The Economics and Utilization of Thorium in Nuclear Reactors

Prepared by
Resource Planning Associates, Inc.
44 Brattle Street
Cambridge, Massachusetts 02138

Subcontract No. 7233

MASTER

OAK RIDGE NATIONAL LABORATORY
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OF THORIUM IN NUCLEAR REACTORS

Prepared by

Resource Planning Associates, Inc.
44 Brattle Street
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Washington, D. C. 20545

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Our study relied on information provided by participants in the Thorium Assessment Program and others; the analysis of that data, and the conclusions derived from them, are the responsibility of the Resource Planning Associates, Inc., study team:

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EXECUTIVE
ABSTRACT

The role of nuclear power in producing electricity has expanded dramatically in recent years. Between 1965 and 1976, nuclear power's share of electrical production capacity rose from a negligible percentage to approximately 9 percent. The federal government and industry have established extensive programs of research and development aimed at improving the performance of nuclear technologies and reducing the cost of electricity with nuclear power. The utilities, at the same time, have purchased nuclear plants for baseload generating capacity to capitalize on the perceived economic advantages offered by nuclear power.

The predominant type of nuclear power plant in the United States is the light-water reactor (LWR) fueled with uranium slightly enriched in the U-235 isotope. However, research of other technologies has continued, most notably of the liquid-metal fast breeder reactor (LMFBR). The LMFBR is believed, in the long term, to be capable of producing power economically through the use of the abundant U-238 isotope. The LWR and LMFBR systems, fueled with U-235 and plutonium, have consequently figured largest in utility and government planning. The LMFBR is generally regarded as the nuclear technology of the future; the LWR, as an interim technology until the breeder becomes available.

This view of the nuclear future has recently been brought into question. The development of the LMFBR has been slower than expected, and concern is growing over the widespread use of nuclear materials -- particularly plutonium -- and the potential hazard that they could be diverted and used for the manufacture of nuclear weapons. Until the problem of proliferation is resolved, President Carter has deferred the demonstration of the breeder reactor and the licensing of a facility for recycling nuclear fuels.

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This decision has led to the examination of alternative or modified nuclear fuels less susceptible to diversion and use in weapons. The thorium fuel-cycle is one of these alternatives.

Thorium is a "fertile" material; that is, it cannot be used directly as a fuel but can be converted into the "fissile" uranium isotope, U-233, that can serve as a fuel. Its use as an alternative fertile material for a variety of reactors, including the LWR, the spectral-shift controlled reactor (SSCR), the high-temperature gas-cooled reactor (HTGR), the heavy-water reactor (HWR), and advanced breeder reactors, has already been considered. The technical and economic aspects of its use in nuclear power plants have been evaluated in a number of studies, which, although varying in their specific conclusions, generally agree on three points:

1. Thorium fuels appear to be technically feasible in certain reactor applications (e.g., LWRs, HTGRs, and HWRs, such as those now in use in Canada)
2. In thermal reactors (including LWRs, HTGRs, and HWRs), thorium appears to offer more energy-efficient use of the available resources of uranium ore than uranium alone
3. However, at the price levels assumed in these previous studies, thorium applications appear to be less economical in the total cost of delivered power than the LWR/uranium system.

The rising concern over uranium supplies and the hazard of proliferation warrant a reappraisal of these conclusions. Consequently, the Thorium Assessment Program (TAP) was initiated in October 1976, under the direction of the Division of Nuclear Research and Applications (NRA) of the U.S. Energy Research and Development Administration (now absorbed into the U.S. Department of Energy), to investigate the possible use of thorium in the nuclear market. The findings of the first year's investigations of this 2-year program indicate that further evaluation of the commercialization of thorium is warranted.

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Because thorium is not in commercial use for baseload power generation, its commercial potential was evaluated under four possible recycle policies:

- No recycle, representing the present federal policy, prohibiting the reprocessing and recycling of any fuel. This policy scenario was included to establish whether or not a change in the present government reprocessing policy is a prerequisite for commercial deployment of thorium.
- Uranium-recycle only, prohibiting the recycling of plutonium. This policy was selected to determine if industry investment criteria would be met for thorium technologies under conditions most favoring the thorium fuel-cycle over the uranium cycle.
- Recycle of plutonium in secure centers only, with recycle only of denatured uranium fuels in reactors outside the centers. This policy was selected to determine the potential market for thorium in reactor/fuel-cycle combinations being evaluated in other government programs aimed at reducing the likelihood of nuclear proliferation.
- Full recycle, permitting reprocessing and recycling of all uranium and plutonium fuels without restriction on fuel composition. This policy was selected to determine whether a reversion from the present federal policy to the policy previously expected by the nuclear industry would preclude the possibility of industry investment in the thorium fuel-cycle.

The present market is obviously shaped by the prevailing federal policy and governmental regulation. Under the present energy policy, and faced with the prospect of fuel-supply problems and rising costs, the electric utilities view oil- and gas-fired baseload capacity as undesirable investment options. Coal-fired and nuclear-powered capacity, on the other hand, are viewed favorably, despite restrictions on the use of coal imposed by air quality controls and limited production capabilities, and on the use of nuclear power by ambiguous federal policy, difficulties with licensing processes, and high capital costs. Despite these restraints, and a cautious -- even pessimistic -- attitude toward investments in the LWR with the uranium once-through cycle, the

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utilities perceive the need for installing over 350 GW(e) of nuclear capacity by 1996, according to the compilation of utility capacity plans by the National Electric Reliability Council. However, unless national policy on nuclear power is perceived to become more favorable to the construction of nuclear plants, the prospect of these plans being realized is small.

A survey of utilities and nuclear suppliers revealed that they do not regard the commercialization of thorium as necessary or useful under present market conditions. The industry's major interests at the moment are the reduction of licensing time and risk and the improved operating performance of LWRs.

More specifically, the survey showed that:

- The utilities foresee the need to add 358 GW(e) of nuclear electric-generating capacity, or 44 percent of all planned capacity additions, by 1996; however, over 65 percent of the additions are planned between 1987 and 1996, indicating that the utilities are awaiting a change to a more favorable federal policy before committing themselves to procurement. The market is therefore still susceptible to the influence of federal policy.
- The electric utilities believe that uranium supplies are adequate to meet their demands and do not perceive thorium as necessary to augment these supplies. In fact, they view the commercial introduction of thorium as likely to be an unnecessary complication in an already difficult licensing climate and fuel market.
- The utilities do not perceive thorium on a once-through cycle as competitive with uranium, a view that TAP investigations so far support.
- Before thorium is commercialized, the utilities surveyed strongly favor the development of a federal policy that permits the recycling of fuel, continues development of the FBR, and streamlines the nuclear regulatory process before thorium is commercialized.
- The supplier industries will not limit the growth of a thorium market if the demand for thorium develops. However, they will not invest in production or service capacity until federal policy clearly establishes a role for thorium, and until contracts for goods and services are negotiated with electric utilities.

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- The financial industry perceives the current market as risky for many of the utilities building nuclear units. The introduction of thorium would constitute an additional risk not justified under current regulatory and energy policy. However, under a favorable energy policy, the supply of capital will not be a constraint on the commercialization of thorium.

The potential market for electric power plants appears to be gaining strength once again, and a strong market should continue into the 1980s. Therefore, the potential for nuclear power is good also, under favorable government policies. However, the present market for nuclear goods is, at best, merely holding its own. Federal policy and regulation must change if the condition of the market is to change. The utilities and supplier industries perceive that the future market potential is delicate and can easily evaporate if uncertainties persist or if future policies or regulations are adverse. A new fuel is viewed as an unnecessary complicating factor in this market.

Stabilizing nuclear policy is the critical step in the commercialization of thorium. The market awaits a clear policy on fuel reprocessing and recycling, on the availability of the FBR, on waste storage, on plant decommissioning, and on regulatory requirements for the licensing of plants. These policies are external to the consideration of thorium, but a stable, more-positive policy toward nuclear power will produce a more-receptive market for thorium in current LWRs or in new reactors. If thorium is to be commercialized, critical decisions must be made by the federal government. First, policy must be stabilized and regulatory procedures streamlined to facilitate the development and use of nuclear units and to forestall the dispersal of expertise and manufacturing capability that will be required in the 1980s and 1990s. Second, the policy and procedures must be implemented and their effects realized in increased procurements of LWRs. Third, the decision to deploy thorium must be made; this will also entail a change in federal policy. TAP studies show that the prerequisite to effective penetration of the nuclear market by the thorium fuel-cycle is a policy permitting

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the reprocessing, fabrication, and recycling of fissile fuel.

While a policy prohibiting recycling of uranium and plutonium remains in force, then, the market is uninterested in thorium and, in fact, as various TAP studies demonstrate, thorium is not economically competitive with coal or with uranium on the once-through cycle except in HTGRs and the German pebble-bed reactors.¹

To examine the market potential for thorium under the three recycling policy scenarios, the quantitative potential of a thorium market was forecast for each policy by the Hanford Engineering and Development Laboratory's ALPS model. However, forecasting beyond the utilities' planning horizon of 20-30 years is uncertain because of the number of imponderables involved: possible shifts in government policy; the future financial condition of the utilities; fluctuations in demand; and changes in fuel prices and in the capital cost of generating equipment. Consequently, the feasibility of introducing thorium in LWRs, SSCRs, HTGRs, and HWRs was also evaluated qualitatively.

Technically, commercializing thorium in the LWR is less difficult than in the SSCR, HTGR, or HWR. The commercialization of the SSCR appears, on the basis of TAP data, to be less difficult than the commercialization of the HTGR or HWR because the SSCR is essentially an LWR modified to use available heavy-water technology. Moreover, the SSCR is adaptable to a nuclear economy consisting of LWRs and LMFBRs. The HTGR has already

1. Keith C. Garel and Michael J. Driscoll, Massachusetts Institute of Technology, Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems (MIT-EL-777-018: October 1977); Combustion Engineering, Inc., Assessment of Thorium Fuel Cycles in Pressurized Water Reactors (EPRI-NP-359: February 1977); E. Teuchert, "Once Through Cycle in the Pebble Bed HTR," presented at the American Nuclear Society Winter Meeting, San Francisco, California, November 27-December 2, 1977; and Reactor Design Characteristics and Fuel Inventory Data, Hanford Engineering Development Laboratory (September 1977).

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encountered difficulty in entering the commercial market, and the HWR has not been designed and built to U.S. licensing standards. Clearly, therefore, the commercialization of thorium is most likely to succeed, initially, in LWRs, with which the regulatory agencies, the utilities, and the supplier industries are most familiar.

If the government acts to deploy thorium, the market potential for thorium between 1977 and 2025 could develop as follows:

- Under a uranium-recycle only policy, a total of 748 GW(e) of nuclear capacity could be installed by 2026, of which 623 GW(e) would be thorium-cycle HTGRs and 125 GW(e), LWRs. This represents a 34-percent nuclear penetration of the electric power generation market. More efficient U_3O_8 ore utilization and lower average levelized costs give the HTGR its competitive edge over the other technologies. (The SSCR would be the next most efficient thorium-fueled reactor under this policy, with a nuclear penetration of 30 percent.)
- Under a recycle of plutonium in secure centers policy, a total of 1,453 GW(e) of nuclear capacity could be installed by 2026, with a 66-percent nuclear penetration of the electric power generation market. Of this total, 861 GW(e) would be SSCRs (366 GW(e) thorium-fueled); 420 GW(e), FBRs; and 172 GW(e), LWRs. The economic edge developed by SSCRs under this policy is due, in part, to their symbiotic relationship with FBRs; SSCRs produce plutonium for use in FBRs, which, in turn, produce U-233 fuel for SSCRs. (The HTGR would be the next most efficient thorium-fueled reactor under this policy, with a nuclear penetration of 63 percent.)
- Under a full-recycle policy, 1,453 GW(e) of nuclear capacity could be installed by 2026, with a 66-percent nuclear penetration of the electric power generation market. Of this total, 818 GW(e) would be HTGRs; 360 GW(e), FBRs; and 230 GW(e), LWRs. With full recycle, the nuclear systems including the HTGR achieve the most efficient uranium ore utilization. (A uranium-fueled SSCR was calculated to be the next most efficient reactor under this policy; however, its performance might have been matched or exceeded by the thorium-fueled SSCR, had thorium-fueled SSCRs been included in the ALPS runs.)

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In summary, the projections show that, under the secure-centers and full-recycle policies (that is, the policies most favorable to the market penetration of nuclear power), the SSCR and the HTGR are closely competitive as far as ore utilization and economics are concerned. The HWR was not competitive with either at the capital costs assumed by HEDL; however, recent studies suggest that the cost of an HWR designed to meet U.S. licensing criteria may be significantly lower than the assumed costs, in which case the HWR's competitive position would be improved.²

The major noneconomic barriers to the commercialization of thorium can be summarized as:

- The constraints on the market for any nuclear goods stemming from the problems already experienced with LWRs.
- The utilities' present lack of interest in thorium as an alternative to the uranium-plutonium fuel-cycle, and in any alternative reactor to the LWR.
- The lack of a clearly defined, permanent federal policy for nuclear fuel reprocessing and recycling, which adversely influences the economics of using thorium fuel in commercial power reactors.
- The lack of a clearly defined, permanent policy on the development of FBRs, creating the risk of a return to a policy favoring plutonium breeders that would jeopardize investments in thorium reactors.
- The lack of a demonstration of thorium fueling, with the related reprocessing and recycling technology, on a commercial scale (approximately 1,000 MW(e)).
- The uncertainty that a reactor using thorium fuels and the supporting reprocessing technology are licensable without undue design changes and delays.

2. United Engineers and Constructors, Inc., Commercial Electric Power Costs: Capital Cost, Pressurized Heavy Water Reactor Plants (COO-2477-13: June 1977).

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The first four of these barriers can be overcome only by policy decisions -- stable policy decisions that will remain in effect for 20-30 years. The last two barriers can be overcome by RD&D programs requiring substantial funding and a commitment to demonstrate that thorium's potential can be achieved on a commercial scale.

Although our primary objective was to identify the barriers to commercializing thorium, not to determine precisely how to overcome them, some actions to overcome the barriers are clearly suggested, although they warrant considerably more analysis and definition.

The lack of commercial interest in thorium stems from the lengthy list of nuclear problems faced by utilities and suppliers. If those problems persist, an interest in thorium will not develop.

When these problems have been resolved to the satisfaction of the utilities, a federal policy decision to deploy thorium would begin to arouse the market's interest. A federal policy favorable to recycling is essential to the deployment of thorium, and the benefits of thorium improve if the recycling of uranium and plutonium is also permitted. Such a policy would be a positive signal to the market for thorium.

Active implementation of a federal policy streamlining the regulatory process would encourage even more interest in thorium and new reactor designs. And finally, a decision on the fast breeder reactor, favorable or unfavorable, would help to establish which thorium-fueled reactor would be most economically efficient.

These are difficult decisions with a high level of public sensitivity, but, without them, there is virtually no prospect of thorium's entering the commercial market. These policy decisions alone, however, will not bring about the commercialization of thorium. Further decisions are needed to select the most-efficient types of reactor and fuel-cycle technology for development, to avoid dissipating the resources of industry and the government. The LWR is the technology in which the commercial potential of thorium can be demonstrated most convincingly because it involves less technical and licensing risk than others.

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The use of thorium in a commercial-scale reactor would have to be demonstrated and licensed, and a joint industry/government RD&D program established to continue research to demonstrate the use of thorium in a commercial-scale reactor, to demonstrate fuel fabrication and recycling, to test the system, and to license the facilities.

It is apparent that thorium can be commercialized only if the federal policy actions discussed above are effective in overcoming the utilities' present reluctance to invest in nuclear units, despite the apparent long-term benefits. Thorium can extend the life of uranium reserves and increase the market share of nuclear power in electric power generation at a lower cost for electricity. But these benefits must be demonstrated to the nuclear industry, a process that calls for firm governmental policy decisions -- particularly on the recycling of fuel -- and a vigorous research, development, and demonstration program.

Introduction

Electric power accounts for an increasing share of the energy used in the United States. Between 1965 and 1976, electricity's share of all energy consumed nationally rose from 21 percent to 29 percent.

The role of nuclear power in generating electricity has expanded even more dramatically. In the same period, nuclear power's share of electrical energy production rose from a negligible percentage to approximately 9 percent. The federal government and industry have established extensive programs of nuclear research and development aimed at improving the performance of nuclear technologies and reducing the cost of producing electricity by nuclear power. The utilities, at the same time, have purchased nuclear plants for baseload generating capacity to capitalize on the perceived economic advantages offered by nuclear power.

The predominant type of nuclear power plant in the United States is the light-water reactor (LWR) fueled with uranium slightly enriched in the uranium-235 isotope. However, as LWR systems have been deployed, the federal government and private industry have continued research and development of other types of reactors and fuels that promise improved fuel utilization and lower cost. The most intensive effort has been made in developing the plutonium-fueled liquid-metal fast breeder reactor (LMFBR), which is believed to be capable of producing power economically by utilizing the abundant uranium isotope, U-238.

Although research and development of other reactors and fuels continue, the LWR and LMFBR systems, fueled with U-235 and plutonium, have figured largest in utility and government planning. The LMFBR, because of its predicted economic performance and more-efficient use of uranium, has generally been considered the nuclear

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technology of the future; the LWR serves as an interim technology until the breeder becomes available.

This view of the nuclear future has recently been brought into question. The development and demonstration of the LMFBR has been slower than expected, in part because of technical difficulties and in part by government decision. Uranium prices have also increased significantly, raising the prospect of uranium shortages in the 1980s. Moreover, concern has been growing in the United States and abroad over the widespread use of nuclear materials, particularly plutonium, and the potential hazard that they could be diverted and used for the manufacture of nuclear weapons. The problems of proliferation are under study by the government, and, until they are resolved, President Carter has deferred indefinitely the construction of the demonstration LMFBR and the licensing of a facility for reprocessing nuclear fuels to recover unused uranium and plutonium fuels. Alternatives to, or modifications of, the present nuclear fuels are being investigated to determine if they would be less vulnerable to diversion and use in weapons.

The thorium fuel-cycle is one of these alternatives.

Thorium is a "fertile" material; that is, it cannot be used directly as a fuel but can be converted in a nuclear reactor into the "fissile" uranium isotope, U-233, which can serve as a fuel. Thorium has been considered in the past as an alternative fertile material for a variety of reactors, including the LWR, the spectral-shift controlled reactor (SSCR), the high-temperature gas-cooled reactor (HTGR), the heavy-water reactor (HWR), and advanced breeder reactors. The technical and economic aspects of its use in nuclear power plants have been evaluated in a number of studies that, while varying in specific conclusions, generally agree on three points:

1. Thorium fuels appear to be technically feasible in certain reactor applications, such as LWRs, HTGRs, and HWRs, such as those now in use in Canada
2. In thermal reactors (including LWRs, HTGRs, and HWRs), thorium appears to offer more energy-efficient use of the available uranium resources than uranium fuels alone

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3. At the price levels assumed in the studies, thorium applications appear to be less economical than the present LWR/uranium system in the total cost of delivered power.

The rising concern over uranium supplies and the hazard of proliferation warrant a reappraisal of these conclusions and a renewed investigation of the role for thorium in the nuclear market.

The Thorium Assessment Program (TAP) was therefore initiated in October 1976 under the direction of the Division of Nuclear Research and Applications (NRA) of the Energy Research and Development Administration (now absorbed into the U.S. Department of Energy). The program involved 12 organizations, including various government agencies, research laboratories, and private firms, whose purpose was to answer three questions:

- Is there a need for thorium use?
- Does the use of thorium provide an advantage over alternatives?
- Is the use of thorium commercially viable?

The organizations participating in TAP are:

1. Energy Research and Development Administration (ERDA), now part of the Department of Energy
2. Argonne National Laboratory (ANL)
3. Brookhaven National Laboratory (BNL)
4. Combustion Engineering, Inc. (CE)
5. General Electric (GE)
6. Electric Power Research Institute (EPRI)
7. Hanford Engineering Development Laboratory (HEDL)
8. Lawrence Livermore Laboratory (LLL)
9. Massachusetts Institute of Technology (MIT)
10. Oak Ridge National Laboratory (ORNL)
11. Resource Planning Associates, Inc. (RPA)
12. United Engineers and Constructors (UE&C).

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RPA was engaged by NRA to evaluate the commercial viability of thorium use, building on the technical work performed by other participants.

TAP was originally designed as a 2-year study.¹
The first year's work consisted of:

1. A review of earlier analyses of thorium. The program participants investigated studies in their respective fields, and an overall review was carried out by NRA, CE, and RPA. Summaries of some of the major investigations are included in Appendix D.
2. Technical evaluations of thorium applications. TAP participants analyzed thorium applications in different reactors and fuel-cycles, investigating optional designs and the technical, cost, and uranium-utilization characteristics of these applications. Technical performance data from these studies were provided to the HEDL for use in the systems analysis described in the report reproduced as Annex 1 in Volume 2 of this report. The results of the various technical investigations have been summarized in a report by CE that appears as Annex 2.
3. Analysis of market structure and decision criteria. As a first step in assessing the commercial viability of thorium-based reactors, RPA analyzed the structure of a nuclear-power industry organized to supply thorium and thorium-fueled reactors. We also examined the criteria likely to be used by the participants in such an industry for deciding whether or not to become involved in a thorium-based industry. We identified the corporations that constitute the present nuclear-power industry and the changes in the industry that would be required to support a market for thorium fuels, both in operating power plants and in future power plants. Representatives of utilities and nuclear suppliers were then surveyed to determine their interest in thorium, the criteria they would use to decide whether or not to enter their sector of the thorium industry, and the conditions under which they would enter it. Potential licensing constraints were

1. Methodology for a Thorium Assessment Program (October 8, 1976), prepared by RPA, is a detailed description of the methodology and organization of TAP.

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established through a survey of regulatory bodies. The results of the survey are embodied in this report and are summarized in Appendixes A and B.

4. Systems analysis of thorium options. The HEDL Advanced Linear Programming System (ALPS) mathematical model of the electrical energy system was used to compute nuclear and fossil power growth patterns. The model is based on the linear programming technique and determines the mix of nuclear and fossil plants that minimizes the total cost of generating electricity over a given period of time. The reactors selected to compete with coal were LWRs, represented by pressurized-water reactors (PWRs); spectral-shift controlled reactors (SSCRs); HWRs, represented by Canadian deuterium uranium reactors (CANDUs); HTGRs; and fast breeder reactors (FBRs), represented by LMFBRs. Different fuel-cycles (U-235, U-233, and plutonium with U-238, thorium, or a combination of both as the diluent) were included in each of the four basic reactor types, resulting in a total of 24 reactor/fuel-cycle combinations. These combinations are discussed in detail in Chapter 2, and are described by HEDL in Annex 1, Volume 2, and in their report, Reactor Design Characteristics and Fuel Inventory Data (September 1977).

Using combinations of these fuel-cycles and reactors, the model determined average levelized power costs for each system and calculated uranium oxide and coal requirements, enrichment services, fissile fuel supply, reprocessing requirements, and capital requirements for building supply facilities under four optional federal policies concerning the reprocessing and recycling of fuels. These policies, selected by NRA for investigation, are:

- No recycle, representing the present federal policy, prohibiting the reprocessing and recycling of any fuel. This policy scenario was included to establish whether or not a change in the present government reprocessing policy is a prerequisite for commercial deployment of thorium.
- Uranium-recycle only, prohibiting the recycling of plutonium. This policy was selected to determine if industry investment criteria would be met for thorium technologies under conditions most favoring the thorium fuel-cycle over the uranium cycle.

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- Recycle of plutonium in secure centers only, with recycle only of denatured uranium fuels in reactors outside the centers. This policy was selected to determine the potential market for thorium in reactor/fuel-cycle combinations being evaluated in other government programs aimed at reducing the likelihood of nuclear proliferation.
- Full recycle, permitting reprocessing and recycling of all uranium and plutonium fuels without restriction on fuel composition. This policy was selected to determine whether a reversion from the present federal policy to the policy previously expected by the nuclear industry would preclude the possibility of industry investment in the thorium fuel-cycle.

5. Analysis of commercial viability. RPA examined the economic potential of different thorium applications under each of the four policies for reprocessing and recycle, on the basis of HEDL's results. The economically preferred options were then evaluated against noneconomic barriers to determine ease of commercialization, and preliminary steps to overcome these barriers were identified.

The results of this analysis are the subject of this report and will form the basis for deciding whether or not to continue the assessment of thorium in the second year of the program. However, these results are subject to a number of important qualifications.

First, the analysis is based on data developed during the first year of the study, which is as yet incomplete because several investigations are still in progress, and data from other applications have not been made available to TAP. Data were not included, specifically, for an HWR with slightly enriched uranium fuel designed for use in the United States; for an LWR design optimized for thorium; for a boiling-water reactor using thorium; and for a light-water breeder reactor (LWBR). These applications have not been considered explicitly, and the results of the investigations could modify our conclusions.

Second, the nuclear market is greatly influenced by the actions of the federal government. A change in policy will change the market for nuclear goods and services

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and the timing of changes in public policy is dependent on the decisions of an Administration and a Congress whose composition and outlook can change. Consequently, policy changes are difficult to predict. We have therefore examined thorium under today's market conditions and also under different policies that we expect to alter today's market conditions.

Finally, our conclusions have not yet been fully reviewed and validated by representatives of the industries that would supply that market.

With these qualifications, we conclude that, with rising uranium prices, thorium appears to have sufficient promise for producing electricity more economically and for extending our uranium resources that the evaluation of thorium should be continued to ensure that the thorium fuel-cycle options under consideration in TAP and other government programs are, in fact, technically and economically viable in the commercial marketplace.

This overall conclusion is based on a number of findings.

Specifically, we find on the basis of interviews with the utilities and the Reliability Councils that, although the electric utilities project a need for over 350 GW(e) of installed nuclear capacity by 1996, they are cautious, and even pessimistic, about investing in the LWR with a uranium once-through cycle. The industry's major interests at the moment are the reduction of time and risk in the licensing process and the improved operating performance of LWRs. The commercialization of thorium does not appear necessary or useful to the industry under the present market conditions.

More specifically, we find that, in the industry's view:

- In a favorable regulatory environment, additions of 358 GW(e) of nuclear generating capacity, or 44 percent of total planned capacity additions, will be needed by 1996. However, 65 percent of the capacity will be installed between 1987 and 1996 with major procurements during the 1980s. The market is therefore still susceptible to the influence of federal policy.
- The electric utilities perceive the supply of uranium as adequate to meet their demands and do not

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perceive thorium as necessary to augment uranium supplies. In fact, they view the commercial introduction of thorium as an unnecessary complication in an already difficult licensing climate and fuel market.

- The electric utilities do not perceive thorium on a once-through cycle as competitive with uranium on a once-through cycle.
- The electric utilities surveyed during the study strongly favor the development of federal policy permitting the recycling of fuel, continuing development of the FBR, and streamlining the nuclear regulatory process, before thorium is commercialized.
- The supplier industries will not limit the growth of a thorium market if the demand for thorium develops. However, they will not invest in production or service capacity until federal policy clearly establishes a role for thorium, and until contracts for goods and services are negotiated with electric utilities.
- The financial industry perceives the current market as risky for many utilities that are building nuclear units. The introduction of thorium would constitute an additional risk not justified under current regulatory and energy policy. However, under a favorable energy policy, the supply of capital will not be a constraint in the commercialization of thorium.

The potential market for electric power plants appears to be gaining strength once again, and a strong market should continue into the 1980s. Therefore, the potential for nuclear power is good also, under favorable government policies. However, the present market for nuclear goods is, at best, merely holding its own. Federal policy and regulation must change if the condition of the market is to change. The utilities and supplier industries perceive that the future market potential is delicate and can easily evaporate if uncertainties persist or if future policies or regulations are adverse. A new fuel is viewed as an unnecessary complicating factor in this market.

Stabilizing nuclear policy is the critical step in the commercialization of thorium. The market awaits a clear policy on fuel reprocessing and recycling, on the availability of the FBR, on waste storage, on plant decommissioning, and on regulatory requirements for the

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licensing of plants. These policies are external to consideration of thorium, but they have a definite influence on its market. A more stable and positive policy toward nuclear power will result in a more receptive market for thorium in current LWRs or new reactors. If thorium is to be commercialized, critical decisions must be made by the federal government. First, policy must be stabilized and regulatory procedures streamlined to facilitate the development and use of nuclear units and to forestall the dispersal of expertise and manufacturing capability that will be required in the 1980s and 1990s. Second, the policy and procedures must be implemented and their effects realized in increased procurements of LWRs. Third, the decision to deploy thorium must be made; this will also entail a change in federal policy. TAP studies show that the prerequisite to effective penetration of the nuclear market by the thorium fuel-cycle is a policy permitting the reprocessing, fabrication, and recycling of fissile fuel.

Under the present policy prohibiting recycling of any fuels, TAP investigations have indicated that thorium cycles are not economically competitive with the low-enriched uranium cycles.² Thorium fuels typically contain much larger amounts of enriched uranium in the initial fuel loading and in the spent fuel in the same reactors. HTGRs and the German pebble-bed reactors are exceptions; in these reactors, the use of thorium fuels in once-through cycles appears to produce slightly better uranium-resource utilization than the use of low-enriched uranium.³

2. Keith C. Garel and Michael J. Driscoll, Massachusetts Institute of Technology, Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems (MIT-EL-777-018: October 1977); and Combustion Engineering, Inc., Assessment of Thorium Fuel Cycles in Pressurized Water Reactors (EPRI-NP-359: February 1977).

3. E. Teuchert, "Once Through Cycle in the Pebble Bed HTR," presented at the American Nuclear Society Winter Meeting, San Francisco, California, November 27-December 2, 1977; and Reactor Design Characteristics and Fuel Inventory Data, Hanford Engineering Development Laboratory (September 1977).

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To examine the market potential for thorium under the three recycling policy scenarios, the quantitative potential of a thorium market was forecast for each policy by the Hanford Engineering and Development Laboratory's ALPS model. However, forecasting beyond the utilities' planning horizon of 20-30 years is uncertain because of the number of imponderables involved: possible shifts in government policy; the future financial condition of the utilities; fluctuations in demand; and changes in fuel prices and in the capital cost of generating equipment. Consequently, the feasibility of introducing thorium in LWRs, SSCRs, HTGRs, and HWRs was also evaluated qualitatively.

Technically, commercializing thorium in the LWR is less difficult than in the SSCR, HTGR, or HWR. The commercialization of the SSCR appears, on the basis of TAP data, to be less difficult than the HTGR or HWR because the SSCR is essentially an LWR modified to use available heavy-water technology. Moreover, the SSCR is adaptable to a nuclear economy consisting of LWRs and LMFBs. The HTGR has already encountered difficulty in entering the commercial market, and requires a different reprocessing technology. The HWR has not been designed and built to U.S. licensing standards. Clearly, therefore, the commercialization of thorium is most likely to succeed, initially, in LWRs, with which the regulatory agencies, the utilities, and the supplier industries are most familiar.

If the government acts to deploy thorium, HEDL simulations indicate that the market potential for thorium between 1977 and 2025 could develop as follows:

- Under a uranium-recycle only policy, a total of 748 GW(e) of nuclear capacity could be installed by 2026, of which 623 GW(e) are thorium-cycle HTGRs and 125 GW(e) are LWRs. This represents a 34-percent nuclear penetration of the electric power generation market. More efficient U_3O_8 ore utilization and lower average levelized costs give the HTGR its competitive edge over the other technologies. The SSCR would be the next most efficient thorium-fueled reactor under this policy, with a nuclear penetration of 30 percent.

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- Under a recycle of plutonium in secure centers policy, a total of 1,453 GW(e) of nuclear capacity could be installed by 2026, with a 66-percent nuclear penetration of the electric power generation market. Of this total, 861 GW(e) would be SSCRs (366 GW(e) thorium-fueled); 420 GW(e), FBRs; and 172 GW(e), LWRs. The economic edge developed by SSCRs under this policy is due, in part, to their symbiotic relationship with FBRs; SSCRs produce plutonium for use in FBRs, which, in turn, produce U-233 fuel for SSCRs. (The HTGR would be the next most efficient thorium-fueled reactor under this policy, with a nuclear penetration of 63 percent.)

- Under a full-recycle policy, 1,453 GW(e) of nuclear capacity could be installed by 2026, with a 66-percent nuclear penetration of the electric power generation market. Of this total, 818 GW(e) would be HTGRs; 360 GW(e), FBRs; and 230 GW(e), LWRs. With full recycle, the nuclear systems including the HTGR achieve the most efficient uranium ore utilization. (A uranium-fueled SSCR was calculated to be the next most efficient reactor under this policy; however, its performance might have been matched or exceeded by the thorium-fueled SSCR, had thorium-fueled SSCRs been included in the ALPS runs.)

HWRs, at the capital costs assumed in this analysis, were not competitive with the HTGR or SSCR under any of the four federal recycle policies. HWRs were projected to develop in a recycle of plutonium in secure centers policy, but only because they were the only converter reactor option included in the scenario analyzed that could utilize bred U-233 fuel. HTGRs and SSCRs both achieved higher levels of penetration in the scenarios in which they were the converter reactors using bred U-233. However, recent studies have indicated that the capital cost for an HWR designed to meet U.S. licensing criteria may be significantly less than assumed by HEDL; with these lower costs, the HWR's competitive position would be improved.⁴

4. United Engineers and Constructors, Inc., Commercial Electric Power Costs: Capital Cost, Pressurized Heavy Water Reactor Plants (COO-2477-13: June 1977).

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The use of thorium with recycling of fissile material produces lower total systems costs than the present once-through system because the economic benefits of the recycled fuel more than offset the costs of recycling. The HTGR and SSCR (in conjunction with the FBR) contribute most to lowering total systems costs. If either SSCRs or HTGRs are deployed, the HEDL model projects reductions in systems costs of \$100-\$125 billion nationally (with a 4.5-percent discount factor) under the recycle in secure centers or full-recycle policies. If a uranium-recycle only policy is selected, the savings drop to \$10-\$17 billion.

As mentioned above, the commercialization of thorium in the LWR is less difficult than in the SSCR or HTGR, and the commercialization of the SSCR is likely to be less difficult than the HTGR. The SSCR is also adaptable to a nuclear economy consisting of LWRs and LMFBRs. Consequently, the technical and economic risks of commercializing the SSCR are lower than, and its economics comparable with, the HTGR. The preferred system for commercializing thorium appears to be its introduction in LWRs, followed by the deployment of thorium-based SSCRs as they become available.

The major barriers to the commercialization of thorium can be summarized as:

- The constraints on the market for any nuclear goods stemming from the problems already experienced with LWRs.
- The utilities' present lack of interest in thorium as an alternative to the uranium-plutonium fuel-cycle, and in any alternative reactor to the LWR.
- The lack of a clearly defined, permanent federal policy for nuclear fuel reprocessing and recycling, which adversely influences the economics of using thorium fuel in commercial power reactors.
- The lack of a clearly defined, permanent policy on the development of FBRs, creating the risk of a return to a policy favoring plutonium breeders that would jeopardize investments in thorium reactors.

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- The lack of a demonstration of thorium fueling, with the related reprocessing and recycling technology, on a commercial scale (approximately 1000 MW(e)).
- The uncertainty that a reactor using thorium fuels and the supporting reprocessing technology are licensable without undue design changes and delays.

The first four of these barriers can be overcome only by policy decisions -- stable policy decisions that will remain in effect for 20-30 years. The last two barriers can be overcome by RD&D programs requiring substantial funding and a commitment to demonstrate that thorium's potential can be achieved on a commercial scale.

Although our primary objective was to identify the barriers to commercializing thorium, not to determine precisely how to overcome them, some actions to overcome the barriers are clearly suggested, although they warrant considerably more analysis and definition.

The lack of commercial interest in thorium stems from the lengthy list of nuclear problems faced by utilities and suppliers. If those problems persist, an interest in thorium will not develop.

When these problems have been resolved to the satisfaction of the utilities, a federal policy decision to deploy thorium would begin to arouse the market's interest. A federal policy favorable to recycling is essential to the deployment of thorium, and the benefits of thorium improve if the recycling of uranium and plutonium is also permitted. Such a policy would be a positive signal to the market for thorium.

Active implementation of a federal policy streamlining the regulatory process would encourage even more interest in thorium and new reactor designs. And finally, a decision on the fast breeder reactor, favorable or unfavorable, would help to establish which thorium-fueled reactor would be most economically efficient.

These are difficult decisions with a high level of public sensitivity, but, without them, there is virtually no prospect of thorium's entering the commercial market.

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These policy decisions alone, however, will not bring about the commercialization of thorium. Further decisions are needed to select the most-efficient types of reactor and fuel-cycle technology for development, to avoid dissipating the resources of industry and the government. The LWR is the technology in which the commercial potential of thorium can be demonstrated most convincingly because it involves less technical and licensing risk than others.

The use of thorium in a commercial-scale reactor would have to be demonstrated and licensed, and a joint industry/government RD&D program established to continue research to demonstrate the use of thorium in a commercial-scale reactor, to demonstrate fuel fabrication and recycling, to test the system, and to license the facilities.

It is apparent that thorium can be commercialized only if the federal policy actions discussed above are effective in overcoming the utilities' present reluctance to invest in nuclear units, despite the apparent long-term benefits. Further investigation into the use of thorium is therefore warranted. Thorium can extend the life of uranium reserves and increase the market share of nuclear power in electric power generation at a lower cost for electricity. But these benefits must be demonstrated to the nuclear industry, a process that calls for firm governmental policy decisions -- particularly on the recycling of fuel -- and a vigorous research, development, and demonstration program.

These conclusions are based upon the evidence presented in the following chapters.

In Chapter 1, "The Market for Nuclear Power," we describe the future nuclear market as it is now perceived by the utilities, and the perceptions of the utilities and the supply industries of thorium's potential role in the market.

In Chapter 2, "The Potential Market for Thorium," we analyze the performance of thorium under various federal reprocessing and recycling policies that will alter the utilities' present view of thorium, and compare the performance of various thorium-based technologies under

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these options to establish the technologies warranting further development and demonstration with government support.

In Chapter 3, "Federal Policy Options for Commercializing Thorium-Based Technologies," we outline a federal policy program for developing preferred thorium technologies to the point of full commercialization.

The argument developed in these chapters is supported by three appendixes:

- Appendix A: The Market for Thorium Potential as Perceived by the Nuclear Industry
- Appendix B: Barriers to Commercialization of the Thorium Fuel-Cycle
- Appendix C: Future Work to Assess Thorium Commercialization
- Appendix D: Summaries of Selected Thorium Evaluations.

Two technical reports providing the data base for our analysis have been appended in Volume 2 of this report with the permission of the authors. They are:

- Annex 1: Thorium Assessment Program Systems Studies*
- Annex 2: Technical Aspects of Thorium Utilization.

* The data base for Annex 1 is included in HEDL's Reactor Design Characteristics and Fuel Inventory Data, Volumes 1 and 2 (September 1977).

1

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NUCLEAR POWER

In the past decade, the utility industry has operated in an increasingly unpredictable environment, and the utilities' investment decisions have become progressively more difficult to make. The rate of increase in the demand for electricity has dropped sharply, from an annual average of 7.1 percent in 1968 to an estimated 5.2 percent in 1978.¹ Environmental regulation of the use of coal has become increasingly stringent. At the same time, the future of nuclear power has been clouded by uncertainty in government policy. Delays in the approval of federal and state licenses have increased the already high capital costs of nuclear plants, and policies regarding the recycling of uranium and plutonium, waste disposal and spent-fuel storage, and the further development of the breeder reactor are unclear.

Despite these uncertainties, the utilities clearly regard nuclear power as a major source of electric generating power over the next two decades, and their decisions, more than any other factor, will shape the future mix of technologies.

The commercial potential for thorium, then, is dependent essentially on the utilities' perception of the most feasible balance of added baseload capacity needed to meet future demand. However, federal and state regulatory agencies must also be convinced that thorium-fueled plants are preferable technologically, economically, and financially.

Our survey of utilities and potential suppliers of a thorium market indicates that under present conditions a spontaneous demand for thorium is unlikely to develop in the utility industry itself. The industry's view of the development of nuclear power has remained essentially

1. National Electric Reliability Council, Fossil and Nuclear Fuel for Electric Utility Generation: Requirements and Constraints 1977-1986, (1977).

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unchanged; they regard the breeder reactor on the uranium-plutonium cycle as the ultimate nuclear technology and the present generation of nuclear reactors -- in effect, the light-water reactor on the once-through uranium cycle -- as an interim technology. They feel they have access to adequate and secure supplies of uranium over the next 20-30 years, their normal planning horizon, and see no convincing reason for adopting the less well known and less-economical thorium as a supplement. The difficulties they have encountered with the familiar LWR technology have also made them cautious of experimenting with other new reactor technologies designed for improved economics, such as the spectral-shift controlled reactor, the heavy-water reactor, or the high-temperature gas-cooled reactor, until regulation becomes reasonable and consistent, and a national nuclear policy is clearly articulated.

Consequently, the utilities' present plans for nuclear baseload additions are confined to LWRs with uranium fuel, and, possibly, plutonium in the future. If thorium is to become a part of the fuel mix in electric power generation, the utilities must perceive the need for changing their investment plans.

From the utilities' viewpoint, such a change would not be contemplated unless the economic conditions under which they operate (particularly system costs and the cost and availability of uranium) change significantly, and governmental policy and regulations favoring thorium are formulated. However, they do not foresee either eventuality as likely. And until the utilities decide to invest in thorium technologies, the supply industry for thorium will not develop.

The nuclear market is unusual in that supply is determined by demand, that is, by the utilities' investment and purchasing decisions. Our survey of potential thorium supply industries indicates that they will not anticipate the development of demand, but can make a rapid transition to thorium if the demand develops.

The future demand and supply for nuclear power form the context for evaluating the commercial potential for thorium. In the following sections, we examine in more detail the potential demand for nuclear power, on the basis of the utilities' plans for investing in additional capacity, and the potential supplier

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industries, with particular emphasis on the utilities' and suppliers' perception of thorium.

THE POTENTIAL DEMAND FOR NUCLEAR POWER

According to our survey of electrical reliability councils and individual utilities, the utility industry plans to add slightly more than 838 GW of capacity to its present baseload capacity by 1996. Nuclear plants will supply 43 percent of the additional capacity, only slightly less than the projected coal-fired share.

The following table shows the additions planned nationwide for every year from 1977 to 1986 and for the period 1987-1996.

Planned Additions to Capacity (GW) in 48 Contiguous States 1977-1996

Total Additions: 838.3 GW
Total Nuclear: 356.4 GW (43%)
Total Coal-fired: 365.1 GW (44%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	32.3	25.8	27.3	34.1	32.6	32.4	33.8	39.4	39.8	32.1	509.1
Nuclear (GW)	9.5	5.1	8.3	11.3	12.6	14.8	17.4	18.0	14.8	32.1	231.9
Nuclear (%)	29	20	30	33	39	46	52	46	37	40	46
Coal-fired (GW)	11.1	11.4	11.8	15.9	12.3	13.1	9.7	15.7	17.0	15.2	231.9
Coal-fired (%)	34	44	43	47	38	40	29	40	43	47	46
Other (GW)*	11.7	9.3	7.2	6.9	7.7	4.5	6.5	5.7	7.8	4.2	45.3

SOURCES: (for 1977-1986 data) National Electric Reliability Council, *Fossil and Nuclear Fuel for Electric Utility Generation: Requirements and Constraints, 1977-86*; (for 1987-1996 data) utilities' capacity projections and anticipated fuel-mix ratios, supplied by regional reliability councils.

*Includes hydroelectric, oil-fired, gas-fired, and geothermal and plant upratings; also plant retirements and deratings as net reductions to the additions. Data are for plants announced by utilities as planned or under construction (80% of plants scheduled for completion by 1986 are under construction).

As the table shows, the addition of nuclear units is modest in 1978 and 1979. However, from 1980 to 1996 a more active nuclear industry will develop, and the orders placed during this period for capacity additions represent a total addition of approximately 356 power plants, with the uranium fuel services, engineering services, and equipment to support the plants.

Exhibit 1.a

Planned NERC Additions
to Capacity (1996)

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These figures are a compilation of projections by the regional reliability councils whose jurisdictions cover the 48 contiguous states (see Exhibit 1.a). Within each region, however, the balance of nuclear, coal-fired, and other capacity varies quite considerably.

The Northeast Power Coordinating Council (NPCC) is almost completely committed to nuclear power, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Northeast Power Coordinating Council

Total Additions: 50.5 GW
Total Nuclear: 38.8 GW (76%)
Total Coal-fired: 1.7 GW (3%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	0.9	1.2	0.6	0.9	0.7	2.5	0.1	3.9	3.0	1.1	35.6
Nuclear (GW)	0	0.3	0	0.9	0	2.2	0	2.2	2.3	1.1	29.6
Nuclear (%)	0	27	0	100	0	100	0	56	77	100	84
Coal-fired (GW)	0	0.3	0	0	0	0	0	0.7	0.7	0	0
Other (GW)*	0.9	0.6	0.6	0	0.7	0.3	0.1	1.0	0	0	6.0

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

This commitment is heavily influenced by the inadequacy of the region's transportation network to meet the demand of the utilities for coal, and by stringent air-quality standards that create difficulties in siting coal facilities near the region's main demand centers.

Because the region's utilities are committed to nuclear power, and their operating experience with nuclear units has been satisfactory, they were open to the consideration of thorium. However, they feel that a supplementary fuel source is not needed because their contracted uranium supplies are secure and reserves adequate. They also questioned the need for new reactors other than the fast breeder. However, NPCC utilities would consider thorium as a fuel in an LWR or in a reactor designed to optimize thorium use if the system were economically competitive with other baseload systems and could be licensed as rapidly as an LWR on the uranium once-through cycle.

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The utilities of the Mid-Atlantic Area Council (MAAC) are also heavily committed to nuclear units, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Mid-Atlantic Area Council

Total Additions: 44.5 GW
Total Nuclear: 26.4 GW (59%)
Total Coal-fired: 10.4 GW (24%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	3.1	0.9	1.5	1.6	0.7	1.8	3.1	1.9	2.7	4.3	22.9
Nuclear (GW)	2.0	0.9	1.1	1.0	0	1.0	2.2	1.1	2.2	3.4	11.5
Nuclear (%)	67	100	73	63	0	56	71	58	81	79	50
Coal-fired (GW)	0.3	0	0.4	0	0	0.7	0	0.8	0	0.8	7.4
Other (GW)*	0.8	0	0	0.6	0.7	0.1	0.9	0	0.5	0.1	4.0

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

The past economic performance of the LWRs has encouraged the MAAC utilities to continue procuring nuclear units, and approximately 60 percent of their capacity additions will be nuclear. Some coal-fired capacity will be built in those areas of the region, such as Pennsylvania, closest to coal reserves; however, the regional air-quality standards limit the use of coal in the region, particularly in the more industrialized sectors.

The cost of nuclear units does not appear to be a constraint in this region because many of the utilities are large corporations, some with assets of over \$2 billion. Project financing is not as difficult for them as it is for the smaller or medium-sized utilities characteristic of other regions.

The MAAC utilities questioned the need for thorium because they consider uranium supplies adequate; they also questioned the need for new technologies other than the fast breeder. The potential of thorium was not dismissed, but thorium would be seriously considered only if demonstrably competitive with coal and with LWRs on the once-through cycle under the present nuclear policy.

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The Southeastern Electric Reliability Council (SERC) projects a more balanced mix of nuclear and coal-fired capacity, but is also heavily committed to nuclear power, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Southeastern Electric Reliability Council

Total Additions: 185.4 GW
Total Nuclear: 88.8 GW (48%)
Total Coal-fired: 76.1 GW (41%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	7.7	5.5	7.8	6.8	4.1	5.5	9.7	11.6	7.1	7.9	111.7
Nuclear (GW)	4.5	1.1	6.0	4.5	1.3	2.1	6.5	7.1	3.8	2.2	49.7
Nuclear (%)	58	20	77	66	32	38	67	61	54	28	45
Coal-fired (GW)	0.1	2.5	1.1	1.2	1.6	3.0	1.9	3.5	2.8	4.8	53.6
Other (GW)*	3.1	1.9	0.7	1.1	1.2	0.4	1.3	1.0	0.5	0.9	8.4

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

Approximately 90 GW of additional nuclear capacity, half of planned new capacity, is scheduled to come on line by 1996; coal-fired units will supply approximately 76 GW, or 40 percent of the new capacity. However, the attitude to nuclear power varies within the region.

In the northern half, the utilities retain a preference for nuclear units despite the fact that some of them have experienced delays in plant availability, cost overruns, and licensing difficulties. Utilities in the Tennessee Valley, Virginia, and the Carolinas plan for nuclear capacity amounting to approximately 65 percent of total additions.

In Georgia, Alabama, and Mississippi, some utilities have failed to obtain adequate rate relief; as a result, they are unable to generate the cash flow needed to finance a nuclear unit. In Florida, the lengthy lead-times for nuclear plants caused by licensing uncertainty have influenced the utilities to favor coal, and in all these states the smaller utilities view nuclear investments as unacceptably risky. The cost of a nuclear unit in the 1,000-MW range would severely strain the resources of smaller utilities, which cannot generate the cash flow internally to finance 35 percent of the investment.

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Unforeseen increases in cost or critical delays due to licensing problems or third-party interventions in the licensing process could place these utilities in financial jeopardy.

In general, the additions planned by the utilities in different parts of the SERC region reflect the utilities' financial capacity. Those favoring coal are adding smaller coal-fired units that can be built more rapidly than nuclear units and that, being less subject to federal regulation, are less susceptible to project delay with the consequent risk of capital exposure. On the other hand, utilities in a strong financial position are adding nuclear capacity because they can absorb the cost of the larger nuclear units and are less exposed to the risk of licensing delays and rising costs.

State regulatory agencies in the SERC region expressed concern over the financial risks of investing in nuclear plants. They feel that federal regulation of nuclear plants creates uncertainty in the scheduling of plant availability, removes control of timing and availability of new capacity from their jurisdiction, and prevents state public utility commissions from meeting their responsibility for continuous electric supply.

The attitude of the SERC utilities toward thorium is guarded; they believe the present nuclear policy needs to be stabilized and the regulation of the LWR-uranium cycle streamlined before any new fuel or reactors are considered.

In the East Central Area Reliability Coordination Agreement (ECAR), coal-fired units will make up the largest share of capacity additions (approximately 56 percent) by 1996, as the following table shows.

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Planned Additions to Capacity (GW) 1977-1996

East Central Area Reliability Coordination Agreement

Total Additions: 137.2 GW

Total Nuclear: 53.2 GW (39%)

Total Coal-fired: 77.4 GW (56%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	6.2	2.7	2.7	4.7	5.9	4.7	5.3	2.6	4.2	1.6	96.6
Nuclear (GW)	1.4	1.9	0	1.1	3.0	2.0	2.2	0	0.9	1.1	39.6
Nuclear (%)	23	70	0	23	51	43	42	0	21	69	41
Coal-fired (GW)	4.1	0.7	1.9	4.6	2.9	2.7	2.6	2.5	2.3	0.5	63.1
Other (GW)*	0.7	0.1	0.8	0	0	0.5	0.5	0.1	1.0	0	3.96

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

The coal reserves in the ECAR region have heavily influenced the preference toward coal; at the same time, the effects of federal regulation on operational availability and cost have induced caution toward nuclear procurements. Even so, over 53 GW of nuclear capacity is planned by 1996.

The ECAR utilities also questioned the need for thorium and for new nuclear technologies. They feel that current uranium reserves are adequate for their foreseeable needs and will not consider a change in fuel type until the present problems in licensing LWRs have been resolved.

The utilities of the Mid-America Interpool Network (MAIN), like the ECAR utilities, project a diversified fuel mix. Additions to coal-fired capacity are slightly larger than additions to nuclear capacity, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996

Mid-America Interpool Network

Total Additions: 77.0 GW

Total Nuclear: 33.4 GW (43%)

Total Coal-fired: 36.4 GW (47%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	2.7	2.7	2.1	1.9	4.2	5.7	0.7	2.4	3.1	3.7	47.8
Nuclear (GW)	0	0	1.1	1.1	2.7	3.9	0.2	0	1.0	0.7	22.7
Nuclear (%)	0	0	52	58	64	68	29	0	32	19	47
Coal-fired (GW)	1.6	1.4	0	0.5	1.2	1.4	0.4	0.6	2.1	2.1	25.1
Other (GW)*	1.1	1.3	1.0	0.3	0.3	0.4	0.1	1.8	0	0.9	0

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

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In this region, as in ECAR, air-quality standards will limit coal use in the more heavily populated and industrialized areas, particularly in Illinois. This constraint more than offsets the utilities' concerns over the cost of, and regulatory delays to, nuclear plants.

Most of the region's added nuclear capacity is projected to come on line between 1987 and 1996. The long delay allows the utilities to postpone construction or to switch to coal-fired units if they encounter difficulties in financing a planned nuclear unit or licensing uncertainties increase.

The utilities in the region were interested in the potential of thorium and would consider adopting the fuel and the reactors using it if they prove to be economically competitive with the conventional LWR and coal-fired units.

The utilities and public utility commissions in the Southwest Power Pool (SPP) region strongly favor coal-fired units for future capacity additions, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Southwest Power Pool

Total Additions: 115.6 GW
Total Nuclear: 33.7 GW (29%)
Total Coal-fired: 70.7 GW (61%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	3.5	3.0	2.8	6.1	4.8	3.7	3.8	5.6	7.4	4.6	70.3
Nuclear (GW)	0	0.9	0	0	2.4	0.8	1.9	2.2	0.9	0	24.6
Nuclear (%)	0	30	0	0	50	22	50	39	12	0	35
Coal-fired (GW)	1.6	2.0	1.6	4.6	1.0	2.6	1.7	2.9	3.3	3.9	45.5
Other (GW)*	1.9	0.1	1.2	1.5	1.4	0.3	0.2	0.5	3.2	0.7	0.2

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

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The utilities in the region are convinced that the LWR-uranium cycle is technically sound and the fuel supply adequate, but are concerned about cost. They expressed the view that licensing requirements were imprecise and design criteria not necessarily developed on a sound technical basis. Consequently, they could not anticipate design requirements with any confidence and, by committing themselves to a nuclear plant, could incur rapidly escalating costs from changed requirements and licensing delays. A number of utilities have abandoned plans for additional nuclear capacity after the units under construction are completed. They will rely on coal-fired baseload units for the future.

Despite the preference for coal, a substantial amount of nuclear capacity -- over 30 GW -- is planned from 1977 to 1996; however, over 70 percent of this capacity is planned to come on line after 1987.

There was very little interest in thorium in this region because coal is abundant and uranium supplies are perceived as adequate. The utilities also feel that problems with the current fuel-cycle should be corrected before a new fuel-cycle is introduced.

The utilities of the Electric Reliability Council of Texas (ERCOT) share the SPP's perceptions of the nuclear market, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996
Electric Reliability Council of Texas

Total Additions: 61.0 GW
Total Nuclear: 16.9 GW (28%)
Total Coal-fired: 30.1 GW (49%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	2.1	2.6	2.9	2.5	4.1	4.1	3.8	3.0	3.6	2.0	30.3
Nuclear (GW)	0	0	0	1.3	1.1	1.3	1.1	0	1.2	0	10.9
Nuclear (%)	0	0	0	52	27	32	29	0	33	0	36
Coal-fired (GW)	1.6	2.2	2.5	1.2	0.9	1.5	1.2	2.5	1.7	1.3	13.5
Other (GW)*	0.5	0.4	0.4	0	2.1	1.3	1.5	0.5	0.7	0.7	5.9

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

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Recent licensing problems and cost overruns have made the ERCOT utilities cautious of investing in nuclear units. The position of the SPP and ERCOT utilities is supported by state policy in the Southwest. In Texas, for example, the Texas Railroad Commission has mandated that the use of natural gas for generating electric power must be reduced by 10 percent by 1981, and by 25 percent by 1985. It has also directed the railroads to upgrade track to accommodate a daily traffic of 1,000 coal cars. Concurrently, the Texas legislature is considering a bill, supported by several utilities, to grant the power of eminent domain to pipeline companies for acquiring rights-of-way for a coal-slurry pipeline.

The lack of interest in nuclear capacity is paralleled by a lack of interest in thorium. The ERCOT utilities and the region's regulatory agencies would prefer a streamlining of the regulatory program for the present LWR before a new fuel or new reactor concept is introduced.

The utilities of the Mid-Continent Area Reliability Coordination Agreement (MARCA) are also heavily committed to coal-fired additions to capacity, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Mid-Continent Area Reliability Coordination Agreement

Total Additions: 35.1 GW
Total Nuclear: 10.2 GW (29%)
Total Coal-fired: 20.3 GW (58%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions	1.3	1.7	1.8	1.1	2.6	0.6	1.8	1.1	2.5	1.1	19.5
Nuclear (GW)	0	0	0	0	0	0	1.2	1.1	0	1.1	6.8
Nuclear (%)	0	0	0	0	0	0	67	100	0	100	35
Coal-fired (GW)	1.2	1.2	1.8	1.0	2.6	0.6	0.6	0	2.5	0	8.8
Other (GW)*	0.1	0.5	0	0.1	0	0	0	0	0	0	3.9

*Includes retirements, upratings, and deratings as net reductions to additions to capacity.

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They have ready access to coal reserves; federal regulation of coal-fired plants is less stringent; the plants can be built and licensed comparatively quickly; and costs can be predicted with greater certainty.

Because of the commitment to coal, interest in thorium was low in the MARCA region. Coal and uranium reserves were perceived as adequate to meet the utilities' needs, and the introduction of a new reactor fuel was perceived as opening up the possibility of further complications in federal regulation. The consensus of this region also was that federal nuclear policy and regulation should be stabilized before a new fuel or reactor concept is introduced.

In the Western States Coordinating Council (WSCC) region, the largest share of added capacity will be nuclear powered, as the following table shows.

Planned Additions to Capacity (GW) 1977-1996 Western States Coordinating Council

Total Additions: 129.5 GW
Total Nuclear: 55.2 GW (43%)
Total Coal-fired: 42.2 GW (33%)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1996
Total additions:	4.4	5.5	5.1	6.2	5.5	3.8	5.3	7.5	6.0	5.8	74.4
Nuclear (GW)	1.6	0	0.1	1.4	2.1	1.5	2.1	4.3	2.5	3.1	36.5
Nuclear (%)	41	0	2	23	38	39	40	57	42	53	49
Coal-fired (GW)	0.6	1.1	2.5	2.8	2.1	1.1	1.3	2.4	1.6	1.8	24.9
Other (GW)*	1.9	4.4	2.5	2.4	1.3	1.2	1.9	0.8	1.9	0.9	13.0

*Includes retirements, upratings, and deratings as net reductions to additions to capacity

However, the deployment of coal-fired and nuclear plants alike faces restrictions. Air quality standards limit the use of coal in the region; seismological restrictions on design, public opposition, and unfavorable state government policy -- particularly on reprocessing and storing spent fuel -- limit the use of nuclear power. For example, two units of Pacific Gas and Electric's Diablo Canyon plant were originally scheduled to come on line in 1971; however, new seismic design guidelines entailed changes in design that will delay the completion

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of the project until late 1978. The California State legislature is considering bills that will prohibit the California Energy Commission from licensing nuclear plants until the federal government formulates a policy regarding reprocessing and storage of nuclear waste, issues that are far from being resolved. Under these conditions, the proposed nuclear development may not be realized.

Nevertheless, the WSCC utilities displayed some interest in thorium, but its economic competitiveness with uranium and its licensability must be demonstrated.

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A demand for thorium-fueled reactors would be supplied by a chain of industries consisting of the thorium-mining and -milling, enrichment, fuel-fabrication, reactor-manufacturing, fuel-reprocessing, fuel-refabrication, and waste-storage or disposal industries. Initially, these suppliers would probably be firms already involved in nuclear supply. The nuclear supply industry has already experienced an unstable business environment, and this experience will color their attitudes toward entering the thorium market. In the late 1960s and early 1970s, fuel suppliers were forced to operate below capacity when earlier government orders were canceled or reduced. Reactor and fuel manufacturers found themselves in a similar situation in the 1970s because of cancellations or postponements of orders for nuclear plants.

Although the uranium mining industry is now operating profitably, most supplier industries have never realized the expected profits on their investments because of unforeseen technical problems, declining demand, changing licensing requirements, and changing federal policy on reprocessing, refabrication, recycling, and waste-handling. Even were these policies firmly established, licensing uncertainties greatly increase their financial risk. The intervention of individuals and groups concerned with, or opposed to, nuclear power has further delayed power-plant construction, increasing costs and confusing still more the market outlook for supplier services.

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The supplier industries are now hesitant about investing in the nuclear market, where previously they were willing to make major investments that were viewed as sound, on the basis of demand projected by the government and the utilities, in an attempt to capture market shares and profits. They now evaluate the risks much more critically. They are carefully reviewing federal and state policy actions and licensing decisions as benchmarks to the level of risk involved in investments and are unlikely to commit themselves unless the risk is lowered significantly. And the uncertainties of thorium, which is less familiar so far as technological feasibility, licensing, economics, and policy are concerned, are even greater than those of uranium.

Despite the hesitancy of the potential suppliers of thorium fuels and equipment, the possibility of their investing in manufacturing capacity can be evaluated.

The willingness of suppliers to invest will be determined primarily by the expected size of the market for their products or services, the potential profit, the degree of risk in the investment compared to other available investment options, and the compatibility of the investment with the firm's marketing strategy overall.

The market for any thorium supplier is directly dependent on the penetration of thorium into the nuclear market, and the certainty of this penetration is critical. The advent of new technologies that render established technologies obsolete or the possibility of changes in federal policy affecting utility investment options must be carefully considered as potential hazards to a stable and secure demand. The profit potential of the investment is determined by the construction and operating costs of the power plant and the price of its fuel. This potential would be jeopardized by unforeseen fluctuations in sales and in the cost of providing the product, stemming in part from the technical difficulty of manufacturing the product and in part from the uncertainties of the licensing approval process. Federal and state policies and licensing decisions are, at present, the primary risk factors.

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The ability of the supplier to finance the investment must be measured against the size of typical investments that the firm might make. The investment should not be so large as to strain the firm's capacity to borrow funds or to generate cash internally, nor should it exceed the normal level of investment for the firm itself or for other firms in the industry. However, if it is sufficiently attractive in other respects, a large financing can be accomplished through a consortium.

The capital cost of supply facilities constitutes a major investment for a single company; the cost of enrichment and reprocessing plants, for example, may be as much as \$3 billion. However, investments of comparable size have been made by private firms in the past, through consortia or other forms of joint venture. Under a government policy that reduced risk, therefore, the supply industries should be capable of providing the capital necessary for their manufacturing investments.

However, according to our survey of potential suppliers for a thorium fuel market, the major suppliers in the chain -- the fuel and reactor manufacturers, fuel enrichers, and reprocessors -- will not invest in manufacturing capacity without a fairly certain market demand and some assurance that the financial risk will be limited.

Under these restraints, the supplier industries are unlikely to commit themselves unless the risks are shared jointly with the utilities and the government. Only the mining and milling sector appears prepared to move without this support, but it will not do so until a relatively stable demand has been established by the action of the utilities and the other nuclear suppliers.

The Potential for Thorium Mining and Milling

Thorium mining and milling would be the first link of the supply chain. Investment by a mining firm involves a sequence of decisions: first, to commit funds for exploration for thorium; second, to purchase or lease mineral rights to specific properties; and third, to develop and operate a new mine. The level of investment

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risers at each step in the sequence, and a progressively more certain return is required.

Exploration funds are allocated on the basis of expected long-term future markets for minerals. Major mining firms seem willing to commit exploration funds for thorium as soon as a federal policy encouraging the development of thorium-fueled reactors is formulated. Because the costs are small in comparison to costs of mine development, the mining firms are willing to accept a higher-than-normal risk that demand will not develop.

The purchase of land or mineral rights to properties requires a larger commitment by the firm and will necessitate a more-certain market potential. The mining companies will probably not make these purchases until the utility requiring the thorium is at least on the verge of purchasing the fuel. Many mining firms were severely hurt by the depressed uranium market and will be cautious about investing in new property to supply a thorium market.

Major funds for developing mining property will probably not be committed until the utility has signed a contract or letter of intent to purchase a large share -- perhaps as much as 50 percent -- of the mine's output; smaller or less-diversified firms may require an even higher share.

Internal funds would be used to finance exploration and the purchase of most land or mineral rights; however, the development of a mine demands a larger investment and may involve project financing from debt or equity markets. However, if a long-term contract for purchase of output had been negotiated, these funds should not be difficult to acquire.

Financing, then, does not appear to be a major barrier for thorium mining.

Many of the uranium mining firms in our survey have considered thorium investments in the past and have identified thorium deposits at least adequate to support the initial demand. Consequently, should the thorium market develop, protracted exploration, which could delay the commercial deployment of thorium fuel, would be unnecessary.

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Many of these firms also have the expertise for mining thorium. Thorium mining technologies are similar to those for uranium, and many firms are experienced in dealing with radioactive materials and meeting occupational safety requirements. Firms now involved in uranium mining could therefore be expected to move into thorium mining first, but others could soon follow. Moreover, the lead-time for developing a mine is considerably shorter than the lead-time for building a power plant. The first mines, which will involve little or no exploration, could be developed in 2-3 years, perhaps with equipment diverted from other uses. In comparison, 10 years are required for the construction and licensing of a power plant, leaving considerable leeway -- even with a late start -- for the development of the mine and further exploration.

Finally, the mining and milling firms surveyed stated that they are willing and able to move very quickly if the market were to become firm; a considerable amount of "wildcat" exploration has been carried out in the past in anticipation of a thorium market. They felt that the government consistently tends to underestimate the speed with which mines could be brought into operation. The consensus was that mining would not be the initial inhibiting barrier to thorium development.

The Potential for Thorium Fuel Fabrication and Reactor Manufacture

The major fuel fabricators and reactor manufacturers are generally subsidiaries or divisions of large, diversified businesses with interests outside the nuclear field. The investment decisions of these firms must be considered in the financial context of the larger firm or parent company.

Fuel fabricators and reactor manufacturers have not realized the expected profits from their activities, largely because of the sluggish growth of the nuclear industry and the increased costs entailed by delays and changes in licensing procedures and requirements. Because of the changing and complicated licensing process, fuel and reactor products have been subject to "constant obsolescence." Moreover, many firms are

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operating below capacity because of canceled, reduced, or postponed orders. The originally estimated demand of 30 power plants per year did not materialize; only 3 plants, for example, were ordered in 1977. Consequently, most parent firms will be reluctant to embark on major new investments in the nuclear industry, particularly for the research and development of different types of reactor or processing methods, until purchase agreements for their products have been negotiated with the utilities.

Before reaching a decision to invest in thorium manufacturing capability, a firm must have some assurance that it can sell its services or products at a price that will provide an adequate return; it must also foresee a sufficiently large market to justify its capital expenditures. But even more importantly, the investment risks stemming from uncertainties in price or the timing and extent of the potential demand must be regarded as acceptable. These risks may develop from uncertainties that the power plant or the manufacturing facility will be licensed, or from technical uncertainties that could increase manufacturing costs. The firm must perceive the potential returns as sufficiently attractive when compared with other investments. The responses to our survey indicate that each reactor manufacturer must build about five reactors per year to remain in business; however, at this minimal level of demand, suppliers would prefer that a single, or, at most, two types of reactor be selected for deployment -- by government policy, if necessary -- so that they are not obliged to dissipate their resources in an attempt to supply a diversity of technologies.

The degree of diversification is another important consideration for firms in this industry. Because of the depressed profits in the nuclear business, parent companies are unwilling to commit more than a certain percentage of their business -- for larger firms, about 20-30 percent -- to the nuclear field. Furthermore, although they may be willing to invest unusually large funds for specific research or development projects, their long-term investments in nuclear business must be consistent with their general diversification objectives. Only if the future nuclear market is more certain than the past would firms be likely to increase their commitment to nuclear ventures.

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The Potential for Enrichment, Reprocessing, and Refabrication

At present, the enrichment, reprocessing, and refabrication of nuclear fuels are entirely in the hands of the federal government. Several bills authorizing private participation in these supply activities are pending before Congress, but the Administration has recently postponed the licensing of private facilities indefinitely and has expanded federal capacity. It would appear that the government will continue to supply these services exclusively, or will at least play the leading role in supplying them. Few private firms are actively seeking licenses, and few more are likely to do so unless the government formulates a clearly articulated policy and provides financial aid and guarantees. Without this support, the potential return does not justify an investment in enrichment and reprocessing facilities, an investment so large that it could be made only by the largest firms or consortia of large firms. However, consortia have been formed in the past, and the required capital is likely to be available as needed; private firms are clearly willing and able to raise it. However, equally clearly, such sizeable funds will not be committed unless the uncertainties that could adversely effect profitable operations are diminished.

The reprocessing and refabrication capacity for thorium fuels cannot be expected to develop without a fairly assured market for the products -- in effect, the purchase of thorium fuels by utilities and the development of government policies permitting reprocessing and refabrication of thorium fuels.

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Under the reprocessing policies now in force, the utilities do not perceive thorium as economically competitive with uranium as a fuel for nuclear reactors. However, certain alternatives to these policies, designed to reduce the risk of proliferation of weapons-grade nuclear materials, are now under consideration by the federal government. These alternative policies on the reprocessing and recycle of nuclear fuels could create a more favorable environment for thorium and warrant the reappraisal of thorium's viability.

RPA evaluated different thorium fuel-cycle and reactor applications under four such recycle policy options to determine which thorium applications are the most attractive. The four policies were selected by the Division of Nuclear Research and Applications of the Department of Energy, in consultation with the Hanford Engineering Development Laboratory and RPA, as representative of the range of possible future policies. The four policies are:

- No recycle. This policy, also called the "once-through" or "open-cycle" policy, is the present policy, which prohibits the reprocessing or reuse of nuclear fuels after their initial use. It was included to establish whether or not a change in the present government reprocessing policy is a prerequisite for commercial deployment of thorium.
- Uranium-recycle only. Under this policy, the reprocessing and reuse of uranium fuels (U-233 and U-235) is permitted; the reprocessing and reuse of the plutonium fuels produced from U-238 during reactor operation is prohibited. This policy was selected to determine if industry investment criteria would be met for thorium technologies under conditions most favoring the thorium fuel-cycle over the uranium cycle.
- Recycle of plutonium in secure energy centers only. Under this secure-centers policy, the reprocessing of plutonium and uranium fuels is permitted only in

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secure energy centers where the handling of potential weapons-grade materials may be strictly controlled. Plutonium-fueled reactors would be permitted only in these centers. In reactors outside the centers, only "denatured" fuel-cycles (i.e., those that include less than 20 percent U-235 or 12 percent U-233 in a U-238 fuel) would be permitted, to reduce the likelihood of the diversion of fuel for weapons use. The policy is designed to limit proliferation; fissile U-233 and U-235 are comparatively difficult to separate from other uranium isotopes, whereas the separation of plutonium from uranium input fuel involves a relatively simpler chemical process. Some experts believe that uranium recycling may consequently be less vulnerable to the proliferation of weapons-grade nuclear materials. This policy was selected to determine the potential market for thorium in reactor/fuel-cycle combinations being evaluated in other government programs aimed at reducing the likelihood of nuclear proliferation.

- Unrestricted recycling of plutonium and uranium. This full-recycle policy imposes no restriction on the reprocessing and reuse of uranium and plutonium; it is, in effect, the policy originally believed to be the most likely federal policy. It would permit unrestricted use of the liquid-metal fast breeder reactor and other reactors using highly enriched uranium and plutonium fuels. This policy was selected to determine whether a reversion from the present federal policy to the policy previously expected by the nuclear industry would preclude the possibility of industry investment in the thorium fuel-cycle.

Various applications of thorium were projected under each of these options by Hanford Engineering Development Laboratory's Advanced Linear Programming System (ALPS). This model projects the future growth of national baseload electric generating capacity by simulating competition among different nuclear reactors and coal-fueled plants on the basis of the levelized cost of power. (The model and the outputs used as a basis for RPA's analysis are described in Annex 1, which was written by HEDL staff and contributed to this report.)

Using the ALPS model, a series of "cases" were run, simulating various mixes of electric baseload capacity from the present to 2026. Four cases, including in most instances thorium applications, were run for each policy scenario. Each of the four cases under each

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policy was designed to include the conventional uranium-fueled LWR and also to allow the introduction of one or more thorium fuel-cycle options in a generic type of reactor: the LWR only, the spectral-shift controlled reactor (SSCR), the heavy-water reactor (HWR), and the high-temperature gas-cooled reactor (HTGR). Liquid-metal fast breeder reactors were included under the two policies permitting the recycling of plutonium.

The following table illustrates the 16 cases:

Reactor Type*	No Recycle	Uranium Recycle Only	Secure Centers	Full Recycle
LWR (L cases)	No recycle(L)	U-recycle(L)	Secure centers(L)	Full recycle(L)
SSCR (S cases)	No recycle(S)	U-recycle(S)	Secure centers(S)	Full recycle(S)
HWR (H cases)	No recycle(H)	U-recycle(H)	Secure centers(H)	Full recycle(H)
HTGR (G cases)	No recycle(G)	U-recycle(G)	Secure centers(G)	Full recycle(G)

* In addition to the LWR and FBR (where permitted).

These 16 cases correspond to the "L," "S," "H," and "G" cases under the "small uranium supply" assumptions described in Annex 1 to this report, which contains the detailed results from these 16 cases and a full documentation of the assumptions used in the ALPS runs. These data formed part of the data base for our analysis.

The analysis of the ALPS cases was a three-step process aimed at screening out progressively the less-promising thorium applications and ultimately determining the applications most deserving of further development by the government.

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In the first step, the economic performance of various thorium applications was compared. Economic performance is the most important investment criterion from the utilities' standpoint. Three factors were considered: the average levelized cost of producing electricity (in mills per kilowatt-hour); the percent penetration of nuclear power into the total electric market; and the efficiency of uranium ore utilization. (Efficiency of ore utilization provides a measure of long-term performance and offsets the comparatively short-term (50-year) time horizon of the scenarios.) The factors were given a weighting of 25 percent, 25 percent, and 50 percent respectively and combined to yield a single index of economic performance on a scale of 0-100.

The economic performance for the entire case, that is, for all nuclear options and coal-fired capacity in the case, is the appropriate measure of cost because the economic effect of thorium is realized not only through the direct thorium applications, but also through the fuel produced from thorium for use in other reactors.

The applications with the highest composite economic indexes were considered preferred technologies and subjected to further screening in the second step.

In the second step, the noneconomic (technical, financial, and regulatory) barriers to commercializing the preferred case were evaluated. To evaluate the ease of commercializing the various types of thorium-using reactor, three factors were considered:

- Degree of technical readiness, that is, the similarity of the technology to known technology and the level of research and development required to bring it to commercial readiness.
- Degree of financial risk, that is, the susceptibility of the technology to unforeseen cost increases or delays in construction and licensing that would increase the risk of capital exposure for the utility. Ease of licensing, adaptability to different federal policies, and other potential causes of financial risk, especially higher initial capital cost, were considered.
- Time to commercialize, that is, the time required to complete necessary R&D to prepare the technology for commercial demonstration.

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In addition to these reactor-specific factors, we considered also the capital investment required for utilities and suppliers for the entire case, to identify the potential constraints to commercializing the entire electric baseload system and to evaluate the combined effects of the thorium-fueled systems and the uranium/plutonium-fueled systems.

The utilities and suppliers in our survey had stated their preference for the development of at most a single new reactor in addition to the existing LWR and planned LMFBFR; and the high cost of developing any new reactor, for all practical purposes, minimizes the likelihood of fully commercializing more than one. With such a narrowing of options likely, those selected must be adaptable to possible future changes in federal recycle policy. Thus in this last step, the performance of the selected applications was compared under each of the policies to allow narrowing the choice of thorium fuel-cycle and reactor applications for further development to the lowest practical level.

Our general conclusion is that, under any policy permitting reprocessing, the use of thorium would improve the economics of electric power generation over the next 50 years, with or without the fast breeder reactor, because U-233 appears to be a preferred recycle fuel for thermal reactors and can be produced either in thermal reactors or in fast-breeder reactors.

From the point of view of long-term economic attractiveness, the HTGR and SSCR appear to be the preferred applications for thorium under HEDL's cost and performance assumptions. The HWR was not economically competitive under HEDL's capital cost assumptions, but other more recent studies have shown that the HWR may become competitive with lower capital cost assumptions.¹

The economic performance of this advanced converter would then be improved when uranium prices are high because of its more-efficient utilization of ore.

1. United Engineers and Constructors, Inc., Commercial Electric Power Costs: Capital Cost, Pressurized Heavy Water Reactor Plant, (C00-2477-13: June 1977).

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Under the uranium-recycle only policy, the case including the HTGR, with an index of 42, is the economically preferred case, largely because of a more-efficient utilization of ore and slightly lower levelized costs than the case including SSCRs. The case including the SSCR ranks second with an index of 31, considerably higher than the case with LWRs (19) and HWRs (11).

Under the secure-centers policy, however, the case including SSCRs is economically preferred, with an index of 95. In this case levelized cost is lower and penetration of the nuclear market higher than the second-ranked case with HTGRs (85); ore utilization was virtually the same in both. The improved performance of the SSCR case is probably attributable to the "symbiotic" relationship of SSCRs and fast-breeder reactors, which were included in that case (that is, the SSCR is a good source of plutonium to fuel the LMFBR, which in turn produces U-233 to fuel SSCRs). Higher economic indexes (compared with the uranium recycle only case) were achieved largely because of the introduction of breeder reactors into both cases. Again, the cases with LWRs (72) and HWRs (67) ranked lower.

Under the full-recycle policy, the case including thorium-fueled HTGRs was economically preferred, with an index of 93. (This case is similar to the secure-centers case with HTGRs; full recycle and the inclusion of HTGRs fueled with highly enriched uranium accounts for the higher economic index.) No thorium-fueled SSCR options were included in this case because input data for an SSCR fueled with highly enriched uranium were not available; however, thorium-fueled SSCRs would probably have performed well. The drop in the economic index of the SSCR cases from 95 for the secure-centers policy, in which thorium-fueled SSCRs were included, to 82 with plutonium reactors in the full-recycle case is a measure of the positive economic effect of thorium. Again, the cases with LWRs and HWRs had lower rankings, with an equal index of 69.

The position of the HWR warrants comment. HWRs were projected to develop only in the secure-centers policy, and then merely because they were the only converter

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reactor option in the scenario that could use U-233. In the other cases under the same policy, the HTGR or SSCR, which could use the bred U-233, were projected to penetrate the market more successfully than the HWR. However, if the estimates of capital costs for an HWR designed to meet U.S. licensing criteria were significantly lowered, the HWR would be a much improved option.

In summary, then, on the basis of the HEDL analysis, our conclusion is that the SSCR appears to have a slight economic advantage over the HTGR, although the advantage is difficult to quantify, implying that the economic performance of the two is virtually the same within the range of uncertainty in the input assumptions. When the noneconomic barriers are considered, the SSCR would probably be somewhat easier to commercialize than the HTGR because of its similarity to familiar LWR technologies and its adaptability to a nuclear economy including LWRs and LMFBRs, its versatile performance under different recycle policies, and its earlier availability (1990). For the same reasons, the SSCR would involve less financial risk to the utilities, and would probably be the preferred application for thorium. However, both the SSCR and the HTGR are more difficult to commercialize than the thorium-fueled LWR, but all three rank higher on this count than the HWR.

The market penetration projected by the ALPS model has been used as an indicator of potential investment by utilities and nuclear suppliers in the various reactor/fuel-cycle combinations under the four policies. However, the sensitivity of these market penetrations to variations in input data, such as capital cost, has not been determined and must be analyzed further if the significance of such variations for market penetration and industry investment is to be fully understood.

In the following sections of this chapter, we discuss first the comparative economics of thorium technologies under the various policies, and then the noneconomic barriers. However, the analysis and our conclusions are subject to certain qualifications.

First, to expedite the analysis, a decision was made to use completed ALPS cases instead of cases designed specifically for the study. Consequently, the reactor/fuel-cycle matches were not always the most appropriate

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for a critical comparison of the different technologies evaluated. In particular, if U-233-fueled LWRs had been included in the S, H, and G cases, the capability of that system to develop economically in competition with the other reactor systems could have been determined; similarly, the inclusion of U-233-fueled LWRs in the L case and SSCRs in the S case under the full-recycle policy would have allowed a better determination of the role of thorium under that policy.

Second, for certain types of reactors, in particular those that are not close to commercial introduction, costs (especially initial capital costs) are difficult to estimate with precision. Changes in the capital cost assumption could produce quite different results, but, at this stage of the Thorium Assessment Program, the sensitivity of the effects of such changes has not been determined. Moreover, in ALPS, as in any such model, the cost assumptions are based on the costs of known technologies and do not account for the economic effects of unforeseen technological advances, such as considerably less-expensive methods for producing heavy water.

Third, the ALPS model, a linear programming system, cannot duplicate nonlinear, real-world conditions precisely. For example, a linear-programming approach could show a large market share for a technology with only a small cost advantage, where, in actuality, closely competitive technologies would probably share the market on equal terms. The linear-programming approach also optimizes for minimum system cost over the scenario's entire time-span. Consequently, the scenario may introduce at an early point certain technologies whose economic preferability is based on the future sale of the fuel they produce to reactors introduced at a later point. In reality, a utility would have to be convinced that the market for fuel was relatively certain before it would invest in such a technology. The potential long-term economic benefits of selling the fuel produced might be discounted and the utility motivated to purchase a technology with more certain economics.

Fourth, some thorium applications, notably the light-water breeder reactor (LWBR) and other advanced LWR designs, have not been explicitly included in HEDL's analysis because performance data on these reactors were not available. (The LWBR design is now undergoing

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initial prototype testing, and advanced light-water reactor designs optimized for thorium are still under investigation.) Consequently, the role of these reactors as a vehicle for commercializing thorium has not been evaluated.

Finally, the results of these cases have not been fully reviewed by representatives of the industries that would take the lead in the commercial deployment of thorium; their verification is critical to validate our initial conclusions on ease of commercialization.

ECONOMIC PERFORMANCE OF THORIUM UNDER DIFFERENT RECYCLE POLICIES

Total systems costs are the ultimate measure of economic performance. Consequently, our comparison of the economic performance of thorium is based on the economics of each case as a whole, not on the economics of the individual technologies within the case. After the comparison of cases, we could identify the reactors and fuel cycles that had contributed to the strong economic performance of the case.

Two measures of economics were used: cost, and uranium ore utilization. Cost is the final measure of economics; however, it must be balanced against the longer-term costs of depleting scarce natural resources, which we have considered by measuring the efficiency of uranium ore use in producing electric power.

Cost can be measured by several different means, but we selected average levelized costs, which are used by utilities as a criterion in making their plant purchase decisions. We used also the degree of penetration by nuclear units into the total market for electric generating capacity, which is a second indicator of relative cost. (In the ALPS model, all cases include constant costs for coal-fired capacity, the alternative to nuclear units.) We calculated the average levelized cost over the period 1977-2026 for each case from the HEDL yearly average levelized cost data by weighting the cost for each consecutive 10-year period by the kilowatt-hours produced in the period. The percent penetration of nuclear units into the utility market was taken

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directly from HEDL data. Efficiency of ore utilization was calculated by dividing the cumulative GW(e) of nuclear capacity in 2026 by the cumulative total (in tons) of uranium ore consumed by that point.*

As a composite measure of performance, we developed an index of economic performance normalized to a scale of 0-100. The cost and ore-utilization factors from which the index was calculated were each weighted 50 percent to offset the possibility that a scenario minimized costs in the short term while depleting uranium supplies and increasing costs after 2026. The two cost measures (average levelized cost and percent penetration of the market) were each weighted 25 percent.

The index does not provide an absolute measure of economic performance, but permits the relative economic performance of the cases to be compared.

In the following sections, we summarize the results of our analysis and the application of the economic index to the cases under each of the four policies.

Economic Performance

Under the No-Recycle Policy

The scenario representing the present no-recycle policy constitutes a base case for comparison of the other three policies. No thorium fuel-cycle once-through cases were considered in the ALPS runs because other studies by TAP participants had shown that these cycles were generally not as economical or resource-efficient as the low-enriched uranium cycles in the once-through mode.² The thorium fuels typically contain much larger amounts of enriched uranium both in the fuel charged and in the spent fuel than low-enriched

* Total kWh of nuclear power generated would be a more precise measure, but the necessary data were not accessible.

2. Keith C. Gavel and Michael J. Driscoll, Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems (MIT-EL-77-018: October 1977); Combustion Engineering, Inc., Assessment of Thorium Fuel Cycles in Pressurized Water Reactors (EPRI-NP-359: February 1977).

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uranium cycles in the same reactors. However, HTGRs and the German pebble-bed reactors are exceptions; the use of thorium fuels in a once-through cycle in these reactors appears to use resources more efficiently than the use of low-enriched uranium once-through cycles.

The significant data for the scenario are summarized in Exhibit 2.a.1.

The reactor/fuel-cycle alternatives permitted in the scenario are:

Case L

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- LWR-U5(LE)/U-T (low-enriched U-235/U-238 fuel, optimized for the no-recycle policy)

Case S

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- SSCR-U5(LE)/U (low-enriched U-235/U-238 fuel)

Case H

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HWR-U5(NAT)/U (natural uranium fuel)
- HWR-U5(SEU)/U (slightly enriched (about 1 percent U-235) uranium fuel)

Case G

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HTGR-U5(LE)/U-T (low-enriched U-235/U-238 fuel, optimized for the no-recycle policy).

(The abbreviations for the reactor types are those used by HEDL. See Annex 1.)

In all cases, the nuclear capacity built amounts to no more than 13 percent of the total electric capacity, reflecting the reduced competitiveness with coal-fired units of nuclear units after the low-cost uranium is consumed when reprocessing is prohibited.

The LWR is the dominant technology in all cases except Case S. The SSCR would therefore appear to be economically superior in the long term to the LWR when both are

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fueled with uranium. The economic performance of all cases is similar, and uniformly poor in comparison to the cases under the three recycle policies, as the following table shows.

Systems Economics: No Recycle Policy (1977-2026)

	Case L	Case S	Case H	Case G
Average levelized cost (mills/kWh)	18.3	18.4	18.5	18.4
Rank	1	2	4	2
Penetration of nuclear market (%)	12	13	9	10
Rank	2	1	4	3
Uranium-utilization efficiency index	8.9	10.4	7.5	7.7
Rank	2	1	4	3
Composite economic index	8	8	0	3

The composite economic indices range from 0 to 8. Case L and Case S perform slightly better than Cases H and G because of the presence of the extended exposure LWR option optimized for the once-through cycle (in Case L) and the SSCR (in Case S).

Economic Performance Under the Uranium- Recycle Only Policy

This policy scenario prohibits the recycle of plutonium, but permits the recycling of uranium fuels (U-235, and U-233 produced from thorium); consequently, the reactor/fuel-cycle alternatives using U-233 produced from thorium are permitted.

The significant data for the scenario are summarized in Exhibit 2.a.2.

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The reactor/fuel-cycle alternatives permitted in the scenario are:

Case L

- LWR-U5 (LE)/U (low-enriched U-235/U-238 fuel)
- LWR-U5 (DE)/U/Th (denatured U-235 fuel (20 percent) in U-238 with thorium feed)
- LWR-U3 (DE)/U/Th (denatured U-233 fuel (12 percent) in U-238 with thorium feed)

Case S

- LWR-U5 (LE)/U (low-enriched U-235/U-238 fuel)
- LWR-U5 (DE)/U/Th (denatured U-235 fuel (20 percent) in U-238 with thorium feed)
- SSCR-U5 (LE)/U (low-enriched U-235/U-238 fuel)
- SSCR-U3 (DE)/U/Th (denatured U-233 fuel (12 percent) with thorium feed)

Case H

- LWR-U5 (LE)/U (low-enriched U-235/U-238 fuel)
- HWR-U5 (NAT)/U (natural uranium feed)
- HWR-U5 (SEU)/U (slightly enriched (about 1 percent U-235) uranium fuel)
- HWR-U5 (DE)/U/Th (denatured U-235/U-238 fuel (20 percent) with thorium)
- HWR-U3 (DE)/U/Th (denatured U-233 fuel (12 percent) in U-238 and thorium with U-233 self-generated recycle fuel)

Case G

- LWR-U5 (LE)/U (low-enriched U-235/U-238 fuel)
- HTGR-U5 (LE)/U (low-enriched U-235/U-238 fuel, optimized for recycle)
- HTGR-U5 (DE)/U/Th (denatured U-235 fuel (20 percent) in U-238 plus thorium, optimized for recycle)
- HTGR-U3 (DE)/U/Th (denatured U-233 fuel (15 percent) in U-238 plus thorium, optimized for recycle).

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In this scenario, uranium recycle allows nuclear units to capture up to approximately one-third of the total baseload capacity for electric generation. Reactors fueled with thorium were heavily used in all cases except for Case H; in fact, more than half the nuclear reactors in all those cases are thorium-fueled. Clearly, thorium-fueled reactors and U-233-fueled reactors are economically competitive under this policy. In Case L, the U-233-fueled LWR captured about one-third of the nuclear market, and U-235-fueled LWRs the remainder. In Case S, the SSCR fueled with U-233 made up almost half the total nuclear capacity, indicating that the SSCR uses the thorium/U-233 fuel system more efficiently than the LWR.* In Case H, no HWR was built, suggesting that HWRs are not competitive (at the assumed capital costs) with the U-235-fueled LWR or with coal-fired units, even when recycling of U-233 is permitted. In Case G, more than 80 percent of the nuclear capacity consisted of HTGRs, which apparently have a clear advantage over LWRs under this policy. However, fewer than a third of these HTGRs were U-233-fueled because they are dependent on the U-233 discharged from HTGRs fueled with denatured U-235.

Of the three cases, the case including the HTGR has the highest economic index (42); the case including the SSCR ranks second with an index of 31. Higher ore-utilization efficiency and a slightly higher penetration of the market provide the HTGR with the advantage over the SSCR; the levelized costs of the two were practically equal. The cases including LWRs and HWRs had much lower indices (19 and 11, respectively).

The systems economics under this policy are summarized in the following table.

* This superiority could have been established more directly, however, if a U-233-fueled LWR had been included in Case S.

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Systems Economics: Uranium Recycle Only Policy (1977-2026)

	Case L	Case S	Case H	Case G
Average levelized cost (mills/kWh)	18.4	18.4	18.4	18.3
Rank	2	2	2	1
Penetration of nuclear market (%)	21	30	16	34
Rank	3	2	4	1
Uranium-utilization efficiency index	16.0	22.0	11.6	27.0
Rank	3	2	4	1
Composite economic index	19	31	11	42

The levelized costs for all systems were very close; the levelized cost for the system including HTGRs (18.3 mills/kWh) is slightly lower than the levelized cost for the other systems (18.4 mills/kWh). This slight advantage resulted in a somewhat larger market penetration of nuclear capacity (34 percent) than the other cases; the SSCR case ranked second with a market penetration of 30 percent. The penetration by LWRs and HWRs was considerably smaller.

The ore-utilization efficiency index of 27 for the case including HTGRs is considerably higher than that of the case including SSCRs (22), but both are markedly higher than those including LWRs and HWRs (16 and 11, respectively). (The lower cost resulting from the greater efficiency of ore utilization of the SSCR and HTGR offsets the higher capital costs of these systems.)

Economic Performance Under the Secure-Centers Policy

This policy permits the recycle and reuse of plutonium in secure energy centers only; it also permits the reprocessing of uranium but limits the use of reprocessed uranium fuel outside the secure centers to denatured fuel mixtures. Under this policy, the use of liquid-metal fast breeder reactors and other plutonium-fueled reactors is possible.

The significant data for the scenario are summarized in Exhibit 2.a.3.

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The reactor/fuel-cycle alternatives permitted in the scenario are:

Case L

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- LWR-U5(DE)/U/Th (denatured U-235 fuel (20 percent) in U-238, with thorium feed)
- LWR-U3(DE)/U/Th (denatured U-233 fuel (12 percent) in U-238, with thorium feed)
- LWR-Pu/Th (recycled plutonium fuel in thorium)
- FBR-Pu-U/Th (Pu/U-238 core feed and thorium blanket feed)

Case S

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- LWR-U5(DE)/U/Th (denatured U-235 fuel (20 percent) in U-238, with thorium feed)
- SSCR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- SSCR-U5(DE)/U/Th (denatured U-235 fuel (20 percent) in U-238, with thorium feed)
- SSCR-U3(DE)/U/Th (denatured U-233 fuel (12 percent) in U-238, with thorium feed)
- FBR-Pu-U/Th (Pu/U-238 core fuel and thorium blanket feed)

Case H

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HWR-U5(NAT)/U (natural uranium fuel)
- HWR-U5(SEU)/U (slightly enriched (approximately 1 percent U-235) uranium fuel)
- HWR-U5(DE)/U/Th (denatured U-235 fuel (20 percent) in U-238 and thorium)
- HWR-U3(DE)/U/Th (denatured U-233 fuel (12%) U-238, and thorium with self-generated U-233)
- HWR-Pu/Th (plutonium fuel in thorium)
- FBR-Pu-U/Th (Pu/U-238 core fuel and thorium blanket feed)

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Case G

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HTGR-U5(LE)/U (low-enriched U-235/U-238 fuel, optimized for recycle)
- HTGR-U5(DE)/U/Th (denatured U-235 fuel (20 percent) in U-238, and thorium, optimized for recycle)
- HTGR-U3(DE)/U/Th (denatured U-233 fuel (15 percent) in U-238, and thorium, optimized for recycle)
- HTGR-U3/Th (U-233 and thorium fuel with self-generated U-233 recycle)
- FBR-Pu-U/Th (Pu/U-238 core fuel and thorium blanket feed).

Under this policy, over half the baseload electrical generating capacity consists of nuclear plants. Thorium-fueled and U-233-fueled reactors penetrated the market heavily in all four cases, providing more than half the nuclear capacity. FBRs with thorium blankets were used extensively in each case, and plutonium-fueled and U-233-fueled reactors were economically competitive.

In Case L, the predominant reactors are U-235-fueled LWRs (594 GW(e)) and plutonium-fueled FBRs (408 GW(e)); some U-233-fueled LWRs were also utilized to use the U-233 produced from the thorium blanket on the FBR. In Case S, the predominant reactors are U-235-fueled SSCRs (495 GW(e)) and plutonium-fueled FBRs (420 GW(e)); however, almost 300 GW(e) of U-233-fueled SSCRs were built. Total nuclear capacity is consequently higher than in Case L. In Case H, where HWRs were included and provided 250 GW(e) of capacity, FBRs (537 GW(e)) and U-235-fueled LWRs (442 GW(e)) predominated; U-233-fueled HWRs were built to burn the available U-233. This case is very similar to Case L, with the HWR replacing the LWR as the consumer of U-233. FBRs and U-235-fueled LWRs also predominated in Case G; however, over 300 GW(e) of HTGRs were built to use the available U-233.

The case including the SSCR has the highest economic rating with an index of 95; the case including HTGRs (85) is also high. The SSCR was apparently able to operate more efficiently because of its "symbiotic"

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relationship with the FBR. Cases L and H ranked lower with indexes of 72 and 67, respectively. However, all systems have considerably higher economic indices than the comparable systems under the uranium-recycle only policy, demonstrating the penalty in terms of economics and resource utilization of restricting recycle to uranium. Even when FBRs are restricted to secure centers, they provide the system with an economic advantage in the long term.

The systems economics under this policy are summarized in the following table.

Systems Economics: Recycle in Secure Centers Policy
(1977-2026)

	Case L	Case S	Case H	Case G
Average levelized cost (mills/kWh)	17.8	17.4	18.0	17.8
Rank	2	1	3	2
Penetration of nuclear market (%)	57	66	56	63
Rank	3	1	4	2
Uranium-utilization efficiency index	33.8	41.3	33.8	41.3
Rank	2	1	2	1
Composite economic index	72	95	67	85

The levelized cost of the case including SSCRs (17.4 mills/kWh) is significantly lower than that of the next most attractive cases, the L and G cases with costs of 17.8 mills/kWh, probably because of the SSCR's symbiotic relationship with the FBR. The case including the HTGR is not economically competitive with the case including the SSCR, primarily because the HTGR apparently cannot produce plutonium as required, and large numbers of LWRs are necessary in the early years to provide plutonium for the FBR. The deployment of HTGRs is consequently limited until the FBR economy approaches plutonium self-sufficiency. The efficiency of the HWR's ore utilization in the H case is not sufficiently better than in the other cases to offset the higher capital costs of the HWR, contributing to the higher overall cost of this case when compared with the other cases.

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The market penetration of nuclear units is highest in the case including the SSCR (66 percent); followed by the G case (63 percent), the L case (57 percent), and the H case (56 percent).

The ore-utilization efficiencies of the cases including the SSCR and HTGR are equal (41.3), and considerably higher than the L and H cases (33.8). In the S and G cases, also, more electricity is generated by nuclear power, but less uranium consumed, than in the L and H cases.

Economic Performance Under the Full-Recycle Policy

This policy permits recycling and reuse of plutonium and uranium fuels without restriction on fuel-cycle design other than the safeguards required by NRC and security requirements. Consequently, no fuel-cycle alternative is excluded.

The significant data for this scenario are summarized in Exhibit 2.a.4.

The reactor/fuel-cycle alternatives permitted in the scenario are:

Case L

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- LWR-Pu/U (recycled plutonium fuel in natural uranium)
- FBR-Pu-U/U (Pu/U-238 core fuel, U-238 blanket feed)

Case S

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- LWR-Pu/U (recycled plutonium fuel in natural uranium)
- SSCR-U5(LE)/U (low enriched U-235/U-238 fuel)
- FBR-Pu-U/U (Pu/U-238 core fuel, U-238 blanket feed)

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Case H

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HWR-U5(NAT)/U (natural uranium fuel)
- HWR-U5(SEU)/U (slightly enriched (approximately 1 percent U-235) uranium fuel)
- HWR-Pu/U (plutonium fuel in natural uranium)
- FBR-Pu-U/U (Pu/U-238 core fuel, U-238 blanket feed)

Case G

- LWR-U5(LE)/U (low-enriched U-235/U-238 fuel)
- HTGR-U5(LE)/U (low-enriched U-235/U-238 fuel, optimized for recycle)
- HTGR-U5(HE)/Th (high-enriched U-235 fuel and thorium)
- HTGR-U3/Th (U-233 and thorium fuel, with self-generated U-233)
- HTGR-Pu/Th (plutonium and thorium fuel)
- FBR-Pu-U/U (Pu/U-238 core fuel, U-238 blanket fuel).

Under this policy, as under the secure-centers policy, more than half the baseload capacity consists of nuclear units; recycling gives nuclear units an economic advantage in the long term over coal-fired units. However, thorium/U-233 systems were included in only one case, the case including HTGRs. Although 863 GW(e) of the capacity in this case was made up of HTGRs, the relative performance of thorium in other reactor applications is consequently difficult to evaluate.

LWRs fueled with U-235 and recycled plutonium and FBRs fueled with recycled plutonium were built in large numbers in Cases L and H, but no HWRs entered the market in Case H, emphasizing the economic disadvantage of their (assumed) high capital costs. In Case S, more than a third of the reactors built were U-235-fueled SSCRs (454 GW(e)), and many FBRs (511 GW(e)) developed. Plutonium-fueled and U-235-fueled LWRs made up the remaining nuclear capacity. SSCRs replaced some LWRs and provided a higher share of total nuclear capacity.

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In Case G, which included HTGRs, the HTGR fueled with highly enriched U-235 dominated the market, providing 472 GW(e) of capacity; plutonium and U-233-fueled HTGRs provided an additional 391 GW(e). FBRs and LWRs were built in smaller numbers than in the other cases, providing 360 GW(e) and 230 GW(e) of capacity, respectively.

Case G, including the HTGR, had the highest economic index (93), followed by the case with the SSCR (82); Cases L and H had identical indexes of 69. The higher index of the case including the HTGR may be attributed to the more-efficient ore utilization and higher market penetration of the thorium-fueled HTGR system.

The systems economics under this policy are summarized in the following table.

Systems Economics: Full Recycle Policy (1977-2026)

	Case L	Case S	Case H	Case G
Average levelized cost (mills/kWh)	17.8	17.7	17.9	17.7
Rank	2	1	3	1
Penetration of nuclear market (%)	53	61	53	66
Rank	4	2	3	1
Uranium-utilization efficiency index	32.4	38.0	34.4	44.8
Rank	4	2	3	1
Composite economic index	69	82	69	93

The levelized costs are the same for the cases including the HTGR and the SSCR; however, market penetration is higher in the case including the HTGR (66 percent) than in the case including the SSCR (61 percent). The former consequently has a slight cost advantage. The cases including the LWR and HWR are comparable because no HWRs were built; both have somewhat higher levelized costs and lower market penetrations than the other cases.

In the case including the HTGR, the HTGR fueled with highly enriched U-235 competes favorably with the FBR until uranium prices have risen significantly, allowing wider deployment of the more resource efficient FBR.

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However, in the case including the SSCR, SSCRs and FBRs develop simultaneously, presumably because of their symbiotic relationship. Ore utilization is markedly better in the G case (44.8) than in the S case (38). The increased use of thorium in the HTGR case may contribute to the higher resource efficiency of the HTGR. In general, however, HTGR and SSCR systems both use ore more efficiently than LWRs and FBRs in Cases L and H.

The comparison of the economic performance of thorium under the full-recycle policy and the secure-centers policy indicates that the economics of some denatured uranium-thorium cycles is better than that of their plutonium counterparts under unrestricted recycle. For example, composite economic indices are higher under the secure-centers policy, which restricts recycle, for the L case (72) and the S case (95) than for the comparable cases under the full-recycle policy (69 and 82, respectively). The contrast suggests that the use of thorium largely eliminates the potential adverse economic impact of a secure-centers policy.

The effect of thorium use on ore utilization can be similarly evaluated. For example, ore utilization in the L cases is higher under the secure-centers policy (33.8) than under the full-recycle policy (32.4); the comparable figures for the S cases are 41.3 and 38, respectively. Again, the higher efficiency is attributable to the use of thorium, which, in this instance, extends the uranium resources. (The effect of thorium can be observed more clearly in the period 2027-2050. HEDL data from Annex 1, Tables F.3 and F.4, show an improvement of approximately 13 percent for the case including LWRs and 25 percent for the case including SSCRs over this period.)

EASE OF COMMERCIALIZATION OF THE ECONOMICALLY PREFERRED CASES

The analysis of the economics of the four cases under each of the recycle policies identified the cases warranting further consideration as options to pursue. In the following table, which summarizes the economic

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performance of all 12 cases, the preferred option for each policy is indicated by boldfaced type.

Composite Economic Indexes

Policy Option	Case L	Case S	Case H	Case G
Uranium recycle only	19	31	11	42
Recycle in secure centers	72	95	67	85
Full recycle	60	02	69	93

The performance of the cases for system average levelized cost and efficiency of ore-utilization is illustrated in Exhibits 2.b and 2.c, respectively.

The next step in narrowing down the thorium-based technologies for development involved the comparison of the noneconomic barriers to commercialization for the preferred cases.

An essential consideration in evaluating the ease of commercialization is the difficulty of commercializing the basic types of reactor using thorium.

A thorium-fueled LWR is the easiest application to commercialize and could be available by about 1987. Uranium-fueled LWRs are the predominant technology in the United States and would require only minor modification to convert to thorium. The Indian Point reactor has already provided a large-scale demonstration of thorium use, and delays in licensing are not as likely as for new reactor concepts. Commercialization of LWRs fueled with recycled U-233 may encounter delays because of the difficulties of recycle; however, similar constraints will apply to all technologies using recycled fuels. The LWR prototype will provide some demonstration experience with U-233, but not a demonstration of recycling capability on a large scale. The principal barriers to commercializing the LWR are summarized in Exhibit 2.d.1. A commercialization schedule is illustrated in Exhibit 2.d.2.

The thorium-fueled SSCR will probably be easier to commercialize than the HTGR or HWR because its technology

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is similar to the conventional LWR technology; the experience of the Canadians with HWRs will also be useful. However, changes to licensing standards could result in design modifications and construction delays. Moreover, the utilities foresee an increased likelihood of delays with a new technology, and this perception in itself is a barrier that must be overcome. Commercialization barriers to a U-233-fueled SSCR would be comparable to those for the U-233-fueled LWR. The principal barriers to commercialization of the SSCR are summarized in Exhibit 2.e.1. A commercialization schedule is illustrated in Exhibit 2.e.2.

The HTGR application will be more difficult to commercialize than the SSCR because the HTGR is less-closely related to the established LWR technology and requires a different reprocessing technology. Some operating experience of the HTGR has been developed in the United States, and considerably more of gas-cooled technology in France and the United Kingdom. However, several other barriers to commercialization must be overcome: the lack of a supply industry; differences in the necessary reprocessing technology; and licensing uncertainties. The principal barriers to commercializing the HTGR are summarized in Exhibit 2.f.1. A commercialization schedule is illustrated in Exhibit 2.f.2.

The HWR application would be the most difficult to commercialize. An HWR has not been designed to meet U.S. licensing requirements, and the domestic capability for the production of heavy water has not been established. Consequently, a major investment would be required to overcome these barriers. Technological expertise would also have to be transferred from Canada, and negotiation of binational agreements on the transfer will undoubtedly be a time-consuming process. The principal barriers to commercialization of the HWR are summarized in Exhibit 2.g.1. A commercialization schedule is illustrated in Exhibit 2.g.2.

These reactor-specific barriers are central to the consideration of the noneconomic barriers to commercialization under each of the policy options. The other major factors to be taken into account are the capital requirements of the utilities and the financial risk involved, and the demands placed on the supplier industries.

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The cases including the HTGR and the SSCR appear to make the most effective use of thorium under the three policies. Generally speaking, the cases including the HTGR appear to have a higher economic potential, but possibly greater noneconomic barriers to commercialization. On the other hand, the cases including the SSCR are probably less difficult to commercialize and more compatible with the existing LWR industrial base. Consequently, the HTGR-based systems would be the preferred approach if a firm policy permitting uranium-recycle only were adopted. In the present uncertain federal policy environment, however, the development of the more-versatile SSCR might well be a preferable approach.

In the following sections, we evaluate the implications of these barriers for the preferred options under each of the three recycle policies.

Noneconomic Barriers Under the Uranium-Recycle Only Policy

Under the uranium-recycle only policy, the G case was economically preferred, with an index of 42, and the S case, with an index of 31, was also attractive.

The utility capital requirements do not appear to represent a commercialization barrier for either case (see Exhibit 2.h.1). The capital demands for the S case, which includes the SSCR, are somewhat higher in the early years (to 2002) than those for the G case, probably because of the cumulatively higher cost of SSCRs. After 2002, however, the G-case capital costs are higher as HTGRs are introduced. However, in both cases, the capital requirements are close to historical trends and should not constitute barriers to commercialization. (Utilities have accounted for an average of approximately 23 percent of the total capital raised in the United States.)

The capital investments for reprocessing and enrichment capability in the S case would place a greater financial strain on suppliers until the early 1990s (see Exhibit 2.h.2). The suppliers' capital requirements for the G case are higher in later years because of the investment in enrichment and U₃O₈ mining. Overall supplier investment is not expected to constrain

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commercialization in either scenario. However, in both cases, the suppliers would be able to raise the necessary capital if federal policy were sufficiently firm to make the investment risk acceptable. (This conclusion should be confirmed, however, with representatives of each major supplier segment.)

As far as ease of commercialization for a new thorium-using reactor is concerned, the S case with the SSCR is probably slightly less difficult than the G case with the HTGR. Neither case is clearly preferable from the point of view of ease of commercialization, but because of its economic advantage, the G case including the HTGR should be considered the preferred case for this policy.

Noneconomic Barriers Under the Secure-Centers Policy

Under the secure-centers policy, the S case was economically preferred, with an index of 95, and the G case case, with an index of 85, was also attractive.

The capital requirements for utilities are similar and are close to historical trends in both cases (see Exhibit 2.i.1.). They are likely to prove a financial burden only if the rate of demand for electricity were to continue as projected but the growth of gross national product and the total capital supply declined. The capital requirements under this policy are higher than under the uranium-recycle only policy because the nuclear share of capacity is higher.

The investments required for suppliers in both cases again exceed the historical trend until the first decade of the 21st century (see Exhibit 2.i.2). The S-case demands, created by the extensive development of the SSCR, are lower than those for the G case until 2000, but are higher after 2000 because of the generally greater demand on all supply sectors. In both cases, enrichment and U_{308} mining requirements decline in the later years while reprocessing increases, reflecting the shift to the self-sustaining breeder nuclear economy. Neither case is strongly favored with regard to the development of the supplier industries. (The high supplier capital costs in the H case reflect the requirements for fabrication and reprocessing of HWRS in the later years of the scenario.)

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In both cases, financial burdens are imposed on the suppliers' capabilities; however, our analysis indicates that if the firms now in the nuclear supply business were to allocate 20 percent of their capital to the nuclear supplier industries, the projected demands would be adequately met. Moreover, in a strong nuclear-growth environment, supported by a favorable federal policy, the suppliers would make the necessary investments, according to our survey. Consequently, the suppliers' investment requirements should not preclude commercialization if a firm, stable government policy is developed. (Again, these conclusions should be verified with the suppliers.)

The S case with the SSCR will probably be slightly easier to commercialize than the G case, and is apparently superior economically. It should therefore be considered the preferred case.

Noneconomic Barriers Under the Full-Recycle Policy

Under the full-recycle policy, the G case has the highest economic index (93). The S case also has a high index (82), but no thorium/U-233-fueled systems are included. Consequently, the G case is preferred.

The utility capital requirements are slightly higher than historical trends from 1995 to 2012 because of the investment in capital-intensive HTGRs and FBRs (see Exhibit 2.j.1). If the projected economic advantage of the G case, and especially of the HTGR, can be realized without undue risk, the utilities can be expected to supply the required capital.

Higher demands are placed on the supplier industries than in any of the other cases because of the enrichment and U₃O₈ mining investments required to supply highly enriched uranium for the HTGRs in the later years of the case (see Exhibit 2.j.2). This additional burden on the suppliers makes commercialization more difficult than in the G case under the secure-centers policy, but, again, should not preclude commercialization if the favorable economics of the case are supported by a firm and stable government policy.

Exhibit 2.a.1

HEDL Results (2026): No Recycle Policy

	Case L	Case S	Case H	Case G
GW(e) nuclear	261	292	204	216
GW(e) fossil	1,934	1,903	1,991	1,979
Thorium-based systems	none	none	none	none
U-238/Pu-based systems				
Reactor types (GW(e))	LWR-U5(LE)/U [36] LWR-U5(LE)/U-T [225]	LWR-U5(LE)/U [95] SSCR-U5(LE)/U [197]	LWR-U5(LE)/U [195] HWR-U5(SEU)/U [9]	LWR-U5(LE)/U [141] HTGR-U5(LE)/U-T [75]
Average levelized cost (mills/kWh)*	18.3	18.4	18.5	18.4
Cumulative U ₃ O ₈ consumption (10 ⁶ /short tons)	2.92	2.81	2.79	2.74
Annual (2025) coal consumption (10 ⁶ /short tons)	5,220	5,170	5,350	5,330

*Averaged over 1977-2025.

Exhibit 2.a.2

HEDL Results (2026): Uranium Recycle Only Policy

	Case L	Case S	Case H	Case G
GW(e) nuclear	459	661	349	748
GW(e) fossil	1,736	1,534	1,846	1,447
Thorium-based systems				
Reactor types (GW(e))	LWR-U5(DE)/U/Th [189] LWR-U3(DE)/U/Th [157]	SSCR-U3(DE)/U/Th [306] LWR-U5(DE)/U/Th [273]	none	HTGR-U5(DE)/U/Th [487] HTGR-U3(DE)/U/Th [136]
U-238/Pu-based systems				
Reactor types (GW(e))	LWR-U5(LE)/U [113]	LWR-U5(LE)/U [82]	LWR-U5(LE)/U [349]	LWR-U5(LE)/U [125]
Average levelized cost (mills/kWh) *	18.4	18.4	18.4	18.3
Cumulative U₃O₈ consumption (10 ⁶ /short tons)	2.88	3.01	2.76	3.01
Annual (2025) coal consumption (10 ⁶ /short tons)	4,790	4,330	5,030	4,090

*Averaged over 1977-2025.

Exhibit 2.a.3

HEDL Results (2026): Recycle in Secure Centers Policy

	Case L	Case S	Case H	Case G
GW(e) nuclear	1,244	1,453	1,227	1,377
GW(e) fossil	951	742	968	818
Thorium-based systems				
Reactor types (GW(e))	LWR-U3(DE)/U/Th [190] LWR-Pu/Th [52] FBR-Pu-u/Th [408]	LWR-U5(DE)/U/Th [2] SSCR-U3(DE)/U/Th [294] SSCR-Pu/Th [72] FBR-Pu-U/Th [420]	HWR-U3(DE)/U/Th [248] FBR-Pu/U/Th [537]	HTGR-U3(DE)/U/Th [273] HTGR-Pu/Th [45] FBR-Pu-U/Th [493]
U-238/Pu-based systems				
Reactor types (GW(e))	LWR-U5(LE)/U [594]	LWR-U5(LE)/U [170] SSCR-U5(LE)/U [495]	LWR-U5(LE)/U [442]	LWR-U5(LE)/U [566]
Average levelized cost (mills/kWh)*	17.8	17.4	18.0	17.8
Cumulative U₃O₈ consumption (10⁶/short tons)	3.68	3.52	3.23	3.63
Annual (2025) coal consumption (10⁶/short tons)	2,910	2,340	3,020	2,560

*Averaged over 1977-2025.

Exhibit 2.a.4

HEDL Results (2026): Full Recycle Policy

	Case L	Case S	Case H	Case G
GW(e) nuclear	1,153	1,333	1,171	1,453
GW(e) fossil	1,042	862	1,024	742
Thorium-based systems				
Reactor types (GW(e))	none	none	none	HTGR-U5(HE)/Th [472] HTGR-U3/Th [291] HTGR-Pu/Th [100]
U-238/Pu-based systems				
Reactor types (GW(e))	LWR-U5(LE)/U [513] LWR-Pu/U [196] FBR-Pu-U/U [444]	LWR-U5(LE)/U [161] LWR-Pu/U [207] FBR-Pu-U/U [511] SSCR-U5(LE)/U [454]	LWR-U5(LE)/U [448] FBR-Pu-L/U [723]	LWR-U5(LE)/U [230] FBR-Pu-U/U [360]
Average levelized cost (mills/kWh)*	17.8	17.7	17.9	17.7
Cumulative U₃O₈ consumption (10⁶/short tons)	3.56	3.50	3.24	3.41
Annual (2025) coal consumption (10⁶/short tons)	3,150	2,680	3,090	2,330

*Averaged over 1977-2025.

Exhibit 2.b
System Average Levelized Costs

Exhibit 2.c

 U_3O_8 Ore-Utilization System Efficiencies

^a See page 2.9 for explanation of index.

Exhibit 2.d.1

Noneconomic Barriers to Commercialization of LWR/Th

Technological Barriers	Financial Barriers			Commercial Availability
	Licensing	Adaptability	Other	
<p>Not demonstrated at commercial scale, only in Consolidated Edison 275-MW Indian Point plant in 1960s.</p> <p>Use of U-233-fueled LWR with thorium not demonstrated; only in LWBR now beginning operation.</p> <p>Nuclear characteristics, less-negative moderator coefficients may require different control procedures.</p> <p>Thorex reprocessing not demonstrated at commercial scale; some technical uncertainties unresolved.</p> <p>Remote refabrication of U-233-bearing fuels.</p>	<p>Minor delays possible due to novelty of thorium use, different nuclear properties.</p> <p>Licensing of reprocessing facilities deferred indefinitely.</p> <p>Utilities expect potential delays from development of new standards, design changes during construction.</p>	<p>Minor barriers; retrofitting and adaptation of new plants feasible. Most adaptable application.</p>	<p>Initial enrichment requirement increases initial capital cost, thus marginally increases financial exposure.</p>	<p>Thorium fertile diluent by 1987, LWR with recycled U-233 by 1991-1995.</p>

Exhibit 2.d.2

Estimated Schedule for Commercial Availability of LWR/Th

SOURCES: Combustion Engineering; HEDL; RPA.

Exhibit 2.9.1

Noneconomic Barriers to Commercialization of SSCR

Technological Barriers	Financial Barriers			Commercial Availability
	Licensing	Adaptability	Other	
<p>Not demonstrated on commercial scale, only in Belgian 10-20 MW plant in 1960s.</p> <p>Some uncertainties regarding pump seals (heavy-water leakage rates, refueling and core-reactivity control)</p> <p>Moderator properties may require new control procedures, equipment.</p> <p>Possible difficulty in retrofitting to LWR because of potential tritium leakage.</p>	<p>First-of-a-kind licensing delays likely.</p> <p>Tritium leakage, control and safety of heavy water raise licensing question; other uncertainties may be minimized by similarity to LWR, Canadian experience with CANDU and West German experience with ATUCHA.</p>	<p>Reprocessing, enrichment, fuel fabrication possible in same facilities as for LWR.</p> <p>Hence, similar supplier infrastructure to established system; however, heavy water plant components supplier needed.</p> <p>Versatility to be operated as a conventional LWR reduces risk.</p>	<p>Domestic heavy-water production capability lacking; delay in heavy-water supply may delay introduction of technology, increase financial risk.</p> <p>Higher capital cost increases financial exposure.</p>	<p>Possibly 1991 with U-235 fuel; with U-233 fuel in 1991-1995.</p>

Exhibit 2.e.2

Estimated Schedule for Commercial Availability of SSCR

SOURCES: Combustion Engineering; HEDL; RPA.

RPA

Exhibit 2.f.1

Noneconomic Barriers to Commercialization of HTGR

Technological Barriers	Financial Barriers			Commercial Availability
	Licensing	Adaptability	Other	
<p>Not fully demonstrated at commercial scale in United States; low power test of 330-MW Fort St. Vrain station in Colorado now underway and 40-MW Peach Bottom plant operated successfully; wide experience with smaller plants in UK.</p> <p>No full-power test of steam generators.</p> <p>Extensive development of fuel element, but commercial-scale reprocessing and recycling of bred U-233 fuel not demonstrated.</p> <p>"Head-end" of reprocessing, disposal of irradiated carbon-14, remote reprocessing and refabrication not demonstrated.</p>	<p>First-of-a-kind licensing delays expected, although Fort St. Vrain reactor provides precedents.</p> <p>No licensed reprocessing and refabrication facilities; licensing may create delays, alter economics, and increase financial risk.</p>	<p>Reactor and fuel supply facilities cannot be adapted for other types of reactor; but financial risk partially offset by flexibility of fuel-element design, allowing modification of design parameters (fertile to fissile, heavy metal to moderator ratios).</p>	<p>Technology adopted only in France and UK because of many difficulties in commercializing; financial risk generally regarded as high.</p> <p>Capital cost higher than LWR particularly for initial units.</p>	<p>Commercially available 1995-1997; on recycled U-233, possibly by 1995-2005.</p>

Exhibit 2.f.2

Estimated Schedule for Commercial Availability of HTGR

SOURCES: Combustion Engineering; HEDL; RPA.

Exhibit 2.g.1

Noneconomic Barriers to Commercialization of HWR

Technological Barriers	Financial Barriers			Commercial Availability
	Licensing	Adaptability	Other	
No demonstration of technology on commercial scale in United States.	Without design to U.S. standards, licensing delays expected.	Little risk of delay in fuel fabrication and reprocessing; facilities same as for LWR could probably be used.	High risk of cost overruns due to lack of manufacturing experience with reactors, heavy-water production.	1995-1997 in United States. (Already available in Canada and international market.)
No design meeting U.S. licensing requirements.	Licensing of fueling and control systems may be delayed; use of thorium likely to increase delays.		Capital costs higher than the LWR's; unacceptably high financial obligation for smaller utilities.	
Negligible manufacturing base in United States; but broad Canadian experience with CANDU.				
No HWRs operated on thorium, but few problems expected in converting CANDU.				
Uncertain conformity of CANDU on-line refueling system, tritium release from heavy-water leakage, emergency core-cooling systems, and computer controls to U.S. licensing standards and practices.				

Exhibit 2.g.2

Estimated Schedule for Commercial Availability of HWR

SOURCES: Combustion Engineering; HEDL; RPA.

*Canada plans commercially available U-233 recycle fuel by about 1990.

RPA

Exhibit 2.h.1

Utility Capital Requirements (nuclear and coal-fired plants): Uranium Recycle Only Policy

Exhibit 2.h.2

Nuclear Supplier Capital Requirements: Uranium Recycle Only Policy

Exhibit 2.i.1

Utility Capital Requirements (nuclear and coal-fired plants): Recycle in Secure Centers Policy

Exhibit 2.i.2

**Nuclear Supplier Capital Requirements:
Recycle in Secure Centers Policy**

Exhibit 2.j.1

Utility Capital Requirements (nuclear and coal-fired plants): Full Recycle Policy

Exhibit 2.j.2

**Nuclear Supplier Capital Requirements:
Full Recycle Policy**

3 FEDERAL POLICY OPTIONS FOR COMMERCIALIZING THORIUM-BASED TECHNOLOGIES

The utility industry, as we have shown, will not adopt thorium voluntarily under the conditions prevailing in the nuclear market. The commercialization of thorium, then, depends upon government action. The decision that thorium-based technologies are desirable to extend our nuclear resources, to prevent the proliferation of weapons-grade nuclear material, or for some other reason, must be made by the federal government. And the barriers to commercialization can be removed only by a large-scale effort involving a number of federal government agencies -- at least the Department of Energy, the Nuclear Regulatory Commission, the Environmental Protection Agency, the Departments of State and the Interior, and the Arms Control and Defense Administration -- acting in concert, with the solid support of the Administration and the Congress.

As we have shown in the preceding chapter, these barriers are not likely to be economic.* Under certain federal policies permitting recycling, thorium could be economically competitive with uranium-plutonium; the major barriers to thorium are institutional, technological, or regulatory. They are:

- The lack of a definite, permanent federal policy on fuel recycle; without such a policy, the absolute and relative economics of all technologies are uncertain.
- The lack of a definite, permanent policy on the development of fast-breeder reactors; without such a policy, the payback period for investments in thorium cannot be determined with confidence.

* The LWR Study Group of the Massachusetts Institute of Technology independently reached the same conclusion. Their study is reported in ERDA's Role in the Development and Acceptance of Light Water Reactors (discussion draft) (August 12, 1977).

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- The lack of a practical limitation on the types of reactor and fuel-cycle technology to be developed; supporting a diversity of technologies will dissipate the resources of government and industry and increase the risk of constant technological obsolescence.
- The lack of a commercial-scale demonstration of a thorium technology; without such a demonstration the utility industry will not be persuaded that thorium is viable.
- The uncertainty that a reactor on the thorium fuel-cycle and its supporting reprocessing and recycling technology are licensable; without a demonstration of licensability, the utility industry and the suppliers will be reluctant to adopt even a technically demonstrated technology.

In this chapter, we go beyond the immediate purpose of this phase of the Thorium Assessment Program, which was to identify these barriers, to suggest a series of policy options that would remove the barriers. These suggestions are highly tentative and must be regarded as no more than a first step toward the formulation of a comprehensive program of research, technology development and demonstration, financial incentives, nuclear regulation and policy amendment, legislation, international agreements, and agreements and joint ventures with utilities and suppliers.

We outline in the following sections a policy program consisting of five steps, the first three of which in combination address the three institutional barriers and the last two, the technological and regulatory barriers.

POLICY OPTIONS TO OVERCOME INSTITUTIONAL BARRIERS

The first three policy steps are:

1. Complete technical investigation of thorium applications. We believe that the technical information now available is almost complete enough to form the basis for an initial policy decision among the thorium options; however, further investigation of a

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number of related topics is necessary to ensure all options are properly considered:

- The performance, cost, and licensability of an LWR design optimized for the use of thorium on a once-through cycle.
- The performance and cost of a thorium/U-233-fueled light-water breeder reactor.
- The cost and performance of an HWR design conforming to U.S. licensing criteria.
- The technical viability and cost of reprocessing and recycling Pu/U-235 and U-233/Th-based fuels.
- The capital costs of power plants, particularly of reactors other than LWRs; these costs may contribute as much as half of levelized cost of the plant, but have not been determined with certainty and estimates should be further developed and reviewed jointly with industry experts.
- The outstanding technical uncertainties of thorium technologies, including those discussed in the preceding chapter.

These evaluations can, and should, be completed within the next year. They should yield sufficient information to confirm or refute our initial conclusions, and to suggest what, if any, additional economic evaluations of thorium systems may be required. A listing of future work is provided in Appendix C.

2. Decide whether or not to commercialize a thorium-based fuel-cycle. On the basis of the information developed in the previous step, the federal government should decide if any thorium technology should be developed. This decision could be based upon one or more of the following criteria:

- The need for a more proliferation-resistant fuel-cycle technology.
- The need for a technology to extend available nuclear fuel supplies.
- The need for a hedge, or "insurance policy," against the possibility that the development of advanced technologies, such as the fast breeder reactor, is delayed or falls short of commercialization.

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3. Develop the minimum practical number of fuel-cycle/reactor combinations. Utilities and suppliers repeatedly stated that one thoroughly researched, well-understood technology is preferable to a diversity of possibly superior, but unfamiliar, technologies, even if the selection is made and enforced by the government.

If a non-LWR technology is selected and developed as the single preferred technology, the retrofitting of LWRs for thorium use and the adaptation of new LWRs and LMFBRS for thorium should still be pursued in parallel. Modifying an LWR in the early stages of construction is likely to be less costly than retrofitting, where the loss of power during the 1-2 years needed to complete the process may not be offset by the potential advantages of thorium use. Nevertheless these alternatives should be considered as supplements to the selected technology or as insurance policies.

These steps complement research and development already under way in DOE. In combination, they address the first three of the five major barriers to the commercialization of thorium.

Completion of the technical and economic studies will document more fully the advantages of thorium in different reactors and fuel-cycle applications, particularly the economics of thorium and ore-utilization characteristics and will reduce or eliminate many technical uncertainties.

DOE and other branches and agencies of government involved with the decision will then be in a position to formulate a policy on fuel recycle that accounts for the role thorium can play in nuclear power development.

The same information will also elucidate a policy decision on the breeder reactor and its fuel-cycle. The decision to develop thorium could affect the arguments for and against developing the breeder reactor; the economically preferred case described in the preceding chapter consists of a system of LWRs, SSCRs, and breeder reactors using uranium/plutonium-based fuels, and U-233/thorium and plutonium/thorium-based fuels.

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A decision to proceed with the breeder reactor would not preclude a market for thorium; thorium-fueled FBRs could operate symbiotically with U-233/thorium-fueled reactors. A decision against the breeder, on the other hand, could favorably affect the thorium market, but would not affect the policy steps required to commercialize thorium. A definite policy, however, would clarify the extent of economic gain resulting from the use of thorium.

Finally, a practical limit on the thorium reactor and fuel-cycle technologies to be pursued will provide a focus for government and industry. Historically, when the development of technologies has been diversified, resources are dissipated in pursuing a variety of uncoordinated research and development efforts. The uncertainties of pursuing several options would make the utility industry and the supplier industries cautious about committing their resources to new technologies and fuel-cycles. The decision to concentrate on a single technology or limited number of technologies will overcome the industries' reluctance; and, as the decision will be made within the federal government, the selection can accommodate related programs in DOE and other federal agencies and be timed to conform to the objectives of these prior commitments.

POLICY OPTIONS TO OVERCOME TECHNOLOGICAL AND REGULATORY BARRIERS

A groundwork must be laid for addressing the technological and regulatory barriers: the lack of a demonstration of a thorium technology on a commercial scale; and the uncertainty that a thorium fuel and supporting reprocessing technology are licensable.

These two barriers encompass many of the noneconomic constraints to commercialization identified in the preceding chapter and discussed in reference to four different reactors.

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Two policy steps are involved:

4. Develop a joint government/industry R&D program. Information developed under DOE's present nuclear program will serve to identify precisely the outstanding technological and regulatory problems that must be resolved before a commercial-scale thorium technology can be demonstrated. The R&D program would be implemented in three stages.

- Identify elements to be investigated. These would include not only technical problems, but also financial and institutional problems; for example, if a CANDU reactor were selected for development, technical R&D could evaluate methods of minimizing heavy-water losses, financial investigations could concentrate on reducing initial capital costs and improving reactor availability, and institutional investigations could determine the proper licensing criteria for new design features. The primary goal would be a standardized reactor design conforming to the applicable, technically evaluated licensing criteria. Licensing criteria would therefore have to be developed in parallel with technical R&D and design.
- Determine participants. The program should involve the government, the utilities, and suppliers. Their efforts could be coordinated through the Electric Power Research Institute to ensure that the maximum funding is obtained from industry and applied to the selected technology. The federal government should serve as the program manager to coordinate the work of the various participants and aim it toward the common goal of licensable reactors and fuel-cycles. In this role, the government would also ensure that the results of research are shared.
- Provide supporting legislation. A firm, stable government policy will be demonstrated to industry only by legislation that precludes changes in the policy by future administrations. This legislation should also provide the necessary funding to complete the research, development, and demonstration; mandate the development of adequately tested licensing criteria and standards in parallel with the technical research; and specify a schedule for completion of the research, development, and demonstration of the selected technology.

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We estimate that designing the program and soliciting industry participation and financial support will take approximately 1 year. The design would incorporate current thorium programs and should begin in 1978. The first two stages should be completed by 1979 if thorium is to be commercially available between 1987 and 1991.

5. Develop a demonstration program to overcome technical, financial, and institutional barriers. The demonstration of the selected reactor, fuel-cycle, and reprocessing technology on a fully licensed, commercial scale is crucial to the ultimate purchase of thorium-fueled plants by utilities. This program should demonstrate not only that the technology is feasible, but also that the requisite federal and state licenses can be obtained. The demonstration program must therefore include a requirement that all normal licensing procedures are followed and approvals obtained for fueling a commercial-scale (approximately 1000-MW) reactor with thorium.

A thorium-fueled LWR or SSCR can probably be commercialized more rapidly than the HTGR and CANDU, and at a lower cost. The cost would be shared with utility owners of the reactor; the federal share should include some percent of capital cost or a compensatory payment to the utility or utilities for power purchased while the unit is out of service.

Fuel fabrication, irradiation testing, and reprocessing and refabrication development could be initiated at a bench or test scale and would continue throughout the demonstration of the reactor. Heavy water for an SSCR demonstration could be purchased (in preference to building a heavy-water facility), and the cost assumed by the government. If demonstration and testing were successful, utilities could begin to place orders for SSCR units by 1984 or convert LWRs going on line after that date.

A very rough estimate of the government costs for an LWR or SSCR demonstration ranges from \$400 million to \$800 million. The largest cost component would be the government's share of the construction and interest costs, which would be incurred over 6 years of construction and demonstration.

The demonstration of a commercial-scale HTGR will take considerably longer. A commercial-scale unit would have to be designed and built from the start; the entire process, including a demonstration period,

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would span approximately 10 years. However, some utilities have already instituted HTGR research, so that a framework for government/industry working agreements has been established. The building and demonstration of the plant would be paralleled by a demonstration of fuel fabrication and reprocessing technologies.

The government's share of the cost for demonstrating a thorium-fueled HTGR is estimated roughly to range from \$1.2 billion to \$2.0 billion. The public cost is heavy, but, without a convincing demonstration of this technology, it appears unlikely that the utilities will invest in a thorium-fueled HTGR.

The most effective method of introducing a thorium-fueled HWR is the transference of the Canadian CANDU technology. The process, however, will be complex. The federal government must negotiate agreements with the Canadian government, Canadian utilities, and Canadian suppliers, presumably through DOE. The CANDU design would then have to be modified to meet U.S. licensing and safety requirements, and a commercial-scale unit built and demonstrated. The government would also have to purchase heavy water for the demonstration or build heavy-water facilities to supply the demonstration unit and any subsequent commercial CANDUs.

The burden of designing and building a demonstration CANDU would also fall mainly on the government; the technology is novel in this country, and the private sector has no experience with it. Consequently, the government would assume almost all of the costs of transferring the technology, which may range from \$1.8 billion to \$2.4 billion, exclusive of the cost of developing the necessary supplier manufacturing base.

Whichever technology is selected for demonstration, the government should also be prepared to provide R&D support for at least 5 years to overcome start-up problems as the utilities adopt the technology on a commercial scale.

A suggested program and schedule for commercializing the SSCR and HTGR are presented in Exhibits 3.a and 3.b, respectively. A similar program for the HWR is presented for comparison in Exhibit 3.c.

Exhibit 3.a.1

Suggested Schedule for Commercialization of LWR/Th or SSCR (Recycle in Secure Centers Policy Case S)

Exhibit 3.a.2

Installed Electric Generating Capacity:
Recycle in Secure Centers Policy Case S

Exhibit 3.b.1

Suggested Schedule for Commercialization of HTGR (Uranium Recycle Only Policy Case G)

Exhibit 3.b.2

Installed Electric Generating Capacity:
Uranium Recycle Only Policy Case G

Exhibit 3.c.1

Suggested Schedule for Commercialization of HWR (Recycle in Secure Centers Policy Case H)

Exhibit 3.c.2

**Installed Electric Generating Capacity:
Recycle in Secure Centers Policy Case H**

Appendix A

THE MARKET FOR THORIUM POTENTIAL AS PERCEIVED BY THE NUCLEAR INDUSTRY

A potential market for thorium will be critically dependent on, first, a strategic decision by the utilities to commit themselves to additional nuclear baseload units and, second, an acceptance by the utilities and their public utility commissions that thorium fuels have distinct technological, economic, and financial advantages.

The utilities' decision to purchase baseload units depends essentially on the projected demand for electricity. If the forecast demand clearly dictates the need for added capacity, the utilities must then make a strategic decision as to whether the added capacity will be coal-fired or nuclear-powered or some mix of the two. In recent years, the business climate of the utility industry has changed considerably, and strategic planning has become hedged with uncertainty in a changing and less-predictable market for electric power.

According to DOE's projections, the national demand for electricity over the next 50 years will grow to between 9.0 trillion kWh and 16.9 trillion kWh. This growth and the need to replace aging units will create a large market for baseload electric power generation stations with a progressive trend to coal-fired and nuclear units.

The Administration's national energy policy will stimulate a shift by utilities from oil and gas to coal. However, some utilities cannot convert their boilers to coal utilization and others are not able to add new coal-burning power plants to their capacity. Air-quality standards, particularly the nondeterioration, nondegradation standards in effect in the early 1980s, will severely restrict the use of coal in many states. Utility managements have cited the difficulties of using coal, not only in RPA's recent survey of utilities, but also in the Federal Energy Administration's Executive Conferences on

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the National Energy Plan and in testimony before Congressional committees. The use of coal, therefore, will depend not only on its availability at competitive prices, but also on the utilities' ability to conform with present and future air-quality standards.

In any case, coal alone cannot support the predicted national demand for electric generation. The level of coal production by 1985, forecast in the National Energy Plan, is 1.2 billion tons per year. This will produce about 550 GWe of the total required demand; the remainder will be supplied by nuclear and other fuels. Consequently, there will be a potential market for nuclear fuels for the remainder of this century. The magnitude of this market will be a critical factor in the planning of baseload power limits by the utilities.

The purchase of baseload units has been governed by projected demand; during the period in which statistics for the electric utility industry have been kept, electrical energy production has never failed to double every 9-10 years. Since World War II, the stability and predictability of growth have been notable characteristics of the utility industry. Load characteristics have varied little from historical trends; regulatory policy has been consistent; and, consequently, the various costs considered in capital investment planning were under control -- generally declining, and quite predictable. Revenues were equally secure. Between 1960 and 1965, total national consumption of energy grew at a constant average annual rate of 7.1 percent. Annual consumption fluctuated between 5.4 percent and 7.8 percent; but, over the last 4 years of the period, increases were virtually identical. Increases varied more widely with individual companies. However, the factors affecting demand, such as shifts in population, number of households, and industrial activity, were all familiar to the utilities concerned; forecasting growth in energy consumption posed few problems. Similarly, forecasting peak demand was uncomplicated. Throughout the 1960s, the annual peak load for the industry as a whole grew at an average rate of 7.0 percent annually, with annual fluctuations ranging only from 6.0 percent to 8.5 percent. And because growth in consumption and peak load were predictable, so too was the annual load factor. The load factor for the industry as a whole remained virtually unchanged during the early 1960s, declining slightly from 65.5 percent in 1960 to 65.0 percent in 1965.

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Under these circumstances, the planning of capital investment was simplified. Planning was based on forecasts of energy demand and peak load for several years ahead, factors that were thought to be known with a very high degree of certainty. The capacity mix presented few problems. Utilities were adding large baseload plants to realize the profit accruing from economies of scale; they were retiring older, less-efficient plants or converting them to peaking use. Only 3 percent of the total generating additions in the early 1960s consisted of peaking units.

This stable environment was disrupted by the Arab oil embargo of 1973. Rapid changes in fuel prices were passed on to consumers through fuel adjustment clauses, and the price of electricity rose sharply. As a result, the demand for electricity decreased in every customer class, and utility system planners found it increasingly difficult to project demand with confidence. The electric utility industry was faced with a shift from stable growth to highly unpredictable growth.

The factors that guide utility planning have become more complicated and less certain. Demand has become less predictable with the rapid change in electricity prices, and uncertainty has been one of the factors leading to the cancellation of 20 nuclear plants and the deferral of 100 others in the last 7 years. The situation has been further complicated by national and local policies that encourage -- and, in some cases, mandate -- reform of utility rate structures and a move toward rates reflecting marginal costs.

Marginal-cost pricing of electricity will tend to increase prices to the customers and customer classes whose demands require expansion of the system. This trend is bound to increase the unpredictability of demand, so that forecasting system demand, particularly baseload demand, by customer class will become difficult. Obviously, the need to add generating capacity will change reciprocally with demand. If demand declines, utility revenues will decline proportionately, as will the utilities' ability to finance costly baseload units. One result of uncertainty has been the recent increase in less capital intensive peaking units, now 17 percent of total new capacity. This trend may be reinforced by industry's renewed interest in cogeneration and

NUCLEAR INDUSTRY SURVEYS

self-generation systems. The price of electricity has led many manufacturing firms to examine the economic potential of these systems, but the utilities are unable to project how many firms in any service area may opt for cogeneration. The uncertainty is compounded where cogeneration is concerned. Industrial consumers who turn to cogeneration reduce baseload demand significantly; simultaneously, they increase the need for peaking capacity to provide backup power, and thus increase the proportion of residential and commercial demand, which is less stable.

The utility's business environment has, therefore, changed rapidly and radically. The stability and predictability that formerly marked this environment have given way to uncertainties in demand, in regulation and policy, and in economics. Utility executives are justifiably hesitant about committing themselves to investment in new baseload capacity. Such commitments, as manifested in the utility plans submitted to the regional electric reliability councils and in purchase orders to equipment manufacturers, reflect decisions to invest billions of dollars yearly over a considerable period of time. The consideration of a new and unfamiliar fuel or type of reactor, then, adds a new dimension of uncertainty to a decision-making process already complicated by the uncertainties of cost, price, return on investment, public policy, and public acceptance of nuclear power.

To gauge the effect of this additional complication to the utilities' strategic planning, we surveyed more than 50 utilities, nuclear supply firms, state regulatory agencies, industrial associations, and members of the banking community. Under a guarantee of confidentiality, we elicited the views of a broad spectrum of respondents intimately concerned with nuclear power on the present and prospective status of the nuclear market and on the potential for thorium in that market.

The results of this survey are summarized in the following sections.

NUCLEAR INDUSTRY SURVEYS

UTILITIES AND STATE PUBLIC UTILITY COMMISSIONS

We surveyed a number of utilities, regional electric reliability councils, and state regulatory agencies. Their responses are summarized by region, corresponding to the jurisdictions of the regional reliability councils.

Northeast Power Coordinating Council

- Strong movement toward nuclear power because of its economic advantage, transportation and environmental constraints on use of coal.
- Uranium contracts and uranium reserves are adequate to meet demand for fuel; hence, no perceived need for thorium as a fuel supplement.
- Nuclear industry needs stability; thorium cycle would add to the present uncertainties of policy and market regulation.
- Difficulties with regulatory process expected to constrain demand for nuclear units, so need for thorium will not develop.
- Alternative reactor concepts to the LWR not considered for units in this region.
- Utilities unwilling to undertake the first thorium project because of risk of delay or rejection during the licensing process.
- Utilities unwilling to undertake the first new reactor (i.e., HTGR, CANDU, SSCR) with thorium because of regulatory uncertainties.
- Utilities believe thorium and reactors designed to optimize use of thorium would require 6-10 years of RD&D before market would begin purchasing.
- Thorium could enter a market if proved licensable and economically competitive, but stable nuclear market has higher priority than changes in fuel or reactor.

NUCLEAR INDUSTRY SURVEYS

Mid-Atlantic Area Council

- Some local opposition to nuclear units, but utilities tend to prefer nuclear units from an economic and environmental viewpoint.
- Consensus that uranium reserves are adequate to meet demand; hence, no perceived need for thorium.
- Uranium supplies should sustain the nuclear units until the breeder reactor is commercialized.
- Federal government should concentrate on correcting policy deficiencies (e.g., permit recycling of uranium and plutonium) and accelerating development of the breeder.
- Alternative reactor concepts to LWR not an important consideration. Insufficient experience and information to justify the risk of increasing already serious licensing problems.
- Utilities unwilling to undertake first thorium project because of risk of delay or rejection during licensing process.
- Utilities would require strong federal interest before thorium would be seriously considered.
- Economic competitiveness of thorium in conventional LWRs or other reactors would have to be convincingly demonstrated before thorium would be considered seriously.

Southeastern Electric Reliability Council

- Region foresees major role for both nuclear and coal-fired units.
- Mining and transport of coal viewed as constraint; hence, slight preference toward nuclear power in region, but northern sector prefers nuclear, southern sector prefers coal.
- Uranium supply viewed as adequate.
- Acceleration of development of breeder reactor preferred over introduction of thorium in the event of a uranium shortfall.

NUCLEAR INDUSTRY SURVEYS

- Utilities in southern half of the region tended to be more conservative in plans for nuclear units because of cost overruns and licensing problems.
- Utilities in Georgia, Alabama, Mississippi, and Florida concerned that nuclear units present financial risk that could jeopardize their financial future.
- Regulatory agencies concerned over the schedule and financial risks of nuclear units to the companies in their states. Concern over the uncertainty in plant availability may prevent state from fulfilling its responsibility in assuring continuous electrical supply.
- Thorium perceived as "good distance away" from commercialization (e.g., 15 years); would create more problems than it would solve, particularly in the regulatory process.
- Alternative reactors to the LWR perceived as presenting too great a risk. A new reactor would have to be proven before interest would develop.

East Central Area Reliability Coordinating Agreement

- Region moving more toward coal than nuclear fuel, but substantial capacity for both fuels is expected.
- Uranium supply appears adequate; hence, need for thorium is not apparent.
- Financial risks of nuclear units caused by cost overruns and schedule uncertainties concern many utilities in the region.
- Thorium would create more regulatory problems; need to correct outstanding regulatory problems first.
- Regulatory agencies are only just beginning to understand how to regulate LWR-uranium system; new fuel or reactor will strain ability of state and federal regulators to maintain control over electric power generation.
- Thorium would need to be demonstrated as workable, licensable, and as economically competitive before interest would develop.
- Alternative reactor concepts to conventional LWR present risk to utilities.

NUCLEAR INDUSTRY SURVEYS

Mid-America

Interpool Network

- Continued use of coal and nuclear in this region.
- Uranium supplies appear adequate, but interest evinced in thorium if the breeder reactor significantly delayed.
- Need to correct regulation and policy constraints on the LWR-uranium once-through cycle before introducing thorium.
- Involvement of state and federal government a constraint to nuclear development; will become more complicated if new fuels and reactors enter the market.
- Considerable R&D necessary, particularly in remote handling, before thorium is viable fuel option; thorium expected to be 10-15 years from commercial reality.
- Thorium needs to be demonstrated and licensed before interest would develop.

Southwest Power Pool

- Coal preferred in this region, yet strong desire for fuel diversification.
- Expanded railroad, and possibly slurry pipeline, transportation of coal planned.
- Discouraged with federal nuclear policy, licensing of nuclear units, and fear of open-ended tax on nuclear units.
- Convinced that uranium supply is adequate and that thorium is not needed to supplement supply.
- Thorium would be acceptable if safety and licensing requirements are met expeditiously and economical competitiveness demonstrated.
- Prefer to correct problems with present fuel-cycle before introducing new fuel.
- Regulatory agencies prefer coal for safety and minimization of federal regulation.
- Alternative reactors to the LWR are of limited interest until the licensing problems of the LWR are corrected.

NUCLEAR INDUSTRY SURVEYS

Electric Reliability
Council of Texas

- Coal preferred in this region by utilities and regulatory agencies.
- Federal policy constraints and licensing problems seen as reducing demand for uranium; hence, no need for thorium.
- If national or state policy restraints on coal use become more stringent, outlook for nuclear power will improve.
- If demand for nuclear units and uranium increases, federal funds are better spent in accelerating breeder reactor program.
- Policy in Texas emphasizes coal utilization. Railroad Commission has ordered upgrading of tracks to accommodate coal traffic; legislature is considering bill to give right of eminent domain to pipeline carriers for coal slurry pipeline.
- Cost uncertainty of nuclear units is a major concern, and would increase with new reactor options; however, new reactors would be purchased if fully tested and proven.
- Concern over federal regulation and desire to minimize requirements; concern with imprecise and constantly changing design standards for nuclear units.

Mid-Continent Area Reliability
Coordination Agreement

- Coal dominant in utility plans because supplies are abundant and utilities prefer to avoid federal nuclear regulatory requirements.
- Uncertainty in plant cost militates against nuclear units, and capital cost of nuclear plants would strain resources of smaller utilities.
- Because of the abundance of coal in region (and nationally), the need for thorium is not perceived unless regulation of coal use becomes considerably more restrictive.

NUCLEAR INDUSTRY SURVEYS

- Introduction of a new fuel or new reactors complicates difficulties with federal regulations.
- Current nuclear policy and regulations should be improved before any new fuel or reactor concepts are introduced.

Western States
Coordinating Council

- Substantial nuclear capacity planned; significant coal capacity also to be constructed.
- Air-quality standards constrain coal use, while seismic conditions constrain nuclear use in certain areas.
- State energy policy and regulatory policy vary from seriously constraining nuclear units to favoring nuclear units.
- Interest in thorium and alternative reactor concepts, but concern over difficulties of introducing new concepts in present regulatory and policy environment.
- Interest in new technologies difficult to develop while problems with present technologies are unsolved.
- Little interest in pioneering use of thorium in present or new reactors; interest will not develop without demonstration of cost-effectiveness.
- Need for thorium not demonstrated.
- State agencies becoming more demanding and stringent in siting requirements and nuclear licensing requirements.
- As regulation of nuclear power increases, interest in innovation and change decreases.

NUCLEAR INDUSTRY SURVEYS

SUPPLY INDUSTRIES

We surveyed a number of firms, including miners and millers, fuel fabricators and reactor manufacturers, and enrichers, reprocessors, and refabricators, who would be the initial suppliers of a developed demand for thorium.

Mining and Milling Industry

- Willingness to commit exploration funds to thorium as soon as a federal policy encouraging the development of thorium is formulated.
- Purchase of land or mineral rights for thorium properties will be made when utilities begin to select thorium as a fuel.
- Firms now in uranium mining have considered thorium investments in the past.
- Wildcat exploration for thorium has been carried out in anticipation of a possible market for thorium.
- Thorium deposits adequate to support initial demand have already been identified.
- With utility commitments for thorium represented by contracts, financing and the timing of thorium's availability will not be a constraint in the commercialization of thorium.
- Thorium presents no unusual difficulties or hazards in mining or occupational safety for firms that have been mining uranium.
- Initial thorium mines, where little exploration is required, could be developed rapidly.
- Mining and milling firms willing to move, and capable of moving, quickly if a thorium market develops.
- Thorium mining will not be a constraint or barrier to the commercialization of thorium.
- Present inventory of mining equipment, some of which is not committed for other purposes, could be diverted to thorium so that mines could become operational in 2-3 years.
- Mine would not be developed and opened without at least 10-year order for thorium supply.

NUCLEAR INDUSTRY SURVEYS

Fuel Fabrication and Reactor Manufacture Industry

- Major fuel fabricators and reactor manufacturers generally subsidiaries or divisions of large, diversified businesses with interests outside the nuclear field; nuclear investments compete with other investment opportunities.
- New technology, new fuel will tend to disrupt the market.
- Minor modifications of current technology preferred to new technologies until current technology demonstrates better financial performance.
- Thorium cycle must be initiated, developed, and demonstrated by government.
- Present policy and regulatory environment does not provide any incentives for risk-taking.
- Firms reluctant to embark on new investments because original estimated demand of 30 plants per year has not materialized.
- Thorium manufacturing capacity will not develop until government policy clearly indicates that the fuel is needed, the market will endure long enough to generate adequate return on investment, and the fuel and reactors developed for its use can be licensed expeditiously.
- Because of depressed profits in the nuclear field, parent companies are unwilling to commit more than about 20-30 percent of their business to the nuclear field.
- Firms unlikely to increase their commitment to nuclear ventures unless nuclear market becomes more certain.
- Flow of capital for fuel and reactor manufacturing will not be a major constraint if government policy, through legislation, clearly commits to a thorium fuel-cycle, and the present policy and licensing problems are eliminated.
- Federal government must demonstrate commitment to thorium by building and licensing the first thorium-fueled reactor.

NUCLEAR INDUSTRY SURVEYS

- Nuclear market perceived as promising in the future, but firms reluctant to invest in major research and development of new technology without stable government nuclear policy.
- Firms reject possibility of supporting more than one reactor technology.
- A fuel-fabrication facility for thorium would take 3-4 years to build and 1 year to license.
- Most R&D investments now are in applied engineering, not basic R&D.
- An existing U-235 facility could be converted for fabrication of U-233; a new facility would take 5 years to build.
- No major plant and equipment investments will be made until utility commitments to purchase are available.

Enrichment, Reprocessing, and Refabrication Industry

- Government expected to continue to provide enrichment services in a thorium fuel-cycle.
- Financial risk of investing in enrichment, reprocessing, and refabrication viewed as too great for private firms.
- Firms previously interested in reprocessing and refabrication have curtailed their interest because of instability of government policy.
- Need for stabilizing nuclear policy and streamlining regulatory process regarded as essential before thorium will be considered.
- Even with policy stability and a more expeditious regulatory process, firms feel that demonstration of federal commitment by constructing and licensing a fuel-reprocessing and -refabrication facility would be necessary.
- Private sector will invest in reprocessing and refabrication only after an assured market develops.

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- Because of failure to license AGNS, future private investment will depend on a strong government commitment.
- Earliest date for significant U-Pu recycle estimated to be 1985; thorium/U-233 recycle facility would take about 5-6 years to build, 1 year to license.

BANKING

To supplement the information provided by the utilities, regulatory agencies, and suppliers, we also surveyed representatives of the financial community familiar with the financing of the nuclear market.

- Nuclear market is not yet economically viable because of outstanding problems with existing technology.
- New fuel and/or reactor technology perceived as high risk in present federal policy and economic climate.
- Because of policy uncertainty, corporate suppliers of hardware and fuel will not invest in market unless utilities guarantee the market.
- Utilities reluctant to guarantee markets, and many bankers unwilling to support utility ventures in fuel or technology because of utilities' financial condition and influence of uncertain federal and state policy on utility finances.
- Investments in thorium regarded as less risky than investments in the LWBR and LMFBR; use of thorium in LWRs viewed as most practical in the near term.
- Likelihood of introduction of thorium regarded as small unless a crisis in uranium supply develops.
- Thorium could be developed and introduced only by financially strong companies who could withstand a credit crunch as the technology is developed for the market.
- Substantial government investment in fuel-cycle facilities (especially reprocessing) and in a commercial-scale reactor demonstration would be necessary to convince market of thorium's commercial viability.

NUCLEAR INDUSTRY SURVEYS

- After government demonstration of technology, favorable federal and state policy, supported by legislation, would be required to ensure a large flow of capital to utilities and their suppliers.

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Appendix B

BARRIERS TO THE COMMERCIAL DEPLOYMENT OF THE THORIUM FUEL-CYCLE

The critical barriers to the commercial deployment of the thorium fuel-cycle are not so much the technical problems, which are admittedly numerous, as the uncertainties of federal nuclear policy and regulation and the effect of these uncertainties on the industry's perceptions of the value and feasibility of introducing a new fuel and new nuclear technologies. These perceptions emerged in the course of a survey of utilities and nuclear supply industries.

In summary, the principal barriers are as follows:

- The introduction of a new fuel-cycle will, in the industry's view, exacerbate the difficulties already encountered in licensing the LWR on the low-enriched uranium once-through cycle. The industry would prefer that the present policy and regulatory problems be resolved before the introduction of a new fuel or the deployment of new types of reactors is considered.
- The utilities believe that uranium resources are adequate for their reactors, operating and planned, over their planning horizon of approximately 20-30 years.
- The utilities believe that a policy to reprocess and recycle uranium and plutonium should be implemented in the event of a shortage in the supply of uranium.
- At present, the industry is unwilling to invest in the development and commercial deployment of the reprocessing, refabrication, and recycling of thorium and bred U-233 without a change in federal policy that would permit fuel recycling. The necessary technology, facilities, and business structure have been partially developed by industry for the recycling phase of the low-enriched uranium fuel-cycle, but a supportive governmental policy and regulatory procedure is lacking and the conditions under which any fissile

BARRIERS TO COMMERCIAL DEPLOYMENT

fuel could be recycled are not clear. Consequently, the industry prefers to commit its resources to the available fuel-cycle.

- Industry does not accept the idea of introducing thorium at present; consequently, the level of federal incentive or subsidy required to promote its commercialization, if some version of the thorium fuel-cycle were deemed necessary (say, in the interests of nonproliferation), is difficult to establish.
- The present federal policy on the commercialization of thorium has not persuaded the industry that the benefits of thorium outweigh the cost.
- The industry is uncertain how long the present federal policy prohibiting fuel reprocessing will remain in force, and, if the prohibition is lifted, what the governmental restrictions will be applied to reprocessing (e.g., reprocessing for spent-fuel storage only; reprocessing for subsequent fabrication and recycling).
- For a number of reasons, federal policy and strategy on the commercialization of thorium is uncertain: the analysis of the economic competitiveness of thorium in new reactors (particularly across a range of capital costs) has so far been limited and has not yet been correlated with utility planning; no consensus has been reached within the government on the reactor/fuel-cycle combination that best meets the needs of the potential market; and uncertainty exists on whether or not spent-fuel reprocessing is essential to the commercialization of thorium; or if partial-core loading to improve average core burn-up of low-enriched uranium fuel or whole-core loadings of thorium for such reasons as nuclear nonproliferation justify its deployment.
- Federal policy on whether to consider commercializing a thorium fuel-cycle in LWRs only or in conjunction with a new type of reactor is uncertain.
- Federal policy on the deployment of a fast breeder reactor such as the LMFBR is uncertain. Consequently, the need for thorium as a fuel supplement is difficult to establish, and the payback period for an investment in thorium becomes extremely difficult to determine.

BARRIERS TO COMMERCIAL DEPLOYMENT

This study has demonstrated the desirability and feasibility of commercializing the thorium fuel-cycle from the federal government's perspective. However, this perspective is based on a long view of the national energy situation, approximately 50 years. The utilities' planning horizon is considerably shorter.

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Appendix C

FURTHER INVESTIGATIONS OF THE COMMERCIAL VIABILITY OF THE THORIUM FUEL-CYCLE

The desirability and feasibility of commercializing thorium has been established in this report from the perspective of the federal government. However, the federal perspective is long-range; it covers a period of approximately 50 years. The utilities' planning horizon, and consequently their perception of the thorium fuel-cycle, is more limited; it is equivalent to the life of a nuclear plant. If thorium is to be deployed commercially, the two perspectives must be reconciled, and further study of the commercial incentives that could encourage the acceptance of thorium appear to be justified.

The following steps could provide the necessary information for an evaluation of these incentives:

1. Representatives of each segment of the nuclear industry and the regulatory agencies should be surveyed to determine if this assessment of the economics and commercialization potential of the thorium fuel-cycle and the barriers to the commercialization of thorium accurately reflects their view of the factors influencing the commercial introduction of the thorium fuel-cycle.
2. Utilities, reactor manufacturers, fuel suppliers, and the regulatory agencies should review the introduction dates, R&D requirements, and commercial demonstration requirements developed in the TAP for the thorium fuel-cycle in the various types of reactor. This review would include the schedules for commercial demonstration outlined in this report, converter reactor R&D requirements for utilization of thorium fuels, and R&D requirements for fuel recycle now being developed in the TAP.

FURTHER INVESTIGATIONS OF COMMERCIAL VIABILITY

3. The four policy scenarios should be subjected to more-detailed analysis. Under the no-recycle policy, the market penetration of reactors optimized for the policy with uranium fuel and thorium fuel must be determined; for example, part-core thorium loadings in BWRs may be advantageous.¹ Under the full-recycle policy, fast breeder and thermal reactors with U-233/Th and Pu/Th fuels must be considered to determine whether the thorium fuel-cycle can achieve a significant penetration of the market in competition with the conventional concept of unrestricted uranium and plutonium recycle in both types of reactor.

4. The more-complete characterizations of alternative reactor/fuel-cycle combinations now under development in programs funded by DOE and EPRI should be introduced into the scenario analysis, in terms of revised estimates for capital cost and fuel performance.

5. The nuclear market penetration achieved in the various scenarios should be compared with nuclear penetration predicted by the National Electric Reliability Council. Discussions should be initiated with the council to determine if improvements to the market-penetration methodology used in TAP are needed.

6. The implications of the 20-30-year utility planning horizons for the conclusions based on the 50-year HEDL scenario horizon should be investigated.

7. The sensitivity of the results of the scenario analysis to variations in input data (particularly in capital costs) should be analyzed and compared with the perceived uncertainty in the results of the market penetration of the various reactor/fuel-cycle options under the four policy scenarios.

8. The financial and other resources needed to deploy the thorium fuel-cycle commercially under federal recycle policies favorable to thorium should be determined. The cost and benefits of public funding

1. General Electric Company, Assessment of Utilization of Thorium in BWRs (ORNL-SUB-43805, NEDG-24073: January 1978).

FURTHER INVESTIGATIONS OF COMMERCIAL VIABILITY

should be evaluated to determine whether or not government investment in the necessary research, development, and demonstration programs is justified. The criteria used by the nuclear industry to determine what, if any, investment by them in thorium RD&D is warranted should then be reevaluated, and the views of the industry on the proper federal role in RD&D, regulatory processes, and funding should be elicited.

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Appendix D

SUMMARIES OF SELECTED THORIUM EVALUATIONS

The following are summaries of a selection of major studies on the use of thorium, arranged in chronological order of publication. The summaries describe the purpose of the study, its focus, and the major conclusions reached by the authors of the documents.

A more comprehensive listing of earlier thorium studies follows the summaries.

"Thorium as a Nuclear Fuel," U.M. Stabler, Il Ciclo Combustibile U-Th, VI Congresso nucleare di Roma, Rome, 1961.

This paper presents the overall status of thorium utilization and those areas that require further research. The main objective cited for thorium utilization is economic, i.e., the production of power at the lowest possible cost.

Although the author recognizes the disadvantages of thorium, he also cites its advantages. For example, LMFBRs with Pu-Th cores and U-233-Th cores have lower void reactivity coefficients than LMFBRs with Pu-U cores and are, consequently, inherently safer. Furthermore, U-233 has a decided advantage over Pu-239 in the thermal and epithermal ranges of converter reactors with respect to breeding characteristics; therefore, it can utilize more efficiently an abundant fertile material (Th-232), which can be converted into a fissionable isotope. In addition, thorium metal is more resistant to radiation than uranium metal.

One disadvantage cited is the less economical production of thorium reserves. Although thorium is 3-4 times more plentiful than uranium in the earth's crust, the process by which thorium deposits are formed and its geochemical properties indicate that potential annual production rates for uranium would be several times greater than those of thorium at current prices (1967).

According to the author, most reactor engineering development is applicable to cores of either uranium- or thorium-based fuels. The article describes existing experimental reactors.

The author recommends that more research be undertaken on the value of η above the 2 electron-volt energy range and that portions of the thorium production cycle be improved. The techniques for melting and casting thorium were found to be inadequate and to result in fuel fabrication problems.

Processing irradiated fuel and refabricating new fuel was considered the most difficult segment of the thorium-uranium cycle, largely because of the radiation problem caused by daughter products of U-232. Four methods have so far been developed to process fuel:

1. High decontamination and direct fabrication. Recovered thorium is stored for 10-15 years before recycling, and virgin thorium is used for immediate recycle.
2. High decontamination and remote fabrication. The advantage of this technique is recycling without a long decay period.
3. Intermediate contamination and remote fabrication. Irradiated thorium is recycled immediately, and all operations are done remotely. Allis-Chalmers, which has designed a plant based on this concept, is planning to construct this plant for the Italian National Committee for Nuclear Energy.
4. Little or no decontamination and remote fabrication.

"Fuel Cycle Analysis of a Th-U235 Reactor," E.R. Mason and M.M. Neill, Il Ciclo Combustibile U-Th, VI Congresso nucleare di Roma, Rome, 1961.

The Nuclear Engineering Department at the Massachusetts Institute of Technology assessed nuclear fuel composition and reactivity charges for the Th-232/U-232 system. The objective of this study, which appears to have been undertaken for either Consolidated Edison of New York or Babcox and Wilcox, was to develop optimum methods of initial fuel loading and subsequent fuel management.

All costs are based on a reactor similar to the Indian Point reactor owned by Consolidated Edison. The fuel cost calculation assumes that spent fuel is reprocessed; it does not assume recycle. The costs are based on AEC prices in effect until July 1961.

The sequence of events is:

- Thorium oxide is purchased
- UF_6 is procured from AEC and converted to UO_2
- Fuel elements are fabricated and stored 30 days
- Fuel is irradiated in the reactor
- Spent fuel is reprocessed, thorium discarded, and settlement made to AEC for the amount of uranium burn-up achieved.

In addition, several other stipulations were made. Uranium use charges at 4 percent are paid annually, while all other payments are made at the end of the specific time period. All costs are discounted at 6 percent.

After fuel cycle costs are calculated, they are combined with estimated capital, operation, and maintenance costs for the Indian Point reactor to provide total energy production costs for the thorium system. Exhibit D.1 provides an aggregate summary of these results.

Exhibit D.1**Total Energy Production Costs**
(mills/kWh)

	Case A	Case B	Case C
Capital costs plus operation and maintenance costs	8.5	9.3	11.9
Fuel-cycle costs	7.4	5.4	4.7
Total cost	15.9	14.7	16.6

SOURCE: E.R. Mason and M.M. Neill, "Fuel Cycle Analysis of a Th-U-235 Reactor."

NOTE: Cases refer to fuel-loading configurations:

A = Graded loading U-235 at outside of core

B = Uniform loading of Th, U-235

C = Inversely graded loading.

"Use of Thorium in Boiling Water Reactors,"
R.L. Crowther, Il Ciclo Combustibile U-Th, VI Congresso
nucleare di Roma, Rome, 1961.

This paper analyzes the effect of several fuel cycles in boiling-water reactors, especially the use of U-233/Th-232 fuel and U-233 recycle. Specifically, it examines the various fuel patterns, including the use of Th-232 as a fertile material and initial make-up cores of either Pu-239 or highly enriched uranium.

The estimates of fuel costs were based on the following assumptions:

- \$12/gram credit for Pu
- Control system costs required for Pu-239 and fabrication costs are not included
- Reactor output is 200 MW(e), 650 MW(t)
- The use of batch peripheral refueling patterns
- 0.8 capacity factor.

It does not mention whether reprocessing or recycle costs are included in the calculation.

From a nuclear standpoint, it was found that plutonium is capable of driving thorium fertile material and may provide economic gains in future nuclear reactor design. The use of Th-232/U-235 fuel in a boiling-water reactor is feasible and appears to provide a number of advantageous performance trends. It was found that a boiling-water reactor, which is designed for U-238, may be converted to Th-232 through changes in fuel rod size. However, the ultimate selection of fertile isotopes depends on economics, material constraints, fuel fabrication, and fuel-processing considerations.

"An Economic Comparison Between the Th-U233 and the U238-U235 Fuel Cycle for Various Reactor Types,"
R.T. Shanstrom, Il Ciclo Combustibile U-Th, VI Congresso
nucleare di Roma, Rome 1961.

The objective of this paper is a comparison of the relative values of thorium and U-238 as fertile materials in four different thermal power reactors. The basis of this evaluation is a comparison of the fuel-cycle costs for fresh fuel composed of U-235 and U-238 and those for U-235 and thorium.

The four reactors examined were:

1. 134 MW(e), pressurized light water reactor with stainless steel cladding, designed by Westinghouse
2. 110 MW(e), pressurized heavy water reactor, based on a design by General Atomic
3. 150 MW(e), graphite-moderated, graphite-clad, helium-cooled version of HTGR being developed by General Atomic
4. 22 MW(e), BeO-moderated, helium-cooled reactor with zircaloy-2 cladding, based on a design by Dupont de Nemour Corporation.

The cost comparisons were based on the following assumptions:

- U-235 enrichments up to 95 percent are available
- Fuel burn-up is only limited by reactivity considerations
- Standard unit U.S. prices, mainly from AEC
- Spent fuel is reprocessed and credit given for U-235, U-233, and Pu.

Calculations were made for 14 different combinations of moderator type, fuel cycle, and fuel management method; however, for each reactor type, different calculation methods are used. For each case, costs are given for purchase of BeO and thorium, sale of U-235, U-238, and Pu, and leasing and processing charges (including fabrication, working capital, reprocessing, conversion, shipping, and net fuel-cycle costs). Exhibit D.2 summarizes the net fuel-cycle costs.

Exhibit D.2

Comparison of Net Fuel-Cycle Costs
 (mills/kWh)

Moderator Type	Case	Cost
Light water	H-U-B	3.8
	H-U-G	2.6
	H-U-I	2.6
	H-T-I	3.2
Heavy water	D-U-I	1.7
	D-T-I	2.2
Beryllin	B-U-I	2.3
	B-T-I	1.9
	B-U-I	2.6
	B-T-I	2.5
Graphite	C-U-B	2.5
	C-T-B	2.0
	C-U-G	2.0
	C-T-G	1.4

Key

Moderator Type	Fuel Cycle	Fuel Management
H = light water	T = thorium	B = batch
D = heavy water	U = uranium	G = graded
B = beryllin		I = intermediate
C = graphite		

SOURCE: R.T. Shanstrom, "An Economic Comparison Between the Th-U235 and the U235-U235 Fuel Cycle for Various Reactor Types."

For the light-water moderated reactors, the uranium cycle had a 0.6 mill/kWh advantage when stainless steel clad was used. However, when a ceramic clad was used with the BeO moderated reactor, the thorium cycle had a cost advantage of 0.4 mill/kWh. Fuel-cycle costs were approximately equal for both reactors when they both used stainless steel clad.

In the HTGR system, the thorium cycle has an ~0.5 mill/kWh advantage over the U-235/U-238 system. For 150 Mw(e) HTGR, a set of equations was derived for calculating its approximate fuel-cycle costs using either thorium fertile material or U-238 fertile material. Costs are calculated as a function of the atomic characteristics and specific power of the fuel core.

For the heavy water moderated reactor, thorium again had a cost advantage of 0.5 mills/kWh, based on the assumption that the processing cost was held to a "low value."

"Economics of Thorium Fuel Cycles," P.R. Kasten, L.G. Alexander, R.S. Carlsmith, and R. VanWinkle, Il Ciclo Combustibile U-Th, VI Congresso nucleare di Roma, Rome, 1961.

This paper concerns the fuel cycle and the conditions necessary for low fuel-cycle costs. It covers three major areas:

1. Conditions, fuel cycles, and costs associated with no fuel reprocessing and refabrication
2. Comparison of uranium and thorium systems, based on the assumption that processing and/or refabrication costs are economically feasible
3. Comparison of advanced technologies, where fuel-processing and fabrication costs are assumed low.

Initially, the study examined the relative merits of the thorium-U/235 and natural uranium cycles for a heavy-water moderated and cooled CANDU reactor, modeled after the Canadian 200 MW(e) plant. Countercurrent fueling on a semicontinuous basis (high fuel exposure) was assumed, and spent fuel was to be stored indefinitely. AEC cost bases were used in the calculation, and fuel costs in mills/kWh were calculated as a function of several technical considerations (including lattice spacing U-233 concentration). This step permitted the calculation of technical specifications for minimum fuel costs.

Based on AEC's formula for estimating costs, thorium-fueled reactors had somewhat lower fuel costs (3.02 mills/kWh) at lower power levels than natural uranium systems (3.09 mills/kWh). However, at higher power ratings, the natural uranium system was more economic.

The second section of the paper compared Th-U systems and the enriched uranium fuel cycle that was common to the power reactors in operation at the time (Dresden, Yankee, Carolina-Virginia, Hallam, and GCR-2). These comparisons were based on the use of AEC economic ground rules and processing-cost schedules and the assumption that all fuel was in an oxide form.

For the initial cycle, the thorium systems have lower fuel costs in LWRs, while uranium systems had lower fuel costs for reactors with better neutron economies, such as

the heavy-water and graphite-moderated reactors (e.g., Carolinas, Hallam, and GCR-2). During recycle, the cost of the thorium system remained constant, while the costs of the uranium systems increased. These results indicated that thorium utilization was economically superior to uranium utilization in poor neutron-economy systems if fuel recycling was to be performed and that, for thermal systems, thorium systems appeared to permit better economic development of a recycle technology than uranium systems. Exhibit D.3 summarizes this cost comparison.

Finally, thermal thorium breeder reactors were considered (aqueous homogeneous breeder reactor, molten-salt breeder reactor, liquid-bismuth breeder reactor, graphite-moderated gas-cooled breeder reactor, and deuterium-moderated gas-cooled breeder reactor). The fuel-cycle cost, breeding ratio, inventory requirement, and fuel processing rate of these reactors were compared, based on the assumption that the technology had advanced to the point where the costs of fuel handling, fabrication, refabrication, and processing are relatively low.

Other assumptions included:

- Each station had a net capacity of 1,000 MW(e)
- All processing was done on-site.
- All reactors have reached equilibrium and are continuously fueled and processed.

The results showed that all of the reactors studied had low fuel-cycle costs (less than 1.5 mills/kWh), while the aqueous homogeneous and molten-salt reactors had the lowest fuel-cycle costs.

Overall results demonstrated that thorium utilization was an economic method for advanced nuclear technology.

Exhibit D.3

Fuel Costs in Thorium and Uranium Systems¹
 (mills/kWh)

Reactor Type/Cycle	Thorium System			Uranium System		
	Initial	1st Recycle	2nd Recycle	Initial	1st Recycle	2nd Recycle
Dresden	4.30	4.37	4.48	4.54	5.09	7.50
Yankee	3.98	4.02	4.13	4.27	8.01	>10
Carolinas Virginia	4.77	5.16	5.95	4.70	3.92	7.48
Hallam	4.53	4.50	4.54	4.19	3.96	4.95
GCR-2	3.06	3.32	3.27	2.78	~4	>4

SOURCE: P.R. Kasten, L.G. Alexander, R.S. Carlsmith, R. VanWinkle paper, "Economics of Thorium Fuel Cycles."

1 Based on fissile plutonium value of \$12/gram and U-233 value of \$15/gram.

"Molten-Salt Reactor Systems," R.B. Briggs, Il Ciclo Combustibile Th-U, VI Congresso nucleare di Roma, Rome, 1961.

The basis of the research described in this article is an attempt to reduce all components of power cost through more efficient conversions of heat into electricity. Specifically, it deals with the molten-salt power reactor (MSR), which is especially attractive as a breeder or highly efficient converter on the thorium-U-233 fuel cycle because of its neutron economy.

The article first describes several suitable designs for MSR, their advantages, and problems. It then describes the fuels and materials required, the current status of these areas, the molten-salt breeder reactor (MSBR), and the economic fuel cycle.

Finally, the paper presents the positive and negative results of the Molten Salt Reactor Experiment performed at Oak Ridge National Laboratories. These results are summarized below.

On the positive side, the fluid fuels used in the MSR are thermally stable at high temperatures and unaffected by high radiation levels. Even at 1,000°C, vapor pressures are less than 1 atmosphere, an inherent safety feature. Preliminary studies showed that simple fluoride-based processes could be developed for recovery and decontamination of the thorium, lithium, and beryllium salts. Metallurgical, ceramic, or mechanical fabrication steps for fuel elements are not necessary as the fuel is reconstituted (both fissile and fertile compounds) by dissolving compounds in the carrier salts.

A new development in the materials field was the finding of a containment metal, called INOR-8. This nickel-molybdenum alloy, which was developed to contain molten salts, has mechanical properties at high temperatures that are equal to or better than those of alloys normally specified for high-temperature power plant or reactor construction. At this stage, experimental data showed that there were uranium and thorium fuels and a container material (INOR-80) that should be satisfactory for use in an MSR.

Three problem areas are identified with respect to the engineering of MSR. First, since the fuels are in the liquid state and melt at above 400°C, the reactor vessel and piping must be preheated before fuel is added. Second, the fuels react with oxygen in air, water, and other compounds, thus precipitating fuel constituents as oxides. Care must be taken to keep the fuel from being contaminated with oxygen-containing materials. Third, high radiation levels are involved in a highly mobile form. Special provisions must be made for containment and maintenance.

Fuel cycle costs were calculated based on a 1,000 MW(e) power station consisting of two reactors and a fluorine volatility-plant for on-site processing. The major assumptions include: 80-percent plant factor; optimization of cycle time, and continuous on-site processing of fuel. Credits are given for breeding.

The cost calculations were made for eight different cycle times, and a cost breakdown given for each case. Exhibit D.4 presents a representative calculation.

The paper concluded that conversion ratios of 1 to 1.07 could be achieved in molten salt thorium reactors and that fuel cycle costs could be low (i.e., in the range of 0.6 to 1.5 mills/kWh) with on-site processing in large power stations.

Exhibit D.4

**Molten Salt Breeder Reactor
Fuel Costs**

80% plant factor
On-site processing
55-day fuel-stream cycle time

Fuel Cycle Step	Cost (mills/kWh)
Uranium inventory	0.08
Thorium inventory	0.13
Fuel carrier inventory	0.02
Thorium carrier inventory	0.17
Fuel-stream processing plant	0.26
Fertile-stream processing plant	0.21
Thorium replacement	0.03
Fuel carrier replacement	0.14
Thorium carrier replacement	0.03
Breeding credit	0.09
Net fuel cycle cost	1.00

SOURCE: R.B. Briggs, "Molten-Salt Reactor Systems."

"Nuclear Fuel Cycles and the P.C.U.T. Program,"
A. Forcella and J.K. Davidson, Il Ciclo Combustibile U-Th,
VI Congresso nucleare di Roma, Rome, 1961.

This paper compares the economics of uranium-thorium and uranium-plutonium fuel cycles. The authors of this paper, which was prepared for the Italian National Committee for Nuclear Energy, argue that the main objective of the nuclear power industry is the reduction of fuel-cycle costs.

The three major cost components of nuclear fuel cycles are identified as: fission material cost, inventory charges, and fuel fabrication and reprocessing.

Several assumptions are made in the comparison of different fuel-cycle costs:

- Low-enrichment fuel cycle conditions
- Reprocessing and recycle of spent fuel
- Equal handling costs in the recycle of plutonium and U-233.

Four fuel cycles were chosen for comparison:

1. Low enriched uranium is burned, plutonium is recycled, and depleted uranium returned to the supplier.
2. Uranium is again fed to the reactor, but plutonium and uranium are recycled. Make-up uranium of full enrichment is added in the fabrication step.
3. Make-up U-235 of full enrichment is mixed with thorium and fed to the reactor. Fertile thorium and U-233 are recycled.
4. Uranium is fed to the reactor, plutonium and uranium are reprocessed, but neither is recycled.

Of the first three fuel cycles, thorium was found to have the lowest cost due to its high conversion ratio (η). However, the advantage of the thorium cycle decreased with lower specific power (a measure of burn-up rate), and it proved to have the highest inventory costs. The cost advantage of the thorium cycle was nearly

independent of fuel exposure rate when expressed in mills/kWh; that is, with high exposure, less fuel would have to be fabricated and reprocessed each year.

The thorium cycle was then compared to an open uranium cycle, where spent uranium and plutonium were returned to the supplier but not recycled. In this case, the supplier charges for reprocessing on the basis of a "hypothetical" plant. As a result of the Phase I design work on the uranium-thorium fuel-cycle (P.C.U.T.) reprocessing plant, a first estimate of a reprocessing cost of \$200/kg was made based on a plant capacity of 60 kg/day and 16-percent annual capital charges.

At a burn-up rate of 10,000 MW days/metric ton, the uranium cycle had a slight advantage, while the costs were about equal at 20,000 MW day/metric tons. Exhibit D.5 summarizes the results of these comparisons.

The authors conclude that the thorium cycle promises to be the most economic of all recycled fuel systems for thermal reactors. Because of the ultimate economic requirement for fuel recycle and because dependence on the established buy-back prices used for spent fuel may result in a distorted reactor development program, the early development of fuel-cycling techniques is found to be essential to any nuclear power development program.

On the basis of these findings, the Italian National Committee for Nuclear Energy and Allis-Chalmers have undertaken the P.C.U.T. program, which consists of a reactor evaluation study and the design, construction, and operation of a facility to reprocess and refabricate thorium-uranium fuel assemblies. One of the prime objectives of this program is to determine the costs involved with the construction and operation of a reprocessing plant.

Exhibit D.5

Fuel Costs of Thorium and Uranium Fuel Cycles

Fuel Cost of Uranium-Plutonium and
Thorium-Uranium Cycles (\$/kg)

Cycle	Burn-up Rate: 10,000 MWd/MT			Burn-up Rate: 20,000 MWd/MT		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
U (Pu recycle)	120	95	97	225	170	150
U (U + Pu recycle)	120	95	87	238	182	164
Th-U (Th + U recycle)	110	70	58	208	130	105

Fuel Cost of Noncycled Uranium
and Thorium Fuel with Recycle (\$/kg)

Cycle	Burn-up Rate: 10,000 MWd/MT			Burn-up Rate: 20,000 MWd/MT		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
U (no cycle)	305	275	265	405	360	335
Th-U (recycle)	315	275	265	405	330	310

SOURCE: A. Forcella and J.K. Davidson, "Nuclear Fuel Cycles and the P.C.U.T. Program."

NOTE: Case 1 = specific power (kW/g) of 0.3
Case 2 = specific power (kW/g) of 0.6
Case 3 = specific power (kW/g) of 0.9

"The Elk River Reactor," J.J. Dickson and J.H. Blachly,
Il Ciclo Combustibile U-Th, VI Congresso nucleare di Roma,
Rome, 1961.

The Elk River Reactor is a boiling-water nuclear reactor producing 58.2 MW(t) and 22 MW(e) and supplemented by a 14 MW(t) coal-fired superheater. The reactor utilizes uranium-thorium ceramic pellets. It was built as part of AEC's Power Demonstration Program to estimate actual construction and operating costs and to demonstrate the feasibility and reliability of continuous operation of a boiling water reactor operated in conjunction with a coal-fired superheater. The impetus for this program was the attractiveness of this type of nuclear power facility, which can be operated in conjunction with existing conventional power stations.

The article describes the Elk River Plant, its physical layout, plant design, and technical operating features. It also provides detailed breakdowns for capital and operating, pre- and post-irradiation, and fuel costs. Credits were given for U-233 production and charges made for reprocessing losses in these cost calculations. No recycle of U-233 is mentioned.

Finally, it compares the costs of conventional and nuclear plants (see Exhibit D.6).

Exhibit D.6

**Cost Comparison of Conventional
and Nuclear Plants**

	Conventional	Nuclear
Plant capacity	22 MW(e)	22 MW(e)
Cost of last unit installed	\$165/kW	\$506/kW
Average plant load factor	62%	80%
Average production cost, excluding Pu	2.82 mills/kWh	6.76 mills/kWh
Average fuel cost	5.65 mills/kWh	5.32 mills/kWh
Average total production cost	8.47 mills/kWh	12.08 mills/kWh

SOURCE: J.J. Dickson and J.H. Blachly, "The Elk River Reactor."

"Advanced Epithermal Thorium Reactor (AETR) Critical Experiments, Reactor Design and Fuel Analysis,"
D.T. Eggen, Il Ciclo Combustibile U-Th, VI Congresso nucleare di Roma, Rome, 1961.

This study summarizes the results of the Advanced Epithermal Thorium Reactor (AETR) program being conducted by Atomics International for the southcentral United States. The objective of this program is the design of a nuclear power plant capable of producing electric energy on a competitive basis. A sodium-cooled reactor operating in the epithermal-to-fast range on the Th-U-233 cycle was chosen for investigation based on its advantages in neutron economy, thermal efficiency, plant construction costs, systems manufacturing and operating costs, and the apparently large thorium resource base. The study started in 1958 and was slated to extend until 1963.

The research described covers a myriad of topics. First, uncertainties in technical considerations are discussed along with the problems involved. Various physics and reactor physics research is documented with respect to fuel burn-up, fuel element design, and reactor design. Fuel-cycle calculations are made, and total energy costs for an AETR estimated.

With respect to technical considerations, the author believes that three areas of uncertainty must be resolved before designing an AETR capable of achieving low power costs:

1. Data in the epithermal-to-fast neutron energy range are insufficient
2. The development of fuel element designs that withstand high temperature and high-speed sodium flows is needed
3. Additional information is required on the effects of temperature, power level, and materials on power level and stability.

The article also describes the calculations of fuel-cycle costs and total energy costs for an AETR. Fuel cost calculations were based on the following major individual charges: in-core and out-core fuel inventory; fuel burn-up (U-233 depletion); credit for fuel

produced in fertile material; reprocessing, refabrication, and shipping of fuel; and fertile material inventory, fabrication, and processing.

Costs used were those estimates set by AEC (e.g., leasing of fissionable material at 4 percent per year). In this case, the spent fuel is reprocessed but not recycled. Thorium (fertile) is valued at \$50/kg.

The reactor used for calculating overall energy and fuel-cycle cost is 50 MW(e) AETR. Capital, operation, and maintenance costs are estimated from knowledge gained from design of the Advanced Sodium Graphite Reactor (ASGR). Load factor is assumed to be 80 percent, while an annual rate of 14 percent is used for capital costs. Exhibit D.7 summarizes these total energy costs and compares them to a fossil fuel plant.

The author concludes that the AETR is economically competitive with high efficiency fossil-fueled plants. They project that, over a 30-year life, the total energy cost for nuclear stations might be considerably less than for fossil-fueled plants, if expected improvements in processing and fabrication result in lower nuclear fuel costs.

Exhibit D.7

**Total Energy Costs for 500 MW(e) AETR
in Comparison with a Fossil Fuel Plant
(1961 dollars)**

Costs	Fossil Fuel (mills/kWh)	AETR (mills/kWh)
Capital costs, 14%	2.40 (\$120/net kW)	3.2-3.0 (\$160-150/net kW)
Fuel-cycle costs	2.15 (24¢/10 ⁶ Btu)	1.7-1.3
Operation/maintenance (includes insurance)	0.20	0.4
Total	4.75	5.3-4.7

SOURCE: D.T. Eggen, "Advanced Epithermal Thorium Reactor (AETR) Critical Experiments, Reactor Design and Fact Analysis."

"The Use of Thorium in Nuclear Power Reactors," U.S. Atomic Energy Commission WASH-1097, June 1969.

In response to a request in 1966 by the Joint Committee on Atomic Energy, the Thorium Task Force, which included Babcox and Wilcox Company (B&W), Gulf General Atomic Company (GGA), Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest Laboratory (PNL), and the U.S. Atomic Energy Commission, assessed the civilian nuclear power program. The objective of this report was to review and compile information and indicate the present status and the factors involved in the use of thorium in power reactors. Since the report is based on information provided by the designers of the various thorium reactors, it should be recognized that this report may reflect their enthusiasm for a particular reactor type.

In general, the report states that the primary incentive for the development of nuclear power is the reduction in the cost of power. The principal basis for the continuing interest in the use of thorium is that the Th-232/U-233 cycle would improve conversion as well as permit breeding in thermal as well as fast reactors.

In the report, several of the more important fuel cycles, their major characteristics, and their effect on reactor performance are reviewed. Uranium and thorium resources are also assessed.

The article makes the following general conclusions on the use of thorium in nuclear power reactors:

- Nuclear Characteristics. U-233 has a higher number of neutrons produced/neutrons absorbed in the thermal spectrum than U-235 or Pu-239. Higher conversion ratios are possible with U-233 than with Pu-239 in the thermal range. In high energy fast reactors, Pu-239 is superior to U-233 with respect to breeding ratio. However, use of U-233 in a sodium-cooled fast reactor yields improved safety features in the form of more negative sodium void and Doppler coefficients. In addition, the mixing of Th-232 with Pu-239 in a fast reactor improves the reactivity coefficient, which is an added safety feature.

-
- Reactor performance. Fissile fuel consumption in a thermal-spectrum thorium-fueled reactor can be lower by a factor of two than in an LWR fueled with U-235 (assuming recycle). The HTGR and MSBR give lowest specific fuel inventory, which is the amount of fissile fuel required/output.
 - Utilization of nuclear fuel resources. The estimates concerning the cost and amount of thorium available are similar to those of uranium. The requirement for uranium in advanced thorium reactors is less than that of LWRs on the uranium cycle, since uranium is conserved. However, because so much fertile U-238 already exists, no incentive exists to develop the use of thorium to extend fertile material supply.
 - Economics. Lower uranium fuel fabrication costs and higher inventory charges have made the uranium cycle more economic in heterogeneous-cored reactors (e.g., LWR, BWR). Because of their high conversion ratio, homogeneous-cored reactors (HTGR, MSBR) are more economic on the the thorium cycle. In the future, the MSBR will be the most economic of all reactors studied. Lastly, because of its better metallic properties, thorium could lead to better (and longer) fuel exposure performance.

The report then describes the status of reactors fueled with thorium. Experience on the HTGR is cited from the start of operation of Peach Bottom on March 3, 1966, and the design of the 330 MW(e) Fort St. Vrain plant. Ultimate potential may include plant efficiencies of 45 percent and fuel-cycle costs less than 1 mill/kWh.

The experience to date on the MSBR includes the Aircraft Reactor Experiment (1954) and the Molten Salt Reactor (MSBR, 1965). This concept has not received significant industrial or utility support, and major R&D is required.

The uranium cycle is clearly favored economically over thorium in the LWR. The Indian Point reactor (PWR) was operated successfully with thorium-based fuel but was changed over to uranium because of economics. Therefore, no economic incentive apparently exists to pursue the thorium cycle unless economic factors change.

Inventory and make-up costs are so low with natural uranium that even a significant escalation in the price of uranium would not make thorium economically feasible in the HWR.

All development work to date in fast breeder reactors has been with uranium. No thorium-fueled fast reactor experiments have been built.

The report recommends further R&D on the thorium cycle in the following areas:

- Physics. More precise values of η in the thermal and epithermal region are needed along with research on the nuclear properties of U-233, Pa-233, and Th-232.
- Fuel Materials. Continued experimentation on present thorium fuels and studies of thorium-plutonium and thorium-uranium alloys for use in fast-spectrum reactors (also cross-progeny fuels) are needed.
- Processing. Development of a U-233 recycle technology for specific reactor types is necessary. More experience is needed in the areas of recovery of thorium from irradiated fuels, separation and decontamination of U-233, and head-end processes for solvent extraction of specific fuel types.

Exhibit D.8 summarizes the fuel-cycle costs for the different reactor concepts.

Exhibit D.8

**Fuel-Cycle Costs for
Varying Uranium Ore Costs¹**
(mills/kWh)

Reactor Type	Ore Cost, \$/lb U ₃ O ₈		
	8	16	30
Thorium cycle			
HWOCR ² (metal fuel)	1.64	2.01	2.66
HTGR ³	1.02	1.24	1.68
MSBR ⁴	0.44	0.47	0.51
Uranium cycle			
LWR ⁵	1.47	1.92	2.73
HWOCR ² (carbide fuel)	1.12	1.42	1.96

SOURCE: U.S. Atomic Energy Commission, "The Use of Thorium in Nuclear Power Reactors."

1 1980 processing and fabrication costs included.

2 WASH-1983: fuel-cycle costs include D₂O inventory charge.

3 WASH 1085.

4 On-site processing for the MSBR is included in these estimates.

5 WASH 1082.

"Views on Uranium and Thorium Resources," M.F. Searl and J. Platt, Annals of Nuclear Energy, Volume 2, Pergamon Press, Oxford, 1975. (Wingspread Conference)

This study presents the contemporary range of viewpoints on the extent of uranium and thorium resources and describes the basis for the differing views. It covers sources of uranium data, approaches to estimating uranium resources, uranium estimates, and identified thorium resources.

The data for uranium and thorium resources at differing grades were found to be inadequate.

"An Evaluation of Alternate Nuclear Strategies,"
W.M. Pardue, Annals of Nuclear Energy, Volume 2,
Pergamon Press, Oxford, 1975. (Wingspread Conference)

In this paper, Battelle-Columbus Laboratories evaluates the current technological status of several nuclear reactors that use the nation's fissile resources more efficiently than existing LWRs. The objective of this study was to determine whether the development of various nuclear options may be more beneficial to the nation than dependence on any one system such as the LMFBR. The reactor types studied include the HTGR, GCFR, MSBR, and LWBR.

Initially, the report describes the technological lack of a demonstrated commercial capability to close the fuel cycle, the status of the various reactors and the associated fuel cycle, and the advantages and disadvantages of these reactors (see Exhibit D.9).

The study then describes the environmental impact of these reactors and ranks each reactor according to different environmental impacts. Finally, it presents a computerized model that can be used to simulate various nuclear strategies.

The study concludes that:

- The strategies associated with alternate reactors/fuel cycles will not produce dramatic increases in short-term fissile demand
- All the advanced systems are considered capable of meeting the applicable environmental requirements
- No apparent technical reason exists for eliminating any of the current development efforts on these reactors, providing commercial interest exists.

Exhibit D.9

The Advantages and Disadvantages of Several Reactor Types

Reactor	Advantages	Disadvantages*
GCFR	Provides lower generating cost Provides great benefits for added development costs Has a high breeding ratio Can be on-line as soon as an LMFBR Utilizes a thorium blanket	DBA uncertainty High-pressure coolant is unproven Safeguards problems of Pu
MSBR	Utilizes thorium Breeds and has a sufficiently short doubling time Can utilize plutonium Has a small initial resource demand	Tritium control problem Maintenance difficulty Uncertain materials status
HTGR	Utilizes thorium Can be efficiently used with dry cooling Has a better conversion ratio than LWRs Has a low generating cost Can be used for process heat	Possible safeguards problem with enriched uranium
HWR	Needs no enrichment Is available commercially in Canada Has high availability Has low generating costs	Not commercial in U.S. Licensing uncertainties
LWBR	Utilizes current technology Provides breakeven breeding Has low generating costs	Available data incomplete Costly fuel fabrication
LMFBR	Has low generating costs Conserves U_3O_8 Has a sufficiently short doubling time Is an insurance policy against inadequate U_3O_8 resources	Safeguards of Pu

SOURCE: W.M. Pardue, "An Evaluation of Alternate Nuclear Strategies."

*Common disadvantage is the lack of a demonstrated commercial capability to close the fuel cycle.

"Performance of Canadian Commercial Nuclear Units and Heavy Water Plants," L.W. Woodhead and L.J. Ingolfsrud, Annals of Nuclear Energy, Volume 2, Pergamon Press, Oxford, 1975. (Wingspread Conference)

The objective of this paper was to present an overview of the lifetime performance of Canada's commercial pressurized heavy water reactors (CANDU-PHR) and heavy water production plants. The paper was given by a spokesman from Ontario Hydro and Atomic Energy of Canada Limited (AECL) at the First International Meeting of the European Nuclear Energy Society in Paris in April 1975.

Initially, it presents a detailed history of the existing power plants with a total capacity of 2,056 MW(e) and the two heavy-water production facilities in service. The paper covers radioactive emissions, on-power refueling, production reliability (i.e., lifetime net capacity factor of 77.8 percent), and costs of total energy generation.

The operating history of Pickering surfaces some interesting points about PHR design. Because of leaks in the pressure tubes, Unit 3 of Pickering suffered a 6 1/2-month shutdown in late 1974 and early 1975. These leaks resulted from tiny axial cracks in regions of high residual stress, which were caused by an inadequate rolling procedure. The cracks were produced during prolonged periods of cold shutdown.

On-power refueling is accomplished with the aid of complex fueling machines and computerized control measures. This refueling method has caused 10.2 percent of the lost production in this plant and an increase in radiation dosage. To combat this problem, Canada is conducting a vigorous development and improvement effort.

Experts have also cited the PHR and all heavy-water reactors as releasing high quantities of radioactive tritium from the refueling device.

Exhibit D.10 summarizes the total causes of lost production. It can be seen from this exhibit that a sizable portion was related to the nuclear steam supply system (NSSS).

Exhibit D.10**Total Costs of Lost Production**

	% of Total Lost Production	Net Reduction in Capacity Factor (% NCF)
Unit 3 pressure tubes	24.4	5.4
Fuel-handling problems	10.2	2.3
Other NSSS problem	13.8	3.1
Total	48.4	10.8

SOURCE: L.W. Woodhead and L.J. Ingolfsrud, "Performance of Canadian Commercial Nuclear Units and Heavy Water Plants."

Exhibit D.11 summarizes the total unit energy costs for Pickering as compared to two similar-sized coal-fired plants in Canada. The assumptions used include 80-percent net capacity factor, low-sulfur coal, 30-year life, 8-percent capital interest rate, and 1975 dollars. No credit was taken for potential recovery of plutonium.

Exhibit D.11

**Total Unit Energy Costs for Pickering Plant
in Comparison with Two Coal-fired Plants**
(mills/kWh)

	Pickering	Lambton (1)	Lambton (2)
Capital	4.60	1.70	1.70
Operation and maintenance	1.10	0.96	0.96
Fuelling	0.98	10.60	13.52
Heavy water upkeep	0.35	—	—
Total energy costs	7.03	13.26	16.18

SOURCE: L.W. Woodhead and L.J. Ingolfssrud, "Performance of Canadian Commercial Nuclear Units and Heavy Water Plants."

"The Status of the Canadian Nuclear Power Program and Possible Future Strategies," J.S. Foster and E. Critoph, Annals of Nuclear Energy, Volume 2, Pergamon Press, Oxford, 1975. (Wingspread Conference)

This paper summarizes the research being undertaken at Chalk River Nuclear Labs and the Manitoba Research Laboratory on more efficient fuel-cycle designs. This research was performed for the Canadian Government (AECL) to provide information concerning future strategies for nuclear power generation.

The paper describes the current status of the Canadian commercial program, including costs for their Pickering Station and plans for Canada's immediate power program. Short-term and long-term strategies are studied with respect to heavy-water reactors and fuel systems of U-235, U-233, and Pu-239. Possible future strategies are explored, including different members of the CANDU family of reactors and the associated fuel cycles. The analyses include energy derived per unit of natural uranium mixed, uranium requirements for each system, present value ($\$/\text{kW(e)}$) of each system, cumulative uranium requirements, and total power costs.

The CANDU-boiling light water (BLW), CANDU-pressurized light water (PLW), CANDU-organically cooled (OCR), and CANDU-gas-cooled reactor (GCR) were compared to the CANDU-pressurized heavy water (PHW) moderated reactor. The fuel cycles compared included a once-through uranium cycle (uranium cycle with plutonium recycle), once-through (Th + U-235) cycle, Th cycle with U recycle and net U-235 fuel, and Th cycle with U recycle and net Pu fuel.

With respect to thorium utilization, reactor design concepts are almost identical to those of uranium, and technical feasibility problems do not occur. Fuel development is needed, especially in the area of thorium carbides, while thorium oxides appear to be acceptable for all CANDU reactor types. The only problem expected in the CANDU design is the potential reactivity perturbations and spatial flux distortions that may be caused by Pa-233; however, this problem is not considered major.

Using the CANDU concept with thorium, it is possible to limit the total cumulative requirements for a nuclear power capacity to less than 1.2 tonnes natural uranium/MW(e), if U-235 (0.3-percent tails) is used for the fissile requirement.

Several results pertaining to thorium arose in the fuel-cycle analysis. First, the once-through Th + U-235 cycle was considered unattractive under any foreseeable circumstance because of the storage of spent fuel, while the Th cycle with U recycle became the most attractive if yellow cake prices increased for a long period of time.

Finally, total energy costs were calculated as a function of reactor type, fuel cycle, and fissile material. Exhibit D.12 presents this comparison.

All economic results are based on reference values for economic parameters. These include 1978 dollar values for reprocessing costs, fabrication penalties, yellow cake prices, and separative work. Other cost data is based on Canada's completed nuclear projects. Tailings from enrichment plants were assumed to be 0.3-percent U-235, the interest rate was set at 9 percent/year, and the capital charge rate was 9.73 percent/year.*

* Note that these interest figures are representative of the Canadian market and are lower than their U.S. counterparts.

Exhibit D.12

Comparison of CANDU Options
 (1978 dollars)

Type	Fuel Cycle	Fissile Material Added	Specific Capital Cost (\$/kW(c))	Total Unit Energy Cost (mills/kWh)
CANDU-PHW	Natural U, once through	—	588	11.0
	Th with U recycle	Pu	566	10.4
	Th with U recycle	U-235	566	11.4
CANDU-PLW	Th with U recycle	Pu	498	9.7
CANDU-BLW	U with Pu recycle (Pu burner)	Pu	484	9.2
	Th with U recycle	Pu	484	9.2
	Th with U recycle	U-235	484	10.4
CANDU-OCR	Th with U recycle	Pu	431	8.3
	Th with U recycle	U-235	431	9.1

SOURCE: J.S. Foster and E. Critoph, "The Status of the Canadian Nuclear Power Program and Possible Future Strategies."

"How Do Converters Affect the Strategies?", Mr. Revensen, Annals of Nuclear Energy, Volume 2, Pergamon Press, Oxford, 1975. (Wingspread Conference)

The objective of this paper is the identification of several issues and their effect on the introduction of converters in the U.S. power generation community. These issues are:

1. Uranium conservation
2. Time limits
3. Timing and cost of technology development
4. Converters vs LWRs vs LMFBRs
5. Uncertainties or risks in converter technology
6. Foreign technology considerations
7. Diversity vs learning curve
8. Sponsorship (financial)
9. Licensing and the environment.

Although much of the paper was based on subjective judgments, several technical and financial points are brought up that are pertinent to thorium reactors and associated fuel cycles.

In general, converter technology lags behind that of the LWR by at least 10 years. The author believes that the large costs related to this lag (in excess, probably, of \$1 billion) will prevent commercialization, unless the government subsidizes the development or large benefits can be identified. Furthermore, the time-scale involved in bringing the required large-scale technology to the marketplace is on the order of 20 years.

Licensing and safety requirements for converters will introduce technical compromises and economic considerations. This is especially true for imported technology, since the U.S. nuclear regulatory position is different enough to require substantial design change.

With respect to environmental issues, the author notes that heavy-water reactors produce significantly more tritium than an LWR and produce 32 percent more waste heat per kW than LWRs. CANDU waste heat is also substantially more than that of the HTGR or LMFBR.

"Attainable Ratings of CANDU-OC-Thorium Set by the Properties of the Organic Liquid Coolant," W.B. Lewis, Annals of Nuclear Energy, Volume 2, Pergamon Press, Oxford, 1975. (Wingspread Conference)

The objective of this paper is to demonstrate that the unit cost of harnessed nuclear energy is less than that of oil, coal, or hydroelectric power in Canada. The author envisions the prospect of worldwide application of the CANDU-OC-thorium reactor and uses data from the Pickering CANDU-PHR to calculate energy costs.

The paper documents several characteristics of organically cooled reactors. Organic coolants have greater heat transfer characteristics than water systems, and thus, they can increase plant thermal efficiency. The coolant itself is derived from HB-40, a 40-percent hydrogenated terphenyl in which high boiler polymeric content is allowed to build up to 30 percent. The chemical and nuclear properties of this coolant are such that very low radioactivity levels are associated with the primary loop; thus, maintenance work is much easier, especially when compared to the radioactivity problems associated with the tritium in heavy-water reactors. Major leaks can be cleaned up quickly and more safely.

One problem associated with organic coolants has been possible fire hazards. Ignition of the volatile components of the coolant when they hit a suitable volume of air can produce a fast-moving flame and an overpressure, but not a detonation.

"Molten Salt Converter Reactors," A.M. Perry, Annals of Nuclear Energy, Pergamon Press, Oxford, 1975.
(Wingspread Conference)

The objective of this paper was a review of molten-salt converter reactors (MSCR), their technology and economics.

The paper describes the MSCR and its operations, discusses fuel salts, the core moderator and its problems, and fuel reprocessing.

The reactor and the complex fuel process have so far been developed separately. The fuel is mainly batch-processed rather than processed on-stream. The processing necessary to recover uranium from the fuel has only been partially demonstrated.

In the fuel areas, the long-term behavior of fission-product metals is not fully established. The procedure for applying coating to the graphite moderator is not yet fully established.

Major difficulties exist in the structural metals. The alloy used for the reactor vessel, Hastelloy-N, has had problems with intergranular cracking, and some uncertainty exists concerning this alloy's compatibility with steam.

Substantial work is required on safety operating measures. Tritium, a radioactive isotope of water, is produced to a substantial degree in the MSCR. Tritium rapidly escapes from the salt and up to 1/3 of it can reach the steam system, where it would be difficult to control.

Substantial further development is also required on scale-up of plant components, development, and testing of a steam generator (one has never been tested with an MSCR) and tools and techniques for maintenance and replacement of activated components.

The author noted that the majority of converter reactor studies have been based on the use of Pu-239, not thorium.

In the study, fuel-cycle costs were calculated for the MSCR based on the following assumptions: \$11.90/g U-235, \$13.80/g U-233, \$9.90/g fissile plutonium, \$19/g thorium, and an inventory charge rate of 13.2 percent per year. Fuel-cycle costs did not include cost of the fluoride volatility process for recovering uranium or the cost of treating and storing the radioactive waste. The author expects that fuel reprocessing will be a minor cost component. Fuel-cycle costs based on these assumptions were found to be in the range of 0.9-1.2 mills/kWh.

"Assessment of Thorium Fuel Cycles in Pressurized Water Reactors," prepared by Combustion Engineering, Inc., EPRI NP-359, Final Report, February 1977.

This study examined the economic and technical feasibility of various thorium-based fuel cycles in a standard large-capacity PWR from 1985 to 2015. Its objective is to provide a baseline for comparison with the conventional uranium cycle and for the evaluation of more advanced concepts. The analysis covers uranium ore and SWU requirements, fuel-cycle economics for alternate fuel cycles, the impact of thorium fueling on plant design and safety, and an assessment of the benefits that might be realized using modified PWR designs and concepts.

Thirty-year levelized fuel-cycle costs were compared for the economic evaluation of PWR fuel cycles. Since the reactors used in all these cases were assumed identical, other segments of the cost of total power generation were assumed equal for each fuel cycle under study. Exhibits D.13 and D.14 summarize the economic assumptions and the fuel-cycle costs.

The authors found that widespread usage of thorium would be required to realize any benefits. Specifically, the use of thorium fuel cycles in present LWRs can increase energy output per mined ton of uranium by approximately 85 percent beyond the once-through uranium cycle and by 22 to 33 percent beyond the plutonium recycle modes. When compared to cycles with poor fuel conservation features, the thorium fuel cycle may not be economically attractive because early in the fuel cycle highly enriched fuel demand is high, with savings occurring later in plant operation.

The study recommends that the spectral-shift control reactor (SSCR) be analyzed in depth. This reactor reduces both annual requirements and initial loadings; implementation of this reactor would probably only require modifications to ancillary components and subsystems. EPRI is planning to fund an analysis of the SSCR, which should be completed in 1978.

Exhibit D.13

Fuel-Cycle Cost Assumptions
(1976 dollars)

Core power	3800 MW(t)
Thermal efficiency	34.2%
Full core loading	
—Uranium core	103 TeM
—Thorium core	94 TeM
Uranium ore	\$35, \$50/lb U_3O_8 and escalating at 6%/year starting with \$35/lb in 1993
U_3O_8 to UF_6 conversion	\$4/kg U
Thorium ore	\$10, \$20/kg
Separative work	\$85, \$42.5/kg SWU
Fuel fabrication	
—Fresh	\$101/kg HM
—Recycle	\$225/kg HM
Fuel reprocessing	
— UO_2	\$213/kg HM
—All others	\$277/kg HM
Nominal diffusion plant assays	
—Feed	0.711%
—Tails	0.200%
Carrying charge rate	9%
Present worth discount rate	4%
Losses	
—Front end	1.5%
—Back end	1.0%
Capacity factor (annual refueling)	75%

SOURCE: EPRI, *Assessment of Thorium Fuel Cycles in Pressurized Water Reactors*.

Exhibit D.14

30-Year Levelized Fuel-Cycle Costs
 (mills/kWh)

Fuel Cycle	U ₃ O ₈ Ore: \$35/lb ¹	U ₃ O ₈ Ore: \$50/lb	U ₃ O ₈ Ore: Escalating	SWU: \$42.50/kg
UO ₂ (no fuel recovery) ²	5.798 [5.088]	6.929 [6.219]	6.836 [6.126]	4.888 [4.178]
UO ₂ (U & Pu recycle)	4.956	5.778	5.551	4.225
ThO ₂ (93% U-235) (U recycle)	5.515	6.267	6.002	4.503
UO ₂ /ThO ₂ (U & Pu recycle)	4.930	5.745	5.503	4.187
Crossed-Progeny	4.944	5.762	5.534	4.201

 SOURCE: EPRI, *Assessment of Thorium Fuel Cycles in Pressurized Water Reactors*.

1 Base case costs.

2 Bracketed values assume no cost to dispose of discharged fuel. Unbracketed values assume reprocessing costs for disposal of discharged fuel.

"Assessment of the Thorium Fuel Cycle in Power Reactors,"
Oak Ridge National Laboratories, ORNL/TM-5565, January
1977.

The Oak Ridge National Laboratory (ORNL) conducted an investigation of the role of thorium fuel cycles in power reactors. Three thermal reactor systems were considered: LWRs, HTGRs, and HWRs of the CANDU type. The performance of several fuel cycles (thorium, uranium, mixed oxides) in LMFBRs and GCFRs was also evaluated. Based on specific assumptions concerning economic factors, U_3O_8 resources, and nuclear power growth scenarios, fuel-utilization characteristics and power costs were estimated for these reactor types.

With regard to LWRs, most information was obtained from open literature; calculations in the report were consistent with Combustion Engineering results.

The HWR analyses were based on several Canadian studies. Calculated reactor performance is influenced to a high degree by the reactor physics analysis of the core. The authors believe these data are too optimistic.

HTGR data are believed to be representative of what can be expected experimentally, and FBR data are based on published literature.

Two nuclear electric growth scenarios representative of those used in the study are:

1. 15 GW(e) nuclear capacity added each year until 450 GW(e) is reached in 2000, which corresponds to a 10.2 percent per year growth rate.
2. 30 GW(e) nuclear capacity added until 900 GW(e) is reached in 2000, which corresponds to a 13.3 percent per year growth rate.

No restrictions were assumed on either fuel use or fuel recycle, which implies that reprocessing facilities are available. Development costs for commercialization of the HTGR (estimated at \$2 billion, undiscounted) and the

HWR (\$0.5 billion, undiscounted) were not taken into consideration, and fuel shipping, storage, and waste treatment costs were not included. The assumptions included: tails of the diffusion plant to be operating at 0.2-percent U-235; a 7.5-percent discount rate; and 2.5- to 3.5-million tons of U_3O_8 were available at several price levels. Generally, the PWR was assumed to be the only reactor in use until approximately 2000, when the other advanced converters become commercially available. Exhibit D.15 assumed fuel-cycle cost factors, and Exhibit D.16 calculates the assumed power cost factors.

The authors did not find that the thorium cycle competed economically in present PWRs, even at uranium prices over \$100/lb. Thorium-fueled HTGRs and HWRs had the best fuel utilization performance, and HTGRs offer the best economic use of the thorium cycle. HWRs (thorium) are a match for HTGRs with respect to fuel utilization but have a higher power cost.

Generally, it appeared more desirable economically to recycle plutonium with thorium than with uranium in thermal reactors.

In FBRs, thorium or thorium/uranium cycles provide a more negative void coefficient of reactivity than does the plutonium-uranium cycle. The use of thorium in FBRs can provide desirable fuel for both thermal and fast reactors while increasing the ratio of thermal-to-fast reactors that can be maintained in an FBR economy.

Of all the thermal reactors investigated, only the HTGR is more economic with thorium than with the uranium cycle.

For U_3O_8 prices less than \$40/lb, lowest power costs for all thermal reactors are achieved when no fuel recycle takes place. However, the practical application of the thorium fuel cycle requires the development of fuel-cycle capability, without which LWR (thorium) and HWR (thorium) would suffer severe economic setbacks.

Exhibit D.17 summarizes these total power costs.

Exhibit D.15

Assumed Fuel-Cycle Cost Factors**Ore and Separative Work Factors**

U_3O_8 (\$/lb/SWU, \$/kg)	ThO_2
25/75	\$30/kg
40/100	(no recycle
100/150	of fertile
300/200	thorium
	considered)

Fuel-Cycle Cost Parameters (\$/kg)

Reactors	Fuel Fabrication	Fuel Reprocessing	Fuel Refabrication
LWR			
U-235/U-238	114	221	
Pu/U		221	500
U-235/Th	152	250	
U-233/Th		250	570
Pu/Th		260	510
HWR			
Natural U	50	150	
Enriched U	80	160	
Pu/U		160	310
U-235/Th	100	210	
U-233/Th		210	390
Pu/Th		220	320
HTGR			
U-235	400	750	
U-233/Th		750	1030
U-235/U-238	360	730	
Pu/Th		750	1030

Effective Fuel Storage Costs (\$/kg)

Reactor Fuel	Storage Costs
HWR (natural U)	25
HWR (enriched)	100
LWR	100
HTGR	400

Cost to Recover Fissile Pu (\$/g)

LWR	20
HWR	24-50

SOURCE: Oak Ridge National Laboratories.

Exhibit D.16

Assumed Power Cost Factors

Capital Charge Rate: 16%/year (15%/year for fuel cycle)

D₂O Cost: \$110/kgD₂O Inventory: ~0.8 kg/kW(e)D₂O Losses: 2%/year

Reactor Type	Capital Cost		Load Factor (%)	O&M (mills/kWh(e))	D ₂ O Cost (mills/kWh(e))
	\$/kW(e)	mills/kWh(e)			
LWR	800	19.5	75	2.0	
HWR(U)	853	19.5	80	2.0	2.26
HWR(Th)	843	19.3	80	2.0	2.00
HTGR-SC	800	19.5	75	2.0	
HTGR-CC	720	17.6	75	2.0	

SOURCE: Oak Ridge National Laboratories.

NOTE: SC = Steam cycle.

CC = Combined cycle, gas turbine topping, ammonia turbine bottoming.

Exhibit D.17

Total Power Costs
 (mills/kWh)

Case	U ₃ O ₈ Cost (\$/lb)/SW Cost (\$/kg SWU)		
	25/75	40/100	100/150
LWR, U cycle, store	26.2	27.8	34.0
LWR, U/Pu recycle	26.7	28.0	32.0
LWR, Th/U-235 recycle, CR ~0.7	27.6	28.6	32.2
HWR, natural U, store	26.9	27.6	30.9
HWR, U-235/Th recycle, CR = 0.82	27.5	28.5	31.5
SC-HTGR, CR = 0.66, store	25.4	26.5	30.0
SC-HTGR, CR = 0.82, recycle	26.2	27.0	29.4
CC-HTGR, CR = 0.82, recycle	23.4	24.0	26.0

SOURCE: Oak Ridge National Laboratories.

NOTE: SC = Steam cycle.

CC = Combined cycle, gas turbine topping cycle, and ammonia turbine bottoming cycle.

CR = Conversion ratio.

HWRs should be evaluated with respect to costs, schedules, and licensing factors for commercialization in the United States. Since fuel recycle may not be allowed for safeguards reasons, thorium-uranium fuel cycles in FBRs should be studied in detail.

Considerable effort is still needed to provide a practical demonstration of recycle technology. Specifically, demonstration of recycle fuel irradiation performance is needed.

The authors found that considerable effort is still necessary to provide a practical demonstration of recycle technology. They noted that, although metallic thorium fuel has a better operating performance than its oxide form, safety features may preclude its use.

The study made various recommendations:

1. LWRs should be analyzed in depth since they are the most direct route to thorium utilization.
2. Strong support should be given to the thorium-cycle HTGR in case significant delays occur in the LMFBR program.
3. Costs, schedules, and licensing factors should be evaluated for HWRs.
4. Thorium-uranium fuel cycles in FBRs should be investigated, since fuel recycle may not be permitted for safeguards reasons.

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