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
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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

CONTENTS

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

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 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.

1

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

<u>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</u>.

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."

The Fast-Fission Power-Only Hybrid 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)

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).

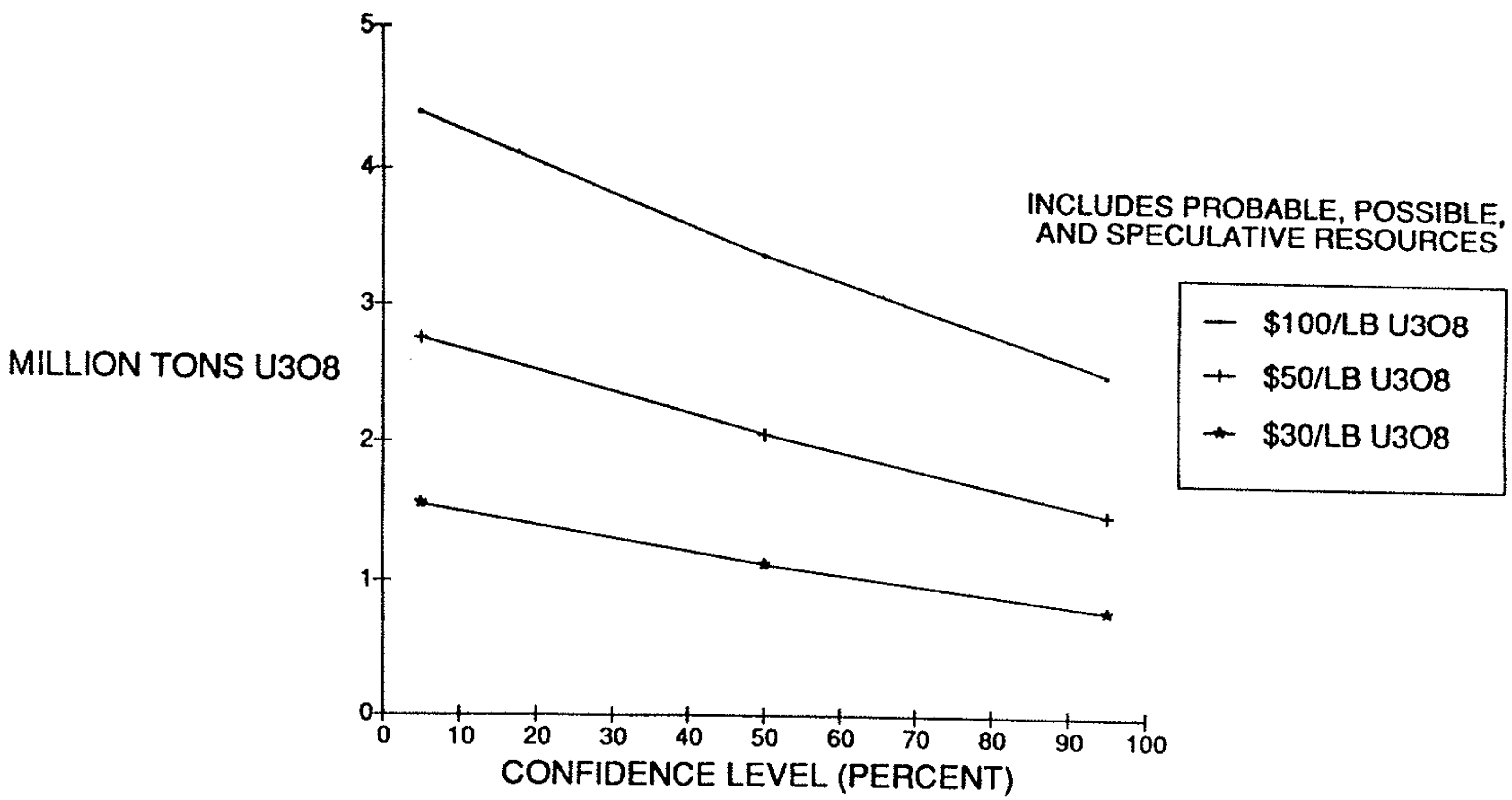

FIGURE 2-1 U.S. uranium resources at various confidence levels (estimated as of January 1, 1983).

SOURCE: 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

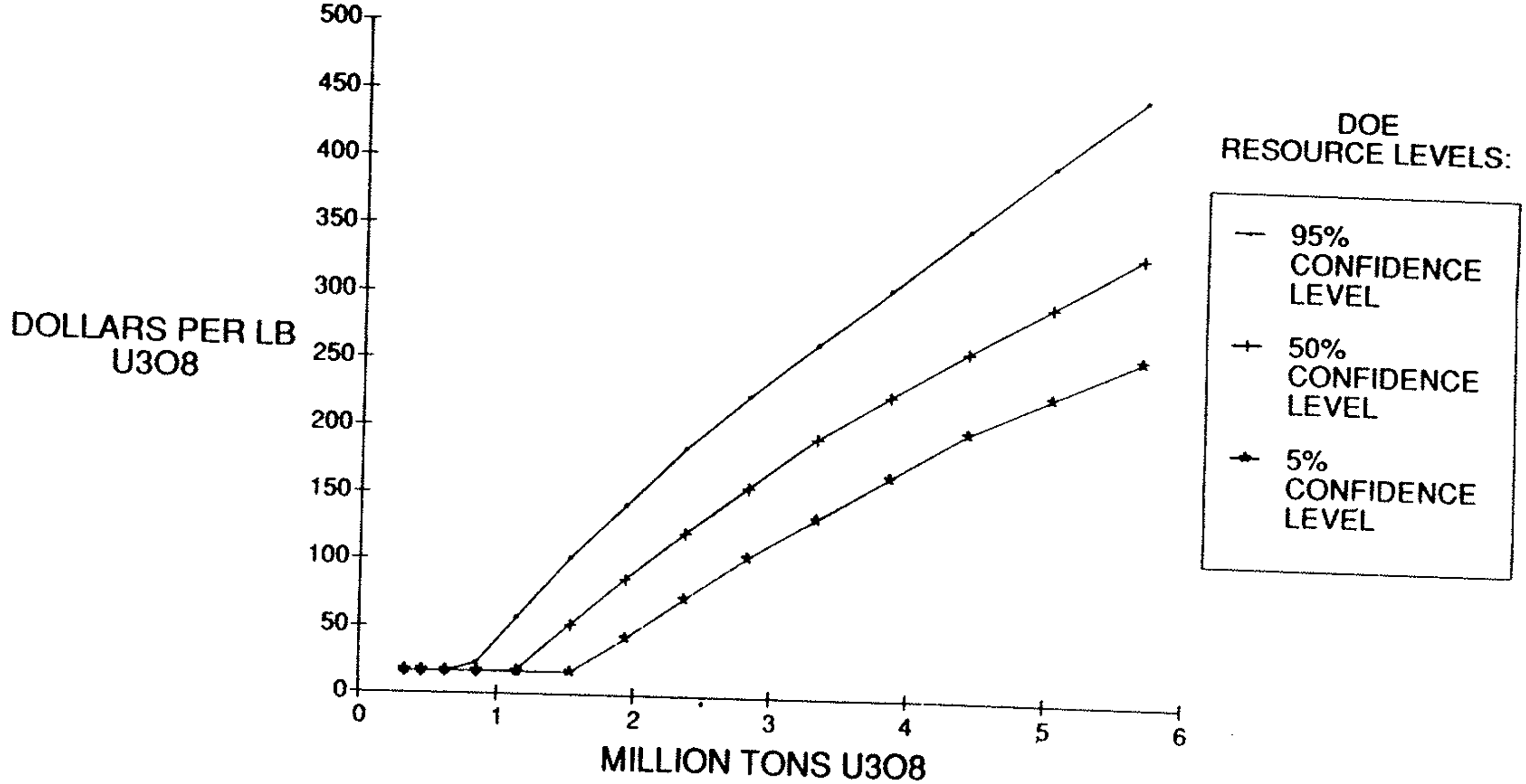

FIGURE 2-2 Simple model for price of U_3O_8 as a function of cumulative use.

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 2025-2068	IS COAL USE LIMITED?	NUCLEAR % NEW ELECTRIC CAPACITY	URANIUM RESERVES < $100/LB (MILLION TONS)	URANIUM TAILS ASSAY	MILLION TONS U3O8 USED CUM. IN 2068	YEARS FOR FUTURE U3O8 COMMITMENT	MILLION TONS U3O8 USED AND COMMITTED IN 2065	U3O8 PRICE IN 2065 ($/LB)	GW ELECT. IN YEAR 2068	GW LWRS IN YEAR 2068	GW LMFRs IN 2065	COAL BURNED PER YEAR IN 2065 (MIL.TONS/YR)
1C	2037	95%	2.5%	1.8%	NO	40%	2.80	0.20	5.60	60	18.01	$454	3091	657	326	3054
8	2044	50%	2.5%	1.8%	NO	40%	3.30	0.20	6.14	60	14.29	$363	3091	731	252	3054
4	2044	50%	2.5%	1.8%	NO	40%	3.30	0.20	6.56	60	17.52	$388	3091	983	-	3054
8A	2044	80%	2.5%	1.8%	YES	40% (67% AFTER 2040)	3.30	0.20	7.10	60	20.94	$420	3091	1241	-	1644
2A	2045	50%	2.5%	1.8%	YES	40% (67% AFTER 2040)	3.30	0.20	6.12	60	14.88	$362	3091	786	455	1644
1A	2046	80%	2.5%	1.8%	NO	40%	3.30	0.20	5.60	60	18.01	$336	3091	657	326	3054
9	2049	80%	2.5%	1.8%	NO	30%	3.30	0.20	5.34	60	18.87	$316	3091	765	-	3054
7	2050	50%	2.5%	1.8%	NO	40%	3.30	0.08	5.31	60	14.19	$314	3091	983	-	3054
13	2054	50%	2.5%	1.8%	NO	30%	3.30	0.20	4.67	60	12.14	$276	3091	765	-	3054
10	2054	80%	2.5%	1.8%	NO	30%	3.30	0.20	4.67	40	9.61	$276	3091	765	-	3054
12	2054	50%	2.5%	1.8%	NO	30%	3.30	0.20	4.67	30	8.34	$276	3091	765	-	3054
18	2058	5%	2.5%	1.5%	NO	40%	4.40	0.20	5.60	60	18.81	$258	3091	657	326	3054
17	2062	50%	2.0%	1.0%	NO	30%	3.30	0.20	3.68	60	8.88	$215	2233	508	-	1918
19	2062	80%	2.0%	1.0%	NO	30%	3.30	0.20	3.68	40	6.98	$215	2232	508	-	1918
6	2064	80%	1.0%	1.0%	NO	40%	3.30	0.20	3.47	60	8.41	$206	1729	443	-	1494
15A	2065	80%	2.0%	1.0%	YES	30% (67% AFTER 2080)	3.30	0.20	3.40	40	6.17	$201	2233	429	193	1644
14	2067	00%	2.0%	1.0%	NO	30%	3.30	0.30	3.27	40	5.67	$192	2233	372	136	1918
11	AFTER 2070	80%	1.0%	1.0%	NO	30%	3.30	0.20	2.65	40	4.97	$144	1729	369	-	1494

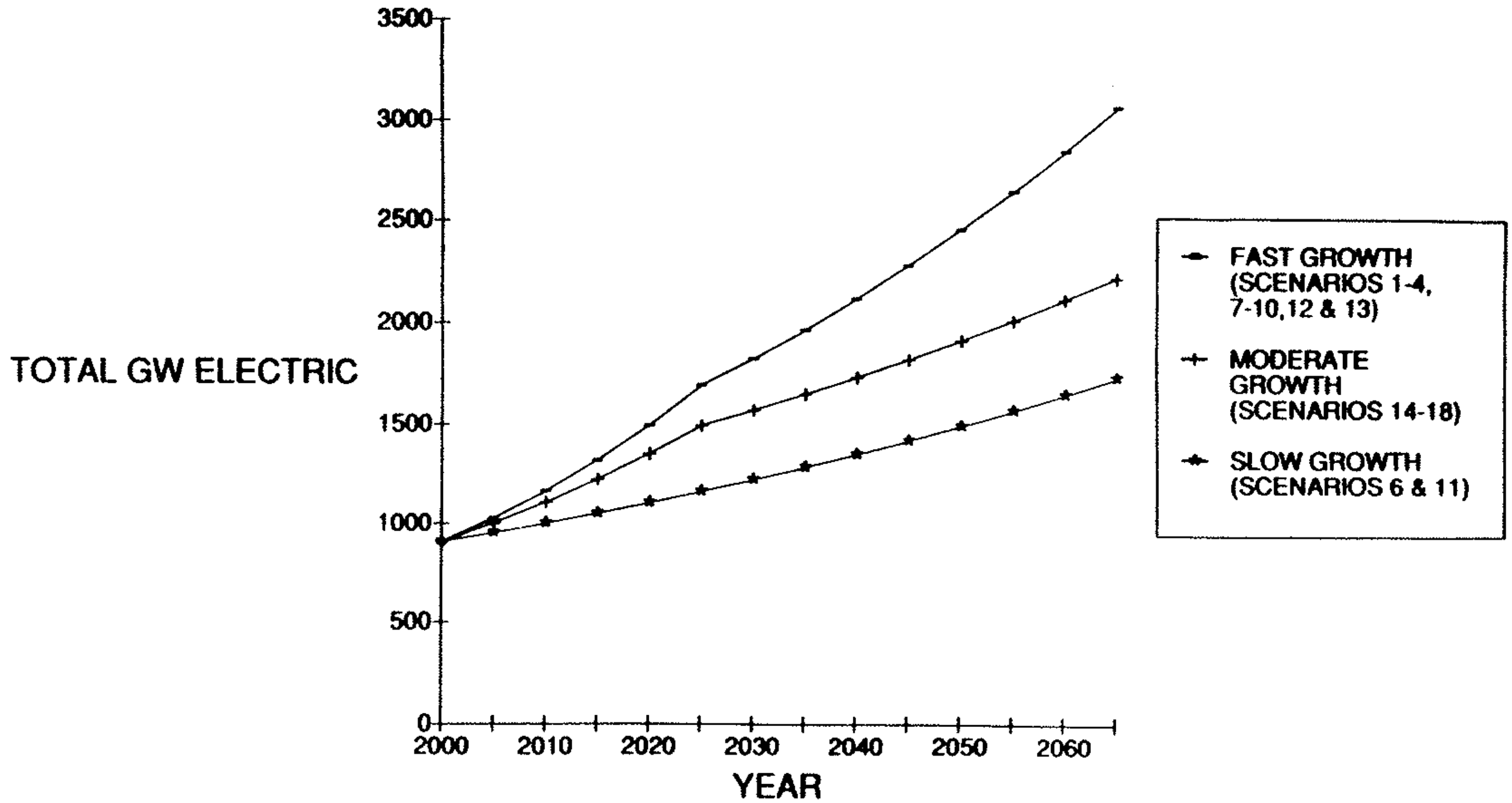

FIGURE 2-3 Growth of total installed electric capacity.

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

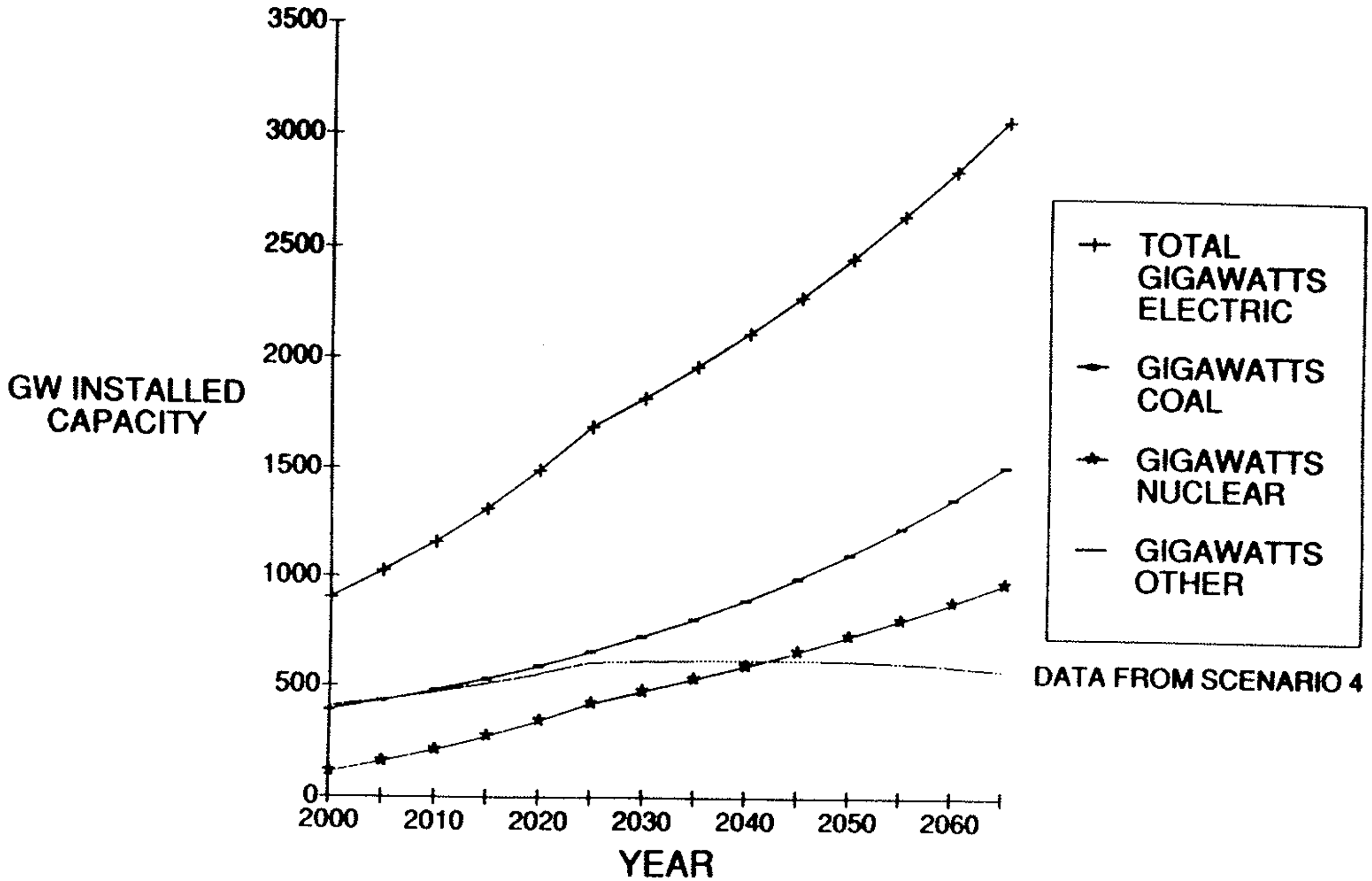

FIGURE 2-4 Growth of installed electric generating capacity for the "fast growth" case (no LMFRs).

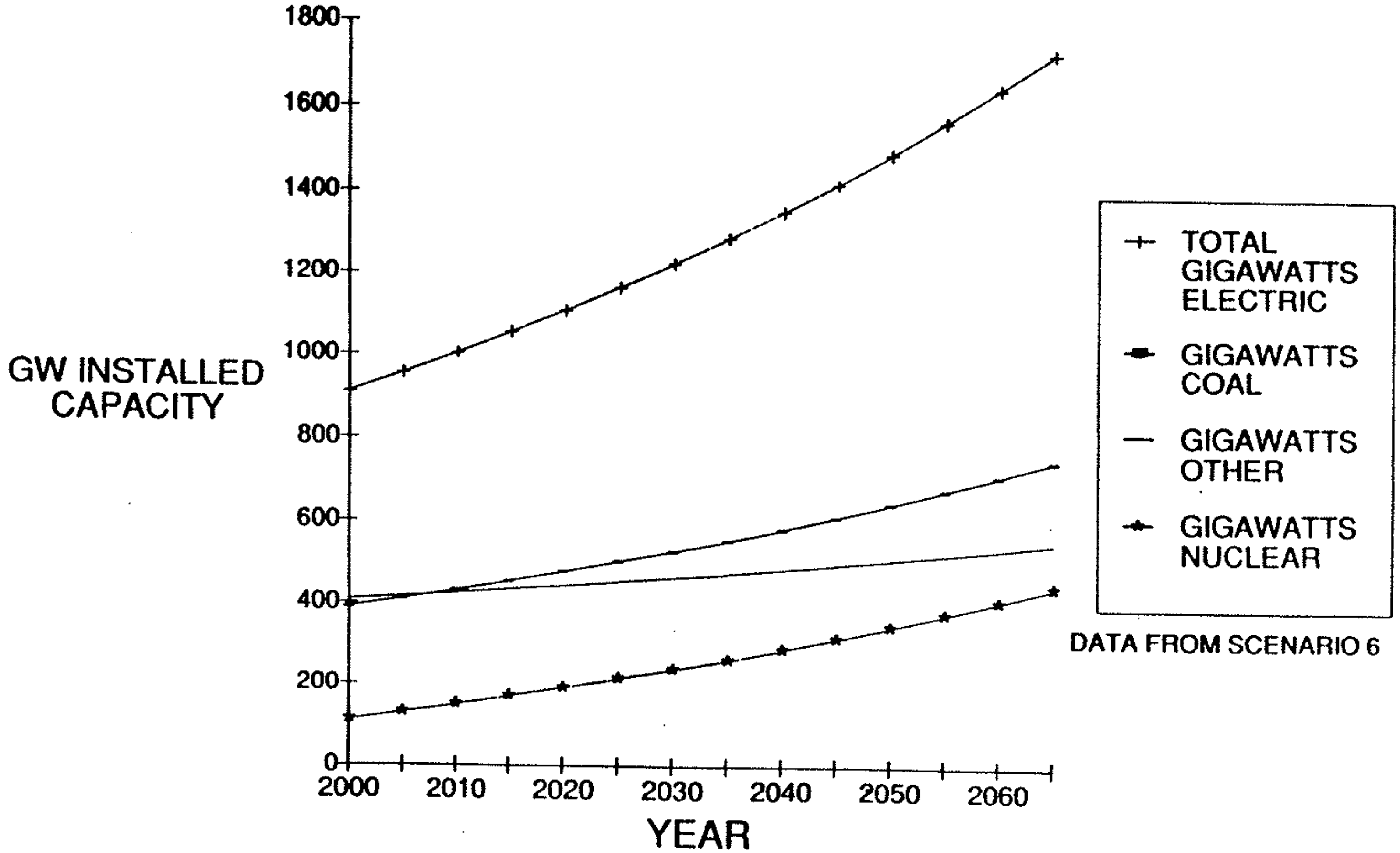

FIGURE 2-5 Growth of installed electric generating capacity for the "slow growth" case (no LMFRs).

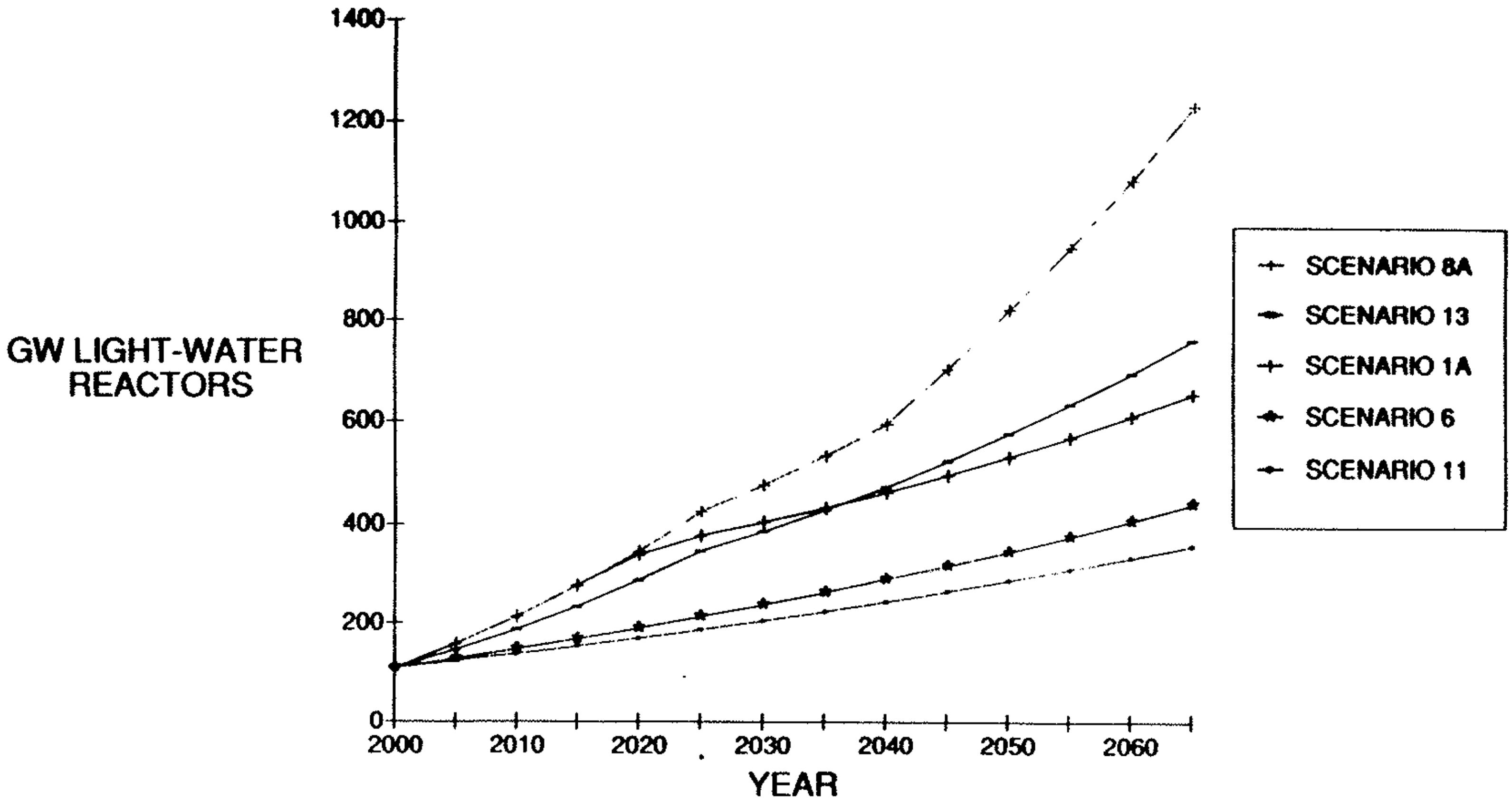

FIGURE 2-6 Growth of installed light-water reactor electric capacity.

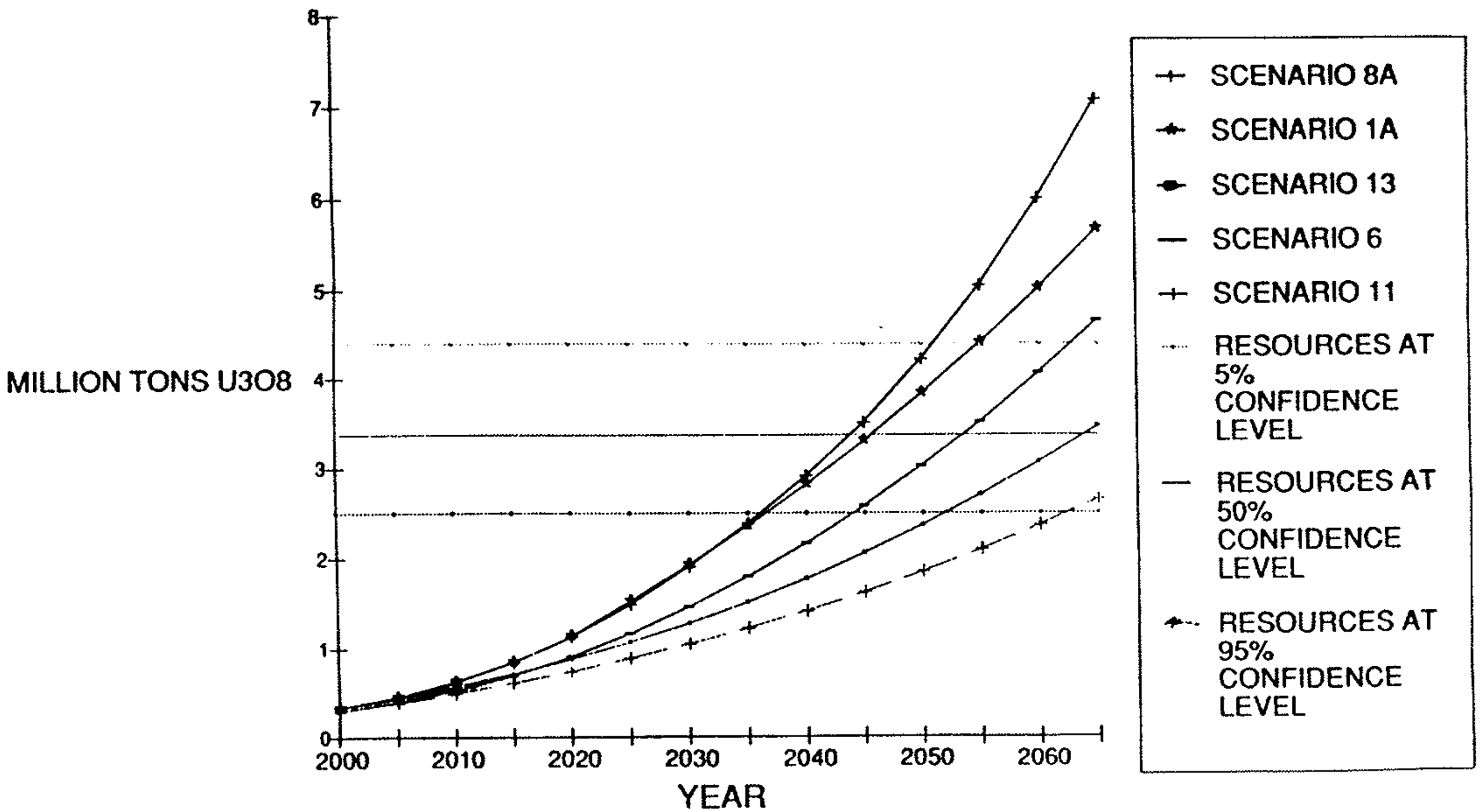

FIGURE 2-7 Cumulative U.S. resources of U_3O_8 used.

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 < $100/LB ALL USED UP	U308 PRICE IN 2065 ($/LB)	COST OF ELECTRICITY IN 2065 (MILS/KWH)	U.S. ELECTRIC GROWTH RATES, 2000-2025 AND 2026-2100	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 U308 USED BY YEAR 2065	MILLION TONS U308 USED AND COMMITTED BY YR 2065
30	2092	$53	48	1.0% 1.0%	2.7% 1.0%	2.7% 1.8%	1604	22.8	12.3	30.2
31	2065	$201	56	1.0% 1.0%	2.7% 1.8%	5.6% 2.7%	3080	22.8	23	66.2
32	2060	$234	58	2.5% 1.5%	5.6% 2.7%	5.6% 2.7%	4678	22.8	26.7	78.8
33	2070	$112	52	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.

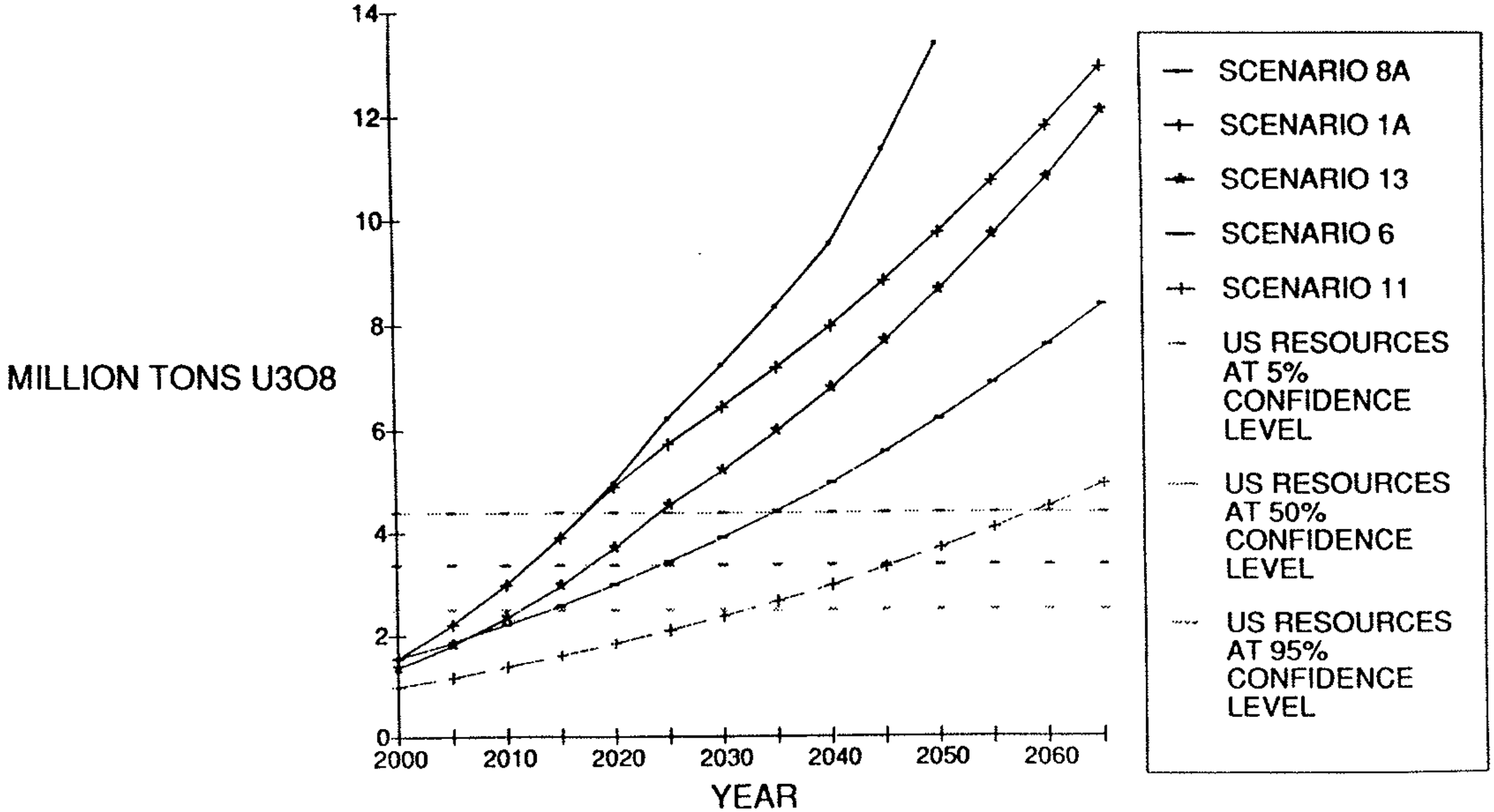

FIGURE 2-8 Cumulative U_3O_8 used and committed vs year.

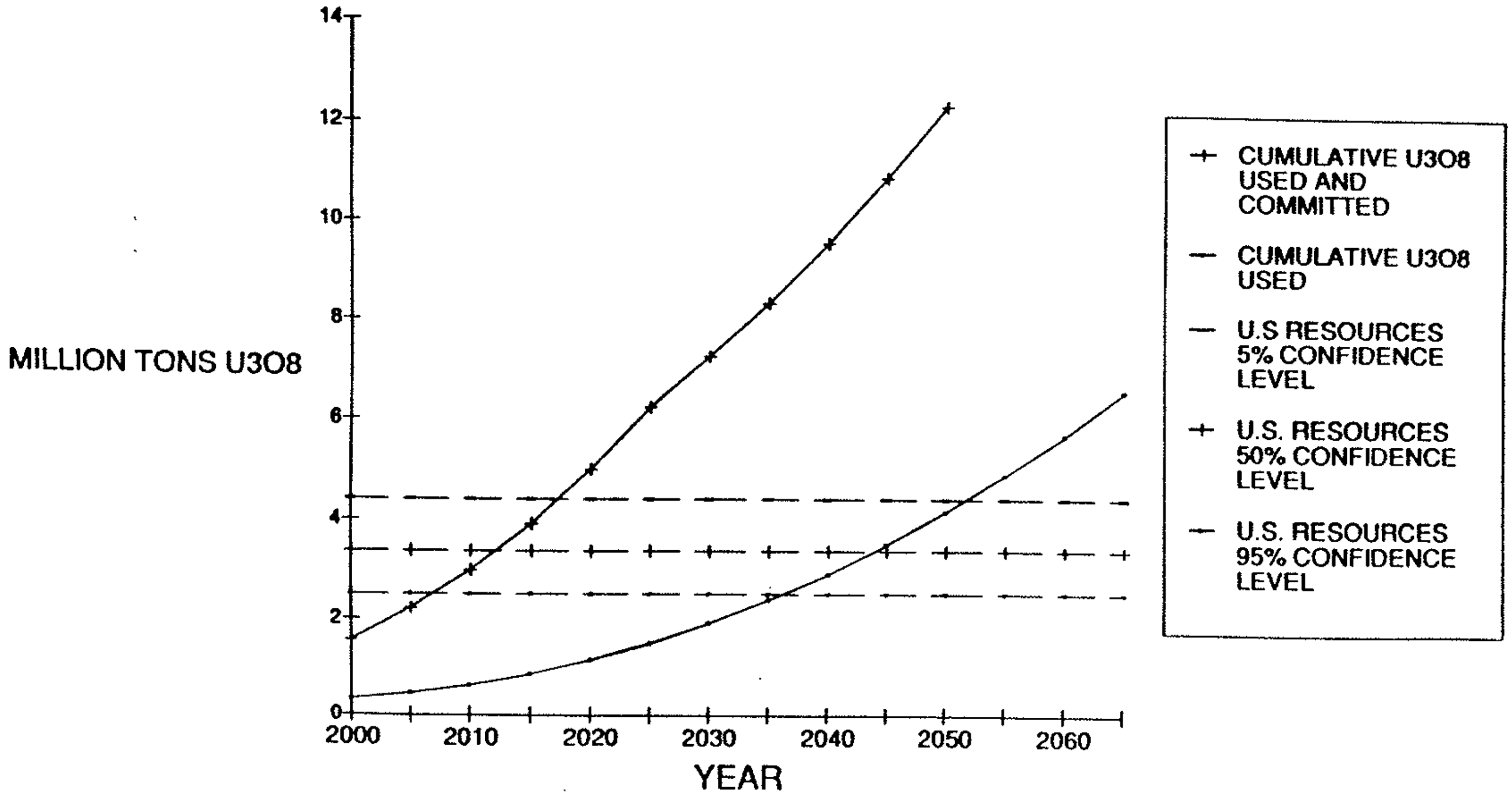

FIGURE 2-9 Comparison of cumulative U_3O_8 used with U_3O_8 used and committed for the "fast growth" case of scenario 4 (no LMFRs).

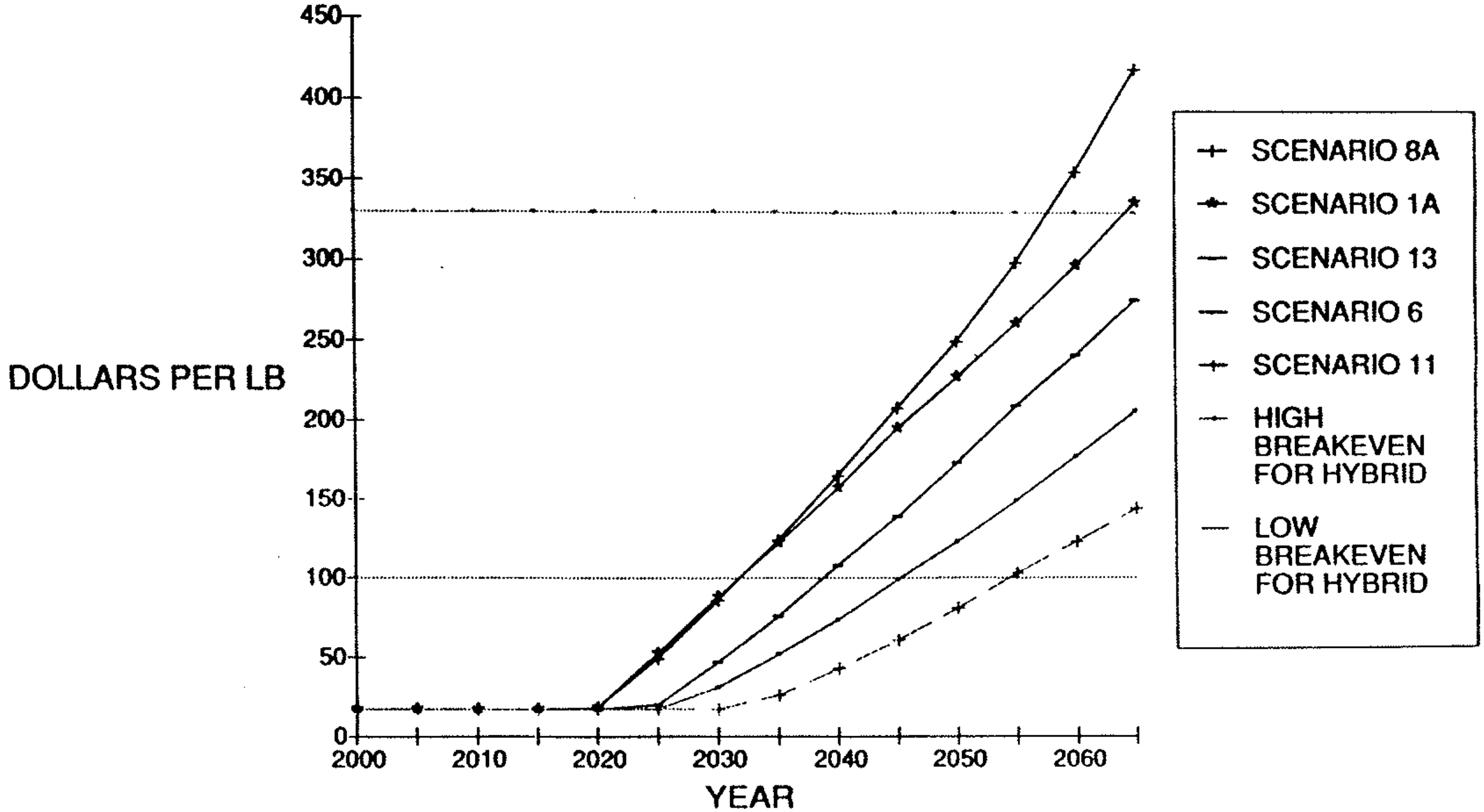

FIGURE 2-10 Projected price of U_3O_8, 2000 through 2065.

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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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

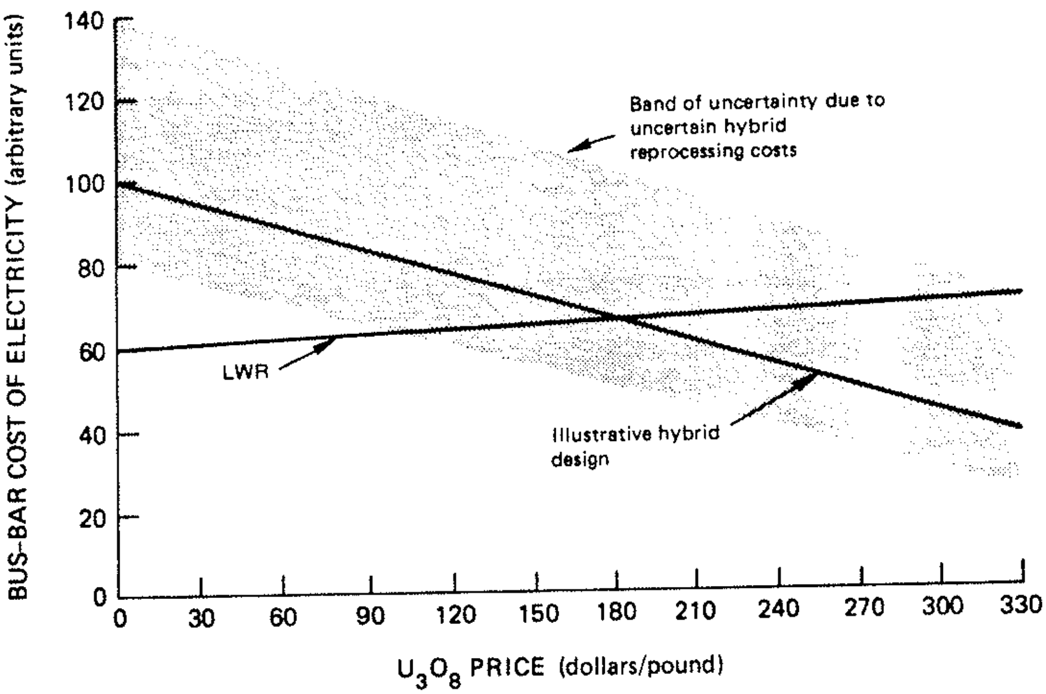

FIGURE 5-1 Illustrative relationship between electricity cost and U3O8 price.

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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