
2100	3210	8843	12053	12053	0	10670	78294	212700	-156633	0	17734	15838	-55494	134406	687	273	39	83	6971

TABLE C-33 Projections Calculated for International Scenario 33 Using the Stated Assumptions

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PSHEET33                                            SCENARIO NO.   33    REVISED   10/26/86
U.S. NUCLEAR GROWTH RATE (N.G.R.), 2000-2025:          5.6%      2025-2100 ----------->  2.7%
N.G.R., WORLD - CENT. PLANNED EC.'S, 2000-2025:        5.7%      2025-2100 ----------->  2.7%
WORLD LESS U.S.& CENTRALLY PLANNED ECONOMIES:          5.6%      2025-2100 ----------->  2.7%
U.S.ELECTRIC GROWTH RATE 2000-2025 (EGR1):             2.5%      2025-2100 (EGR2) --->   1.5%

PERIOD OF COMMITMENT FOR U3O8 (UL):                    60 YEARS
U3O8 FOR NEW CORE (NC):                               373 TONS   CAPACITY FACTOR --->    80%
ANNUAL U3O8 RELOAD PER 1000 MW (REPC):                189 TONS   TAILS ASSAY ------->    0.20 %
U3O8 SAVED/YR BY U & Pu RECYCLE (EQU3O8):              46 STD TONS/GW
ENTER 1 IF LMFR DEPLOYMENT IS FAST:                     1
LMFR DEPLOYMENT SCENARIO:                             FAST
YEAR OF FIRST COMMERCIAL LMFR:                        2020
U3O8 NEEDED TO START 1000MW LMFR:                     1298 STD TONS
U3O8 COMMITTED FOR ALL LMFRs UNTIL:                   2065 IN YR
LMFR PERCENT OF NEW NUCLEAR GENERATION:                50%

U3O8 RESOURCES ARE AT MEAN (MOST LIKELY) IAEA LEVEL

YEAR ALL U3O8 <$50/LB USED :                 2064
YEAR ALL U3O8 <$100/LB USED:                 2070
YEAR ALL U3O8 <$100/LB COMM.:                2019
YEAR $100/LB U3O8+EQU3O8 COMM.:              2024
CAPITAL COST OF LWR PER KW :                $1500
CAPITAL COST OF LWR (MILLS/KWH)                39
U3O8 RESOURCES BELOW $100/LB :              22800 THOUSAND STD TONS
U3O8 RESOURCES BELOW $50/LB :               19800 THOUSAND STD TONS
CONV,ENRICH,FAB COST/GW RELOAD :           $13.7 MILLIONS
COST OF U3O8 PER POUND (NOW) :               $17
OPERATING AND MAINTENANCE COST:                5 MILLS/KWH
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NOTE: ALL U3O8 AMOUNTS IN TABLE BELOW ARE IN UNITS OF 1000 STD TONS

YEAR	GW NUCLEAR U.S.	GW NUCLEAR OUTSIDE U.S.	GW NUCLEAR TOTAL	GW LWR	GW LMFR	U3O8 USED PERIOD	U3O8 USED CUM.	U3O8 USED AND COMMITTED	TOTAL U3O8 & EQU3O8 UNCOM.	U3O8 NEEDED FOR LMFRs CUM.	PRESENT EQUIVALENT U3O8 BY RECYCLE	FUTURE EQUIVALENT U3O8 BY RECYCLE	U3O8 REMAINING	U3O8 COMMITTED END OF YEAR	PRICE U3O8 DOLLARS PER LB	COST REPL. CORE (MILLIONS)	FUEL COST MILLS / KWH	C.O.E. LWRs MILLS/KWH	C.O.E. LWRs IN YEAR BILLIONS
1986	80	147	227	227	0	43	43	2574	20852	0	182	445	22757	2531	17	20	3	46	74
2000	110	288	398	398	0	842	884	5321	18577	0	234	864	21916	4436	17	20	3	46	129
2005	158	381	539	539	0	443	1327	7336	16951	0	326	1162	21473	6009	17	20	3	46	178
2010	213	504	717	717	0	593	1920	9915	14864	0	458	1529	20888	7994	17	20	3	46	238
2015	275	667	942	942	0	784	2704	13206	12194	0	615	1988	20096	10502	17	20	3	46	306
2020	346	882	1228	1200	29	1012	3716	24110	1993	37	831	2480	19084	20402	17	20	3	46	390
2025	425	1167	1592	1382	211	1220	4935	27131	-510	273	1107	2706	17865	22195	17	20	3	46	449
2030	478	1336	1814	1492	322	1358	6293	29581	-2662	417	1425	2694	16807	23288	17	20	3	46	488
2035	535	1529	2064	1618	447	1469	7763	32283	-5018	580	1768	2696	15037	24520	32	26	4	47	536
2040	597	1750	2347	1759	588	1595	9358	35272	-7618	763	2148	2715	13442	25914	52	33	5	48	598
2045	707	2003	2710	1940	770	1748	11106	38809	-10653	999	2545	2811	11694	27702	45	31	4	48	652
2050	826	2293	3119	2145	974	1930	13037	42751	-14032	1264	2991	2929	9763	29715	57	35	5	49	738
2055	954	2624	3578	2374	1204	2135	15172	47150	-17796	1562	3484	3069	7629	31978	71	40	6	49	828
2060	1092	3003	4095	2633	1462	2366	17538	52064	-21997	1898	4030	3237	5262	34526	86	46	7	50	925
2065	1241	3437	4678	2925	1754	2626	20164	57563	-26691	2276	4636	3436	2636	37399	112	56	8	52	1086
2070	1421	3934	5356	3263	2092	2924	23088	63823	-32016	2716	5309	3698	-288	40738	203	98	13	56	1290
2075	1628	4503	6131	3651	2480	3267	26355	70909	-38033	3219	6059	4017	-3558	44595	231	101	14	58	1480
2080	1865	5154	7018	4095	2924	3660	30014	78942	-44840	3795	6899	4402	-7214	48927	263	113	16	60	1713
2085	2136	5898	8034	4603	3432	4109	34124	88056	-52553	4454	7841	4863	-11324	53933	299	127	18	62	1988
2090	2447	6751	9198	5184	4013	4624	38748	98411	-61302	5209	8899	5409	-15948	59663	340	142	20	64	2310
2095	2802	7727	10529	5850	4679	5214	43962	110184	-71238	6073	10092	6054	-21162	66222	386	159	23	66	2717
2100	3210	8843	12053	6612	5441	5888	49850	123582	-82532	7063	11437	6812	-27080	73732	437	179	26	69	3200

GLOSSARY

AVLIS: Atomic Vapor Laser Isotope Separation

Beta (β): (1) The ratio of plasma pressure to the magnetic pressure containing the plasma; (2) beta particle

Be: Beryllium

CDFR: Designation for a liquid-metal cooled fast reactor under study in the United Kingdom

CRBRP: Clinch River Breeder Reactor Project

DFBR: Designation for a liquid-metal cooled fast reactor under study in Japan

DOE: U.S. Department of Energy

EBR-I: Experimental Breeder Reactor (first model)

EBR-II: Experimental Breeder Reactor (second model)

EPRI: Electric Power Research Institute

ETR: Engineering Test Reactor

FER: Fusion Engineering Reactor, Japan

FLIBE: Molten salt containing flourine, lithium, and beryllium

FINESSE: A study on fusion nuclear technology led by University of California at Los Angeles

GWe: Gigawatt(s) (electric)

HTGR: High-temperature gas-cooled reactor

IAEA: International Atomic Energy Agency

ICF: Inertial Confinement Fusion

INTOR: International Tokamak Reactor

IUREP: International Uranium Resource Evaluation Panel

JET: Joint European Torus, at the JET Joint Undertaking, near Abingdon, Oxfordshire, England

JT-60: Tokamak device at the Japan Atomic Energy Research Institute

kW: kilowatt(s)

kWh: kilowatt hour(s)

lb: Pound

Li: Lithium

LiO_2: Lithium oxide

LiPb: Mixture of lithium and lead

LMFR(s): Liquid Metal Fast Reactor(s)

LWR(s): Light water reactor(s)

Magnetic confinement: Any scheme that seeks to isolate a hot (fusion) plasma from its surroundings by using magnetic lines of force to direct the charged particles

MFPP: Magnetic Fusion Program Plan

MT: Metric ton

MW: Megawatt(s)

MWe: Megawatt(s) (electric)

MW/m^2: Megawatts per square meter

MWt: Megawatt(s) (thermal)

n: Neutron

NET: Next European Torus

NGR: Nuclear percent of new generation capacity

NSSS: Nuclear supply steam system

ORNL: Oak Ridge National Laboratory

Plasma: A gas comprising some large fraction of charged particles

PRISM: Power Reactor Inherently Safe Module, reactor design under study by General Electric Company

Pu: Plutonium

Q: Plasma power gain, the ratio of fusion power output to plasma heating power provided by external sources

SAFR: Designation for a liquid-metal cooled fast reactor under study in the United States

SNR-2: Designation for a liquid-metal cooled fast reactor under study in Germany

SPX-2: Designation for a liquid-metal cooled fast reactor under study in France

T-15: Tokamak device in the Soviet Union

TFTR: Tokamak Fusion Test Reactor, at Plasma Physics Laboratory, Princeton University

Th: Thorium

Tokamak: A magnetic containment device in which the magnetic lines of force are closed on themselves in the shape of a torus, with a large current flowing through the plasma.

Toroidal: The azimuthal direction, about the central axis, within a toroidal containment device

TPA: Technical Planning Activity

U: Uranium

U_3O_8: Triuranium octaoxide

W: Neutron wall loading, the energy per unit time transported per unit area through the first wall by the kinetic energy of the fusion neutrons