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Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Volume III: Resources and Fuel Cycle Facilities

U.S. Department of Energy
Assistant Secretary for Nuclear Energy

December 1979

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Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Executive Summary

- Volume I: Program Summary**
- Volume II: Proliferation Resistance**
- Volume III: Resources and Fuel Cycle Facilities**
- Volume IV: Commercial Potential**
- Volume V: Economics and Systems Analysis**
- Volume VI: Safety and Environmental Considerations for Licensing**
- Volume VII: International Perspectives**
- Volume VIII: Advanced Concepts**
- Volume IX: Reactor and Fuel Cycle Descriptions**

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Volume III: Resources and Fuel Cycle Facilities

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U.S. Department of Energy
Assistant Secretary for Nuclear Energy
Washington, D.C. 20545

December 1979

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ACRONYMS AND ABBREVIATIONS

AGNS	Allied General Nuclear Services
CANDU	Canadian deuterium-uranium reactor
FBR	fast breeder reactor
GW	gigawatts
HTGR	high-temperature gas-cooled reactor
HWR	heavy-water reactor
IAEA	International Atomic Energy Agency
INFCE	International Nuclear Fuel Cycle Evaluation
LWR	light-water reactor
NASAP	Nonproliferation Alternative Systems Assessment Program
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NURE	National Uranium Resources Evaluation
OECD	Organization for Economic Cooperation and Development
Pu-Th/Th	plutonium-thorium core with thorium blanket(s)
PWR	pressurized-water reactor
RD&D	research, development, and demonstration
WOCA	world-outside-centrally-planned-economy areas

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1. INTRODUCTION AND FINDINGS

1.1 INTRODUCTION

Purpose

The NASAP assessment of alternative reactor and fuel cycle paths to the proliferation of nuclear weapons found that no system offers more proliferation resistance in the next few decades than the light-water reactor on the once-through fuel cycle, provided spent-fuel facilities and the enrichment process are adequately controlled. The once-through fuel cycle is less resource efficient, however, than some other fuel cycles assessed, and varying amounts of uranium and plutonium fissile materials remain in the spent fuel. Some nations, including the United States, have planned or are planning to recycle these residual materials to alleviate potential uranium supply constraints on nuclear-power growth. In several nations, programs have already begun to develop reactors such as the fast breeder which, through reprocessing of spent fuel and recycling of the uranium and plutonium that is recovered, increase the energy generated from uranium resources. These same systems also increase the risk of proliferation because they employ or produce weapons-usable material. For this reason, it is important to examine the relationship of uranium supply to demand for the currently deployed light-water reactors on the once-through cycle and determine what reactor or fuel-cycle alternatives might be pursued in the future should uranium-supply pressures necessitate the deployment of less proliferation-resistant systems as a hedge against supply interruptions or excessive increases in uranium prices. This assessment, which begins with the United States and proceeds to the world-outside-centrally-planned-economy areas (WOCA)¹, addresses the following questions:

- When and under what conditions would the ability to fuel the current design of the light-water reactor on the once-through fuel cycle be limited by uranium supply?

¹ For the purposes of this report, WOCA nations exclude the People's Republic of China, the U.S.S.R and associated countries.

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- To what extent would improvements in light-water reactor fuel use extend the viability of the once-through fuel cycle?
- How would the use of recycle or breeders mitigate uranium-supply constraints?
- What are the supply and demand outlooks for WOCA and for the principal foreign uranium suppliers and consumers if they remain on the once-through cycle?
- What are the supply and demand outlooks if the large industrial countries employ the breeder?
- Would fuel cycles that use thorium and/or heavy water be limited due to resource or supply inadequacies?
- What fuel-cycle services are required to support alternative reactor and fuel cycle deployments?

Approach

These questions will be analyzed by first evaluating the potential supply capability outlook in the United States and comparing uranium demand with that supply capability under several energy demand-growth scenarios. The comparison of potential uranium supply capability with uranium demand for alternative reactor/fuel cycle systems is divided into two parts. Recognizing the greater proliferation resistance of the once-through cycle, and current U.S. policy, once-through fuel cycles are analyzed first, beginning with the present light-water reactor system, proceeding to light-water reactor fuel-utilization improvements and then proceeding to the longer-term alternative of advanced converter reactors on the once-through fuel cycle. The second part of this analysis will focus on recycle options for light-water reactors and advanced converters, as well as upon light-water breeder reactors and fast breeder reactors. These alternative reactor and fuel-cycle systems were chosen because they represent systems that are in use or undergoing major developmental programs in the world. The analysis also considers the supply and demand for thorium, heavy water, and fuel-cycle services in the United States. Similar analyses of supply and demand for resource and fuel-cycle services supply and demand will be conducted for the WOCA countries as a group and for several major countries within that group.

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The two-part approach of this assessment is designed to allow analysis of supply-demand relationships given the continuation of the present once-through fuel-cycle, and to illustrate the effect of reprocessing and recycle upon the supply-demand variables used in this analysis. It is necessary to point out that, while these reactors and fuel-cycle systems are mutually-exclusive in the nonproliferation policy-making sense, light-water reactors would continue to be a part of either reactor/fuel-cycle regime considered within the time frame of this analysis.

Nuclear Growth Projections

United States

Nuclear energy growth projections developed by the Department of Energy in 1978 and discussed in Volume I were used to cover the possible range of nuclear energy demand in the future. Three forecasts were considered: low growth (255 GW in the year 2000 to 320 GW by 2025), median growth (325 GW in the year 2000 to 615 GW by 2025), and high growth (395 GW in the year 2000 to 910 GW in 2025).

More recent Department of Energy projections, also through the year 2000, indicate reduced growth for nuclear power in the United States, such that the 1978 median and low growth projections are reasonably representative of the latest range of expectations through the year 2000. Beyond that time, there are major uncertainties which could possibly lead to a continued reduction in the nuclear power growth projection, or could lead to a return of the 1978 high growth rate projection in the post-2000 period. Given these limitations, this assessment will emphasize the results based upon the 1978 median and low projections, although results from the 1978 high growth projection will also be presented to indicate what supply/demand relationships would prevail should high growth resume.

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WOCA Countries

The assessment of nuclear energy growth projections in WOCA nations is based on the 1978 projections developed by the International Atomic Energy Agency for use in the International Nuclear Fuel Cycle Evaluation. Two forecasts were employed: low growth (850 GW in the year 2000 to 1,800 GW by 2025), and high growth (1,200 GW in the year 2000 and 3,900 GW by 2025).

Recent Department of Energy analysis of foreign nuclear growth shows a trend, through 1995, which is below that of the 1978 low growth projection. As in the United States, there are major uncertainties which could cause the continuation of this downward trend or create a return to the 1978 high growth projection in the post-1995 period. Accordingly, this assessment will emphasize the 1978 WOCA low growth projection.

Definitions

In an assessment of this nature, essential terms need to be defined to avoid possible misinterpretation of data. The following is a list of terms and definitions considered to be critical to the understanding of these assessments of resources and fuel-cycle services.

Annual Supply: Supply is the actual amount of uranium that can be produced from existing mines and mills in a given amount of time from reserves. The potential supply for the future considers reserves, potential resources, and new mines and mills that can be constructed within the limitations of industrial constraints. In this analysis, annual supply is the amount of uranium that can be produced in a particular year, and is expressed in short tons.

Forward Cost: One measure of the economic availability of uranium resources is the forward cost. Forward cost includes the estimated direct costs of developing, building, and operating uranium mines and mills. Forward costs are used in this analysis because they can be estimated from industry cost elements and thereby allow consistency of estimates among various

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estimators. A word of caution: forward cost is not to be confused with price, which includes additional economic considerations such as costs, exploration costs, cost of money, marketing costs, rate of return, profit, some taxes, etc. For this study, a rough rule of thumb is that prices are usually up to 2 times as much as forward cost of the particular increment of resources being utilized. Because the forward cost category includes all resources at or below the stated value, the average price of all the resources being used at any given time will depend on the relative amounts of the lower cost categories comprising the production.

High-Grade and Low-Grade Resources: In this analysis, high-grade resources are assumed to have a uranium concentration of greater than 250 parts per million (ppm) and to be recoverable through conventional mining and milling techniques. Resources with lower concentrations or those recovered by nonconventional mining technology are considered to be low grade. Usually the higher the uranium content of the resource, the less it will cost to produce. High-grade, low-cost resources are our current source of supply.

Reserves: Reserves are reasonably assured supplies which are based on quantities of uranium ore already discovered, and on some quantities of adjacent ore which are inferred from geologic knowledge of the deposits.

Resources: Uranium resources include known uranium deposits (reserves) plus uranium believed to exist on the basis of geologic information and which is producible at an estimated cost using current or near feasible technology.

Separative Work Units: The capacity of an enrichment plant is measured in separative work units. This unit represents a measure of the work required to separate a mixture of isotopes into two components, product and tails, of different isotopic composition. Since the separative work unit has a thermodynamic basis, it is valid for comparing enrichment processes involving different technologies. In the United States, separative work units are measured in kg SWU's but denoted merely as SWU's.

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Uranium Ore: This is a mineral which contains uranium in useful quantities and is exploitable at a profit under prevailing economic conditions. The concentration of uranium in ore varies widely. For example, some uranium ore contains more than 25 percent uranium, while other ore contains less than 0.025 percent or 250 ppm. In 1978 the average grade of ore processed in the United States was 1,400 ppm.

Uranium Oxide: Uranium oxide (U_3O_8), also referred to as yellow-cake, is the chemical form in which uranium is usually produced and sold before entering the fuel cycle. U_3O_8 is normally produced in uranium mills operated in conjunction with one or more mining operations. Prices and quantities of uranium are usually expressed in pounds or short tons of U_3O_8 . A pound of U_3O_8 contains about 0.85 pound of uranium metal.

1.2 FINDINGS

1.2.1 United States Uranium Supply-Demand

Once-Through Systems

The ability to fuel light-water reactors on the once-through fuel cycle is not likely to be limited by uranium supply capability through 2025, provided the following conditions are met:

- o Nuclear power in the United States grows from 50 GW in 1979 to about 600 GW or less in 2025 (an average growth of 12 GW per year); higher nuclear growth does not now appear likely, although it might occur after the year 2000 if demand for electrical energy grows faster than presently expected and non-nuclear technologies cannot supply these needs.
- o United States annual uranium supply is expanded four-fold to about 80,000 short tons U_3O_8 per year, if

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needed, in about 30 years. This appears to be achievable based on the present assessment of resources and factors in the supply process.

- There is a successful development and use of retrofittable improvements, fuel management techniques, and operating improvements by the year 2000, which could reduce by at least 15 percent the uranium usage of current light-water reactors. Further application of these retrofittable techniques could reduce usage by 25 percent. A 30 percent or more reduction in uranium usage appears technically feasible with changes in the design of new light-water reactors. These changes could be introduced in new reactors starting after the year 2000.
- Enrichment plant tails assay are reduced from the present 0.20 percent U-235 content to 0.10 percent. This would result in about a 13 percent reduction in annual uranium requirements and is achievable with current enrichment technology, although it requires a 40 percent expansion of enrichment capacity beyond current commitments beginning in the 1990's. Successful development of advanced isotope separation techniques has the potential to provide a further reduction of another 5 percent in uranium requirements and offers improved economics for isotope enrichment.

One means of meeting nuclear growth rates higher than about 12 GW/year after the year 2000, and/or providing more substantial uranium exports, is the development and large-scale use of low-grade uranium resources, resources which contain much less uranium than the resources mined today, in combination with the light-water reactor once-through fuel-cycle improvements discussed above. This option would extend the range of growth rates which can be supported on the once-through cycle or the time period for which the once-through cycle is viable. The feasibility of this option is uncertain, however, because of significant questions concerning the environmental impacts, economics, and pace of implementation needed to achieve the necessary contribution to uranium supply.

Introduction of advanced converter reactors, such as the heavy-water or high-temperature, gas-cooled reactor, if operated on the once-through fuel-cycle, would have a minimal effect on reducing uranium demand beyond that

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believed achievable with the improved light-water reactor. A 10 percent reduction in annual uranium requirements might be achieved by 2025 through the use of advanced converter reactors as opposed to using only light-water reactors with fuel use improvements.

Fuel Recycle Systems

Recycle systems, including breeders, are another approach to meeting fuel needs for nuclear growth rates higher than about 12 GW/year after the year 2000 (that is, growth exceeding about 600 GW in 2025) or to compensate for substantial uranium exports. Findings for specific recycle alternatives are:

- Introduction of fast breeder reactors into the nuclear power system is the most effective means of meeting high nuclear growth over the long term; fast breeder reactors can level uranium demand within about 10 years after commercial introduction and can reduce demand in later years to an extent that depends upon the proportion of fast breeder reactors in the system. Fast breeder reactors have the ability to provide an essentially inexhaustible source of nuclear power.
- Light-water reactor recycle of uranium and plutonium can be a means of meeting high growth, although this strategy would only be effective for a short period. If the spent fuel stockpile is used, the demand for mined uranium can be reduced for about a decade, providing sufficient reprocessing capacity is constructed. This appears technically achievable about one or two decades earlier than the fast breeder reactor becomes commercially available. If the spent fuel stockpile is not used, and only the spent fuel generated each year is recycled (i.e., self-generated recycle), then light-water reactor recycle will reduce uranium demand by 10 to 20 percent as compared to what appears feasible with once-through fuel-cycle improvements.
- The introduction of light-water breeder reactors, which require U-233 fuel to achieve high resource efficiency, would result in very high uranium demands over a period

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of a few decades to satisfy high nuclear growth if they were fueled by U-233 bred from enriched uranium/thorium fuel. This high peak in uranium demand could be reduced if plutonium recovered from the light-water reactor spent fuel stockpile were used with thorium to produce the U-233 needed for the light-water breeder reactor fuel. This approach would make it feasible from a uranium supply viewpoint for light-water breeder reactors to meet a moderately high nuclear growth rate of less than 15 to 20 GW/year through 2025, although this approach would be limited in the next decade by exhaustion of the spent fuel stockpile.

- Advanced converter reactors operating with recycle would have an effect on uranium demand similar to that described for the light-water breeder reactors, and with high nuclear growth would experience supply-demand imbalances sometime after 2025. More specifically, use of enriched uranium/thorium fuel to make U-233 would lead to very high uranium demands over a few decades in order to satisfy a high nuclear growth, but use of plutonium/thorium fuel to make the U-233 would reduce the uranium demand to levels that could sustain nuclear growth rates of less than 15 to 20 GW/year.

1.2.2 WOCA Uranium Supply-Demand

This analysis was performed separately for foreign WOCA countries and the United States, as well as for WOCA countries including the United States. This section provides a perspective on uranium supply/demand for WOCA countries excluding the United States and then considers uranium supply/demand when the United States is included in the WOCA assessment.

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Foreign WOCA Countries

Once-Through Systems

Supply-demand imbalances for light- and heavy-water reactors on the once-through fuel cycle can be avoided until the year 2025, provided the following conditions are met:

- Nuclear power grows at a moderate rate, averaging 14 GW/year or less. This is consistent with recent Department of Energy estimates of lower nuclear growth through 1995, averaging 11 to 14 GW/year; the outlook is now about 121 GW in 1985 and 264 GW in 1995 as compared to the 1978 projection of 149 GW in 1985 and 423 GW in 1995. High nuclear growth, as for the United States, appears unlikely at present, although similar uncertainties apply in the post-2000 period. Higher growth could resume if present electrical demand were underestimated, or non-nuclear technologies were unable to meet demand-growth projections.
- Present uranium supply outside the United States is expanded about 2-1/2 times, to approximately 100,000 short tons U_3O_8 in the year 2000, and further expanded to 220,000 short tons U_3O_8 in 2025. This appears achievable provided vigorous exploration and development are conducted by foreign countries to bring in necessary reserves by the year 2000.
- A 15 percent improvement in fuel utilization in light-water reactors is achieved and put into general use by the year 2000. Further application of retrofittable improvements, fuel management techniques, and operating improvements could reduce uranium usage by 25 percent; a 30 percent reduction appears technically feasible with changes in light-water reactor design. It appears that foreign WOCA nations will adopt these fuel utilization improvements.
- Sufficient enrichment capacity to reduce the tails assay from 0.20 percent to 0.10 percent is achieved by the year 2000. If current enrichment plant expansion plans are carried out, there will be excess capacity

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through the mid-1990's, and if supply-demand imbalances occur, reduced enrichment tails assay would become more attractive, especially as uranium prices increase.

- The principal uranium consumers have access to the supplies of uranium which must be developed in other countries. This appears likely if current market conditions continue.

It is possible that relatively small, temporary supply-demand imbalances will be encountered shortly after the year 2000 if sufficient incentives to expand supply are not provided to the market or by government actions. These imbalances are thought to be manageable, however, particularly in view of the present growth trend and because the annual demand will not substantially exceed the low supply estimate. After the year 2000, the expanded production of uranium will increasingly have to come from possible and speculative resources, uranium that may exist but has yet to be discovered.

One means of meeting nuclear growth rates higher than 14 GW/year is the development and large-scale use of low-grade uranium resources in combination with the light-water reactor once-through fuel cycle improvements discussed above. This option would extend the range of growth rates which are supportable, or would extend the time period for which the once-through fuel cycle is viable. The feasibility of this option is uncertain, however, because the major suppliers of uranium in foreign WOCA countries are not also the major consumers, and limitations in ability and willingness to exploit these resources loom as major constraints to expansion of supply.

Fuel Recycle Systems

The principal recycle system studied for the foreign WOCA nations was the fast breeder reactor. This alternative is largely being pursued by the major industrialized nations within WOCA, and recognizes that there is a discrepancy between domestic uranium requirements and indigenous supplies in many countries. Since the major industrial nations are also expected to have a large portion of world nuclear capacity, breeder deployment in these nations will have a significant effect on total foreign uranium demand, although whether or not this is important in the aggregate depends to a great extent on uranium supply and access to it.

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The introduction of the fast breeder reactor in the major industrial countries will not significantly affect uranium demand through the year 2000. If the current nuclear growth rate persists after the year 2000, the fast breeder will probably not be crucial in avoiding supply-demand imbalances through 2025. Fast breeder reactor introduction would reduce demand by about 15 percent as compared to use of the 15 percent improved light-water reactor and reduced enrichment tails to an assay of 0.10 percent U-235. It appears that uranium supply can be expanded adequately through 2025 to meet the needs of the reference once-through system.

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Once-through systems will probably not be adequate to meet high growth rates such as the 1978 projected range through 2000 of 24 to 34 GW/year, or long-range needs beyond 2025. Fast breeder reactors can meet this high growth, under certain conditions:

- There must be an expansion of supply to 330,000 short tons U_3O_8 in the year 2025. This will be difficult to achieve, given the constraints mentioned earlier.
- 50 percent of the installed capacity by the year 2025 must consist of breeder reactors within the major industrialized countries of WOCA, excluding the United States. The achievement of this level of installed capacity would require tremendous commitments on the part of the installing nations.

WOCA With the United States

The above analysis assumed the United States was neither an importer nor an exporter of uranium, but supplied domestic requirements with indigenous resources. If the United States is included in the aggregate analysis, the excess U.S. uranium supply would become available for export to other WOCA nations, and U.S. demand could be partially met by purchasing uranium from WOCA nations. The effect of combining a median growth projection of about 12 GW/year for the United States with a low growth projection of about 14 GW/year for foreign WOCA nations under a once-through fuel cycle regime is not significant. This is because the United States is self-sufficient and not expected to import or export uranium through the year 2025. If a high growth rate occurs in the WOCA countries in the post-2000 period, early deployment of the fast breeder reactor in the United States as well as in the other industrial nations of WOCA will be important in avoiding uranium supply/demand imbalances.

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1.2.3 World Supply and Demand for Other Resources and Fuel Services

Enrichment

Enrichment supply does not appear to be a problem either in the short or long term. In the past, the United States has been the primary supplier of enrichment services to foreign WOCA countries, but expansion plans inside WOCA nations will result in the United States having only about 40 percent of projected enrichment capacity in 1990. If current expansions are completed as scheduled, a 25 to 30 percent overcapacity will exist worldwide by 1990. Thus, enrichment capacity appears more than adequate through the mid-1990's.

Long-term adequacy of world enrichment supply does not appear to be a problem. For reactors operating on the once-through cycle under the current world nuclear growth trend, capacity would have to be added at the rate of 4 to 5 million separative work units per year, a rate comparable to that planned for the late 1980's. If recycle systems such as fast breeder reactors are introduced in some highly industrialized countries, enrichment requirements would be significantly reduced once adequate recycle facilities were in operation.

The United States has an enrichment capacity of 36.1 million separative work units per year now operating or firmly planned, and this will be adequate to meet a median domestic nuclear growth rate to about 240 GW in the year 1995. This capacity would also be adequate to meet an additional 50 GW/year of foreign light-water reactor needs. Addition of about 1.8 million separative work units per year would be necessary to supply a median nuclear growth of 12 GW/year beyond 1995, assuming a system of improved light-water reactors operating on the once-through fuel cycle with enrichment tails assay reduced to 0.10 percent U-235. This appears to be technically feasible, but to achieve this additional capacity using current technology would require an annual investment of several billion dollars. Alternative reactors and fuel cycles employing recycle generally require a lower rate of capacity addition.

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Spent-Fuel Storage

Spent-fuel management is a growing problem which needs national and international actions if it is to be adequately resolved. At this time, most nations are pursuing independent approaches to spent-fuel management. No permanent storage or disposal techniques have been implemented yet, and no international facilities exist for spent-fuel management. Most spent-fuel is currently stored at reactor sites or in receiving pools at reprocessing plants, and this practice is expected to continue until at least the year 2000. Storage capacity at some reactors in both the United States and WOCA countries will have to be expanded as early as the 1980's or the reactors will have to shut down.

For WOCA countries excluding the United States, spent-fuel storage facilities outside reactor storage pools will have to increase in capacity from 45,000 to 70,000 tons by the year 2000 if the current nuclear growth trend persists and current types of reactors continue in use. United States spent-fuel storage in away-from-reactor facilities would grow from about 32,000 to 45,000 tons by the year 2000 under similar growth conditions. To put this in perspective, a new facility, such as has been studied by the Department of Energy for establishing spent-fuel storage charges, might have an initial capacity of 5,000 tons and cost \$200 million (in 1978 dollars). This facility could be expanded in increments of 1,000 to 15,000 tons. With the exception of light-water reactor fuel recycle, alternative reactors and fuel cycles do not significantly reduce spent-fuel storage requirements through the year 2000. Light-water reactor recycle could reduce annual storage requirements in the United States by about one-third, if a 1,500 ton capacity reprocessing plant began operation in the 1990's.

In the post-2000 period, light-water reactor improvements could significantly reduce the rate of increase in spent-fuel storage requirements for the once-through fuel cycle. With these improvements, spent-fuel storage requirements for median nuclear growth would be 185,000 tons in the United States by 2025, a 35 percent reduction compared to the continuation of the current light-water reactor fuel design.

Adoption of recycle alternatives would have the greatest impact on spent-fuel storage requirements in the post-2000 period. Spent-fuel requirements can be reduced in proportion to the expansion of reprocessing plant capacity. A

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relatively slow expansion of reprocessing capacity, for example the addition of 200 to 300 tons of capacity per year for a median nuclear growth rate of 12 GW/year, would eliminate the need for new away-from-reactor storage facilities after the year 2000. The reprocessing would, of course, generate high- and low-level wastes which would require interim storage and, eventually, permanent disposal.

Reprocessing

Reprocessing capacity does not appear to be a problem in the long term, except that it might limit the rate of fast breeder capacity expansion in the United States.

Commercial reprocessing is being developed in about eight foreign countries in preparation for breeder deployment and to a lesser extent for thermal recycle. France is the only country which currently has in operation a large, commercial-size plant for reprocessing light-water reactor oxide fuel. Reprocessing plants are being built to meet domestic needs in the other countries, and excess capacity may exist in several of these countries by the late 1980's. These countries may, because of the projected excess capacity, be able to reprocess fuel from other nations and have made commitments to do so. Planned capacities of the reprocessing plants appear adequate to meet announced plans for breeder deployment through the year 2000. The expansion of reprocessing capacity after the year 2000 to meet the requirements of the scenarios discussed in Chapter 5 for foreign WOCA countries does not appear to present any major technical obstacles.

Reprocessing might begin in the United States about 1990 if approval is given by the Federal Government. This occurrence would also be contingent upon a decision by the Federal Government and industry that the Allied General Nuclear Services plant at Barnwell, South Carolina, would be completed without major design revisions and that operation of the plant is not dependent on the availability of a geologic high-level waste disposal facility. The Allied General Nuclear Services plant has a designed annual capacity to reprocess spent fuel containing 1,500 tons of uranium and plutonium. The plant would be able to handle the requirements of about 50 GW of light-water reactors of the current design, or about 80 to 100 GW of spent fuel from improved light-water

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reactors. For nuclear growth to about 325 GW in the year 2000 and reprocessing occurring at the same annual rate at which spent fuel is being discharged, requirements would expand to between 5,800 and 9,700 tons. This is probably an unrealistically rapid expansion of capacity, and as a result would slow light-water reactor recycle. For nuclear growth to 615 GW in the year 2025, an additional 5,000 tons of capacity would have to be added in the period between 2000 and 2025. This post-2000 reprocessing capacity buildup appears to be achievable. The reprocessing capacity requirements assume improvements will be made to extend the burn-up of light-water reactors such that fuel utilization is improved and spent-fuel discharge is reduced.

Reprocessing needs would grow rapidly for fast breeder reactor deployment averaging 10 to 15 GW/year in the 2015 to 2025 period, requiring the annual addition of capacity about 1-1/4 to 2-1/4 times that of the Allied General Nuclear Services plant, a rate that appears difficult to achieve. Thus, reprocessing capacity expansion could be a constraint to fast breeder deployment.

Thorium

Thorium is principally used in alternative fuel cycles such as for the high-temperature gas-cooled reactor, the light-water breeder reactor or the fast breeder reactor. The supply of thorium for world or U.S. needs in these alternative fuel cycles is not likely to be a problem.

Thorium-based fuel cycles are not well developed at a scale necessary for commercial-sized reactor systems, and there are no current deployment commitments. Any significant use would be after the year 2000, because of the amount of time needed to develop and implement the technology (see Volume IV).

Although exploration for thorium has not been undertaken in most parts of the world, over 1,000,000 short tons of ThO_2 resources have been estimated to exist in foreign WOCA countries, and over 3,000,000 short tons in the United States. Large, unassessed thorium-bearing deposits are also known to occur

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in several countries and it is reasonable to expect these deposits to contribute to significant increases in resources. Thus, the potential for supplying world thorium requirements is good.

The thorium supply requirements per unit of nuclear power production are substantially less than mined uranium requirements because uranium enrichment results in a more than 80 percent loss to tails. Almost all of the thorium could be recovered from spent fuel and reused for fresh fuel, although a storage period of about 10 years might be needed for radioactive decay.

Present thorium production is very small because of low demand. Adequate market incentives and lead times would be needed to achieve expansion of supply. It is likely that this expansion could be accomplished to match the needs for thorium in even the highest nuclear growth rate scenarios for the post-2000 period.

Heavy Water

The heavy water resource is essentially unlimited, because the sources are the world's water supply and the oceans. Expansion of the supply is constrained only by the willingness of industry to construct the required facilities. Heavy water supply is not expected to limit the deployment of heavy-water reactors.

Current plans may quadruple heavy-water production capacity in the foreign WOCA countries by 1985. This capacity should be about adequate to meet demand through 1985. The lead time for heavy water plants is less than that for reactor plants, so it will be possible to expand capacity rapidly enough to meet anticipated demand. There is no current U.S. demand for heavy water except for military purposes and a small amount required for research and development activities. It appears feasible to expand U.S. heavy-water supply capacity to meet the maximum needs considered credible.

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2. ESTIMATES OF U.S. URANIUM RESOURCES AND SUPPLY

This chapter presents estimates of the quantities of uranium that could be supplied from uranium resources within the United States. Presented first are estimates of high-grade resources, that is, uranium which could be produced at a forward cost of \$50 or less per pound of U_3O_8 . Presented second are estimates of annual supply. Supply is the more critical variable because the quantity of uranium in the ground is irrelevant if it cannot be developed and produced at the rate necessary to meet the annual requirements of the nuclear industry. Two projections of the ability of the U.S. uranium industry to produce uranium from conventional high-grade, relatively low-cost resources are presented. Then, projections of estimated production capability from the unconventional or low-grade resources with a generally higher production cost are shown. The estimates of potential production capability from high-grade resources are subsequently combined with the estimates for low-grade resources to produce ranges of possible supply that may be available through the year 2025. Also presented is a summary of the critical factors affecting the process of converting uranium resources into uranium supply.

2.1 CURRENT ESTIMATES OF HIGH-GRADE URANIUM RESOURCES IN THE UNITED STATES

The Department of Energy and its predecessors, working closely with the uranium industry, have published annual estimates of uranium resources and reserves since the 1950's. The latest estimates as of January 1, 1979, for high-grade reserves and the three categories of potential resources are presented in Table 1.

The estimates are for U_3O_8 contained in ore considered extractable through mining. Losses occurring in the milling process have not been deducted. The total of these resources is about 4.1 million short tons U_3O_8 . The estimates for each of the categories, i.e., reserves and probable, possible, and speculative potential resources, do not have the same degree of reliability; the uncertainties in the less reliable estimates can only be resolved by further exploration and data analysis. As noted in Table 1, the U_3O_8 reserves are estimated to be 920,000 short tons at \$50 per pound forward cost or lower with an uncertainty of ± 17 percent at the 90 percent confidence level. Uncertainties associated with the various potential resource categories are greater than for reserves.

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Table 1. Department of Energy Estimates of Recoverable Domestic U_3O_8
Reserves and Potential Resources as of January 1, 1979^{3,8}
(in thousands of short tons of U_3O_8)

Forward Cost (\$/lb U_3O_8)	Reserves	Potential Resources				Total Reserves and Potential Resources
		Probable	Possible	Speculative	Total	
<u>≤15</u>	290	415	210	75	700	900
15-30	<u>400</u>	<u>590</u>	<u>465</u>	<u>225</u>	<u>1,280</u>	<u>1,680</u>
<u>≤30</u>	690 ^a	1,005	675	300	1,980	2,670
30-50	<u>230</u>	<u>500</u>	<u>495</u>	<u>250</u>	<u>1,245</u>	1,475
<u>≤50</u>	920 ^b	1,505	1,170	550	3,225	4,145

Byproduct U_3O_8 that could be produced from phosphate and copper leach through the year 2000⁸ is estimated to be 120,000 tons.

^aEstimated +15 percent uncertainty at 90 percent confidence level

^bEstimated +17 percent uncertainty at 90 percent confidence level

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Potential resources, as shown in the table, are estimates of the quantity of uranium believed to be present in deposits that are incompletely defined or undiscovered. The potential resources are divided into three categories in order of their decreasing reliability: probable resources or undiscovered deposits estimated as extensions of known deposits and new deposits within known geologic formations; possible resources or undiscovered deposits in geologic settings elsewhere within productive geologic formations; and speculative resources or those estimated for geologic settings not previously within productive geologic formations. Most of the data used to make resource estimates have come from information supplied by the uranium industry. A productive province is defined as an area with more than 10 short tons of U_3O_8 produced in the past or in reserves.

The Department of Energy uses all available company data and information developed by the National Uranium Resources Evaluation (NURE) program in estimating potential resources. A comprehensive report on the evaluation of currently known favorable areas believed to contain the majority of U.S. resources is to be completed in late 1980, and the balance of these areas will be evaluated by 1983. Other areas will be evaluated from 1983 through 1985. Most past exploration has been in the sandstone deposits in the Rocky Mountain States and in Texas. The National Uranium Resources Evaluation program includes these areas as well as unfamiliar geologic regions without past production history. The program's analyses are to be based on the data available at the time and should not be considered as estimates of the total national uranium endowment, which will tend to increase as more data become available and gaps in basic knowledge of uranium deposition and transport are resolved.

In preparing the NASAP analysis, a number of alternative uranium resource estimates were evaluated. The estimates reviewed included those by the Uranium Resource Subpanel to the Committee on Nuclear and Alternative Energy Systems of the National Academy of Science (Reference 1), the Ford Foundation-Mitre Corporation report, "Nuclear Power: Issues and Choice" (Reference 2), and the Nuclear Regulatory Commission report, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors" (Reference 3). The Department of Energy estimates were the only ones used, however, because they alone provided estimates developed by systematic evaluation of actual data.

There are some limitations to the Department of Energy estimates. First, only quantities presently known or surmised to exist are included; that is, those

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based on relatively conservative geologic judgments from current data. Second, the reliability of estimates is a function of the amount of geologic information available, with increased knowledge of the geology implying increased reliability of the estimate. Finally, the quantities do not address any schedule of producibility; technical and institutional factors will determine whether the resources will be produced at the indicated cost and what the production schedule will actually be.

2.2 URANIUM SUPPLY

Resource estimates have little to do with the time required to find and develop a resource. In order to meet demand in any given year, sufficient uranium resources must be discovered and delineated in previous years, mines and mills must be constructed, and production capacity must be achieved. Thus, the critical question is not how large the resource base is, but whether or not the annual production of uranium will be adequate to meet annual needs.

There remains a wide divergence of opinion as to what future uranium supply capabilities may be, much of it the result of confusing ideas about the meaning of the terms "resources," "production capability," and "supplies." Resource estimates at a stated forward cost are time-independent variables based on the quantity and grade of uranium deposits considered to exist in the ground based on available data, and on the estimated costs to produce them with a particular technology. Production capability is an estimate of the uranium industry's ability to find, develop, and produce uranium. Supply is the actual amount of uranium finally delivered to the market, and depends strongly on actual reactor demand. Reserves are only that part of the resource estimate which are known to exist and can be produced economically with current or near-term technology. Reserves are a conservative measure of resources for long-term supply estimation, and consequently potential resources should be considered as an estimate of material which might be discovered with sufficient exploration.

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Potential supply, in contrast, is that portion of the resource that may be discovered and produced with diligent effort. Unless exploration and development of new reserves keeps well ahead of demand, potential resource estimates are not meaningful indicators of the supply outlook over long periods of time.

The supply process occurs in several stages, each influencing the development of the uranium resource. The process begins with exploration to find the resource, a stage which lasts an indeterminate amount of time. After discovery, the resource must be developed by drilling to determine its extent and to estimate the type and cost of production. This stage usually lasts from 2 to 4 years. If the resource is judged to be economic, design and planning for mines and mills begins. Applications for State and Federal licenses add an additional 2 to 4 years to the process. Completion of mine and mills is accomplished within 2 to 4 years of the beginning of construction. Thus, a decade can elapse between the discovery of a new ore body and the start of production from the associated mine and mills.

Many uncertainties and constraints can interrupt and extend the process. The scale and uncertainty of exploration and development efforts, the success such exploration will produce, and, ultimately, the return on investment, are the principal uncertainties influencing whether or not expansion of supply will occur. The future exploration yield is inherently uncertain, and data from past exploratory drilling is ambiguous. The firmness of the market and the institutional framework substantially affect the willingness to make high-risk exploration and mine-mill investments on a schedule complementary to nuclear industry demands. Industry is not likely to produce large quantities of uranium in an environment of low demand for nuclear power. Conversely, a strong nuclear demand has in the past led to rapid expansion of supply. Another major uncertainty contributing to the investment risk and production capability forecast is what the actual cost of recovery will prove to be, as compared to the forward cost used in making the resource estimate. For these and other reasons, the reliability of production capability estimates decrease rapidly as the time-frame is lengthened.

This chapter assesses the production capability of uranium from both high-and low-grade resources. High-grade resources, extracted from conventional sources, can be developed at relatively low costs using current mining and extraction technologies. Low-grade resources are generally extracted from lower uranium content sources and in some cases require the development of new technologies. For these reasons they are more expensive to process

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than high-grade resources. Low-grade resources are known to be quite large, but whether or not they can provide an adequate source of supply over the long term is uncertain.

2.2.1 Production Capability Outlook from High-Grade Uranium Resources

Estimates of production capability from high - grade resources have been derived from two sources: the Department of Energy Division of Resource Assessment Operations and the S.M. Stoller Corporation. These estimates are shown in Figure 1, and their derivation is described below.

Production Capability Projections by the Department of Energy - Division of Resource Assessment Operations

The Department of Energy - Division of Resource Assessment Operations projections were developed for input into the International Nuclear Fuel Cycle Evaluation (INFCE) Working Group 1 report on global uranium resources. The projections are essentially an estimate of the maximum feasible levels of uranium potential production capability from known and surmised high-grade resources under favorable assumptions for economic and political conditions. The projections were developed by considering possible future production from existing and projected uranium-processing plants with tributary mines. The shaded area in the upper portion of Figure 1 encompasses four potential production capability estimates which combine two levels of possible and speculative potential resources (high and low) and two resource development rates (accelerated and delayed). The reserves and probable potential resources are as shown in Table 1. The accelerated and delayed development categories are based on an analysis of the expansion capabilities of industry and the key activities necessary for that expansion. They represent the feasibility for discovering and converting potential resources into reserves, that is, into proven deposits of economically recoverable materials.

The key features of the Department of Energy - Division of Resource Assessment Operations projections are that annual production from currently estimated high-grade resources at forward costs of not more than \$50 per lb U_3O_8 could be expanded to about 80,000 to 86,000 short tons U_3O_8 per year in about 25 to 30 years; this production level could be sustained for about 5

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Figure 1. Annual Uranium Supply Capability Estimates from High Grade Resources

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to 15 years, and would then decline as the resources were depleted. It is emphasized that this is a production capability estimate, not an actual supply forecast. The actual supply would be close to the actual demand, except for inventory buildup.

Since the Department of Energy-Resource Assessment Operations potential production capability estimate is greater than expected demand over the next 10 to 20 years, as is shown in Chapter 3, U_3O_8 production and actual production capacity will probably be less than the projected potential capability levels, and over the long term supply of uranium from high-grade resources may not decline as rapidly as shown because the high-grade resources will not have been depleted as rapidly or at the time shown in Figure 1. In this event, the actual annual supply would more closely resemble the S.M. Stoller Corporation projection.

Supply Projections by the S.M. Stoller Corporation

The S.M. Stoller Corporation supply projections were based on a uranium industry analysis presented in Reference 4. In contrast to the Department of Energy analysis, the S.M. Stoller Corporation analysis attempts to couple production capability with specific forecasts of uranium demand as well as with the critical factors affecting the industry's ability to expand supply. The analysis was based on consideration of the following: domestic uranium requirements as established by Department of Energy demand projections and specified reactor and fuel cycle characteristics; necessary additions to the existing mine/mill production base; the rate and quantity of discovery of new domestic uranium reserves; the extent of the uranium exploration effort; ore mining and milling output; and critical manpower needs.

The S.M. Stoller Corporation estimates describe an optimistic and conservative forecast related to the 1978 median nuclear growth. The top curve of the projection, as shown in Figure 1, is the optimistic forecast based on 1978 trends. The bottom curve is a conservative forecast which takes into account possible near-term market adjustments and the effect of constraints and disincentives on expanded supply. The optimistic forecast demonstrates a leveling trend by the year 2025. When the required pace of new reserve delineation and the present knowledge of potential resources are taken into consideration, the optimistic S.M. Stoller Corporation projection could be sustained for about 5 years after 2025, and the conservative projection for

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about 2 decades after 2025. The projections include a small amount of imports that were not part of the original estimate. Net imports of about 600 short tons of U_3O_8 /year have been added starting in 1980, reaching 3,000 to 4,000 short tons of U_3O_8 /year in 2000, and 5,000 short tons/year by 2025. This reflects the current net import trend through 1990, which averages 2,500 short tons/year.

Estimates of the critical factors in the supply process considered in the S.M. Stoller Corporation analysis are described in the following section.

Needed Rate and Quantity of Discovery of New Domestic Uranium Reserves

The discovery and delineation of new reserves normally precede the required expansions of production capacity by 10 to 15 years. They must also be larger than the annual additions because an adequate body of reserves must be described before new mine and mill ventures are committed. The amount by which the delineation of new reserves must be larger than the annual additions to production depends on the rate of increase in production, and ranges from 50 percent larger for rapid expansion of supply to an amount about equal to a stable annual production. To estimate the required rate of discovery and description of new reserves, the assumption was made that a 15-year reserve would be in place before production from new reserves begins.

For the conservative supply forecast, the current reserves are adequate for the forward requirements, based on the S.M. Stoller Corporation criteria, and new reserves can be described at a pace about equal to annual production. Cumulative new reserves of about 0.6 million short tons of U_3O_8 would have to be delineated by the year 2000 and 1.9 million short tons by 2025. The cumulative new reserves delineated by 2025 would be 60 percent of the currently known potential resources of 3.2 million tons; the remaining potential resources could sustain the reserves delineation at the pace of about 60,000 short tons U_3O_8 /year in the year 2025 for approximately another two decades.

For the optimistic supply forecast, it would be necessary to delineate about 1.0 million short tons of new recoverable U_3O_8 reserves by the year 2000 and 2.8 million short tons by the year 2025. The cumulative requirement for new reserves delineation through 2025 would be about 90 percent of the potential

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resources presently estimated by the Department of Energy; the remaining potential resources could sustain the delineation of reserves at the pace of 77,000 short tons/year in 2025 for approximately another 5 years.

Uranium Exploration Effort - Drilling

Additions to the present uranium reserves depend on the future trend in the discovery of new ore bodies, principally through exploratory drilling. Exploration yields have declined since the 1950's; during the 1950's the yield averaged 10 pounds of U_3O_8 per foot of exploratory drilling. This has declined to 3 to 4 pounds per foot or less in recent years. This decline is partially explained by the fact that earlier discoveries of ore bodies were near ground surface and were found from surface outcroppings. In the past decade, deeper drilling has been required; the average drill depth in 1977 was 430 feet, but 25 percent of the holes were deeper than 1,000 feet. Unless larger or richer ore bodies are found at the greater depths, which has not occurred to date, more drilling will be required per pound of uranium discovered.

In 1977 and 1978, about 47 million feet of drilling occurred. To achieve the optimistic supply forecast, the number of feet drilled annually must be about 25 percent greater than the 1978 level by the year 2000 and be 65 percent greater by 2025. This assumes that the discovery rate of U_3O_8 declines from the current 3.5 pounds per foot drilled to 2.0 pounds per foot. For the conservative supply forecast, using the same discovery rate assumption, the 1978 drilling rate is about adequate through 2000, but must be 30 percent greater in 2025. The required drilling rate is inversely related to the actual discovery rate; that is, the higher the discovery rate the lower the drilling rate required on a proportionate basis.

Drilling activity nearly quadrupled in the two decades between 1957 and 1977. Considering the industry's past performance, the projected expansions of drilling appear technically achievable but could be constrained by cost and access to favorable land areas.

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Forecast of Domestic Uranium Ore Mining and Milling

In the 1950's the average grade of uranium ore mined and processed was about 0.30 percent (6 pounds of U_3O_8 per short ton of ore). By 1978 the average grade of ore had declined more than half to 0.13 percent. Thus twice as much ore per unit of U_3O_8 produced is needed now as in the 1950's. This is attributable to the fact that low-grade portions of an ore body were bypassed in many cases, and now that the higher-grade portions have been depleted and prices have increased, remaining lower-grade portions are being mined. Additionally, greater use of surface mining has permitted economic mining of the lower grade ores. The trend to new surface mines is now starting to decrease, however, as ore deposits are being consumed faster than new surface-minable discoveries. This state of affairs may reverse as prices increase even further, making it economic to mine even lower grade ore.

For the optimistic supply forecast, the 1980 annual mined ore requirement of 10 million short tons would grow at a very substantial rate to 65 million short tons by the year 2000, a compound annual growth rate slightly less than 10 percent per year. This assumes a decline in ore grade from 0.13 percent to 0.09 percent. Ore requirements would increase to 80 million short tons/year by 2025 if the ore grade remained at 0.09 percent, and to 145 million short tons/year if the grade decreases further to 0.05 percent.

For the conservative supply forecast, production requirements by the year 2000 would represent a more modest, but still significant, increase to 45 million short tons, a production figure more consistent with present industry expansion trends. A growth rate in mined ore to about 62 million short tons would occur by 2025 if the ore grade remained at 0.09 percent.

An increase in ore production must be accompanied by similar expansions of milling capacity. In 1978, expansion of milling capacity was about 3 million short tons per year ore throughput compared to 1 million short tons a year in 1977. The milling capacity at the end of 1978 was about 15.8 million short tons per year throughput, an increase of about 23 percent from 1977. For the optimistic supply forecast, milling capacity would have to expand at an average rate of about 2.4 million short tons per year between 1979 and 2000; additions of 0.6 to 3.2 million short tons per year would be needed during the period 2000 to 2025, depending on the ore-grade assumptions described previously. For the conservative supply forecast, capacity would have to be added

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at the rate of 1.4 million short tons per year from 1979 to 2000, assuming a decline in ore grade from 0.13 percent to 0.09 percent. From the year 2000 to 2025, annual average additions would need to be only about 0.7 million short tons/year if ore grade remained constant at 0.09 percent. These expansion rates appear realistic, based on past experience.

Forecast of Manpower Needs

The labor categories most apt to be in short supply are underground miners and mining professionals (mining, chemical, and safety engineers), thereby placing a limitation on further expansion of production. For the optimistic supply forecast, the number of miners would increase from 3,200 in 1977 to 39,000 in 2000; a further increase would be needed to between 48,000 and 108,000 by the year 2025, the range depending on the productivity of the miners and the grade of ore assumed. These very large increases would be difficult to achieve. The increases for the conservative supply forecast to 27,000 miners in the year 2000 and 37,000 in 2025, while still substantial, appear to be more achievable. Similarly, there may be difficulties in expanding the professional manpower needed for the optimistic supply forecast. The current manpower level of about 800 would have to grow to 5,900 by the year 2000, an increase of 730 percent, and reach a level between 7,300 and 15,000 by 2025, an increase of 900 to 1,800 percent from the 1977 level. This problem is compounded by the increasing need for supporting personnel to ensure compliance with safety and environmental regulations. For the conservative supply forecast, the number of professionals would grow to 4,100 in the year 2000 and to 5,000 in 2025. These increases, again substantial, appear to be achievable.

It is obvious that extensive efforts will be needed to expand the mining work force. The Department of Energy-Division of Resource Assessment Operations believes this expansion is achievable, given sufficient time to attract and train the work force and stable employment conditions. The need to expand the mining work force and maintain productivity nevertheless appear to be significant uncertainties with a direct effect on the ability to expand output.

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Summary of High-Grade Production Capability

Production capability estimates range from the demand-related estimates of the Stoller Corporation at one extreme to the Department of Energy-Resource Assessment Operations maximum-capability estimates at the other. The low range of supply estimated by the S.M. Stoller Corporation, which is appropriate for a median uranium demand, projects annual production of 42,000 to 48,000 short tons U_3O_8 in 2000 and 57,000 to 77,000 short tons in 2025. The Department of Energy-Resource Assessment Operations estimate, which is appropriate for a high uranium demand, projects a maximum range of production capability of 73,000 to 79,000 short tons U_3O_8 per year in the year 2000, 80,000 to 86,000 short tons in 2010, and a decline to 30,000 to 48,000 short tons in 2025; the timing of the peak production and the decline will depend on the actual production in the future from these high-grade resources. In using these projections, the Department of Energy-Resource Assessment Operations estimate should be used in assessing the potential for supply-demand imbalance in the post-2010 period because this estimate indicates that, given 25 to 30 years, the uranium industry could probably expand production about four times from today's level to reach 80,000 to 86,000 short tons U_3O_8 per year. The S.M. Stoller Corporation estimate should be used in the period before about 2010 because it better reflects the current trend in nuclear growth.

As a point of reference, 18,500 short tons U_3O_8 were produced in the United States in 1978 from a production capacity of about 20,000 short tons. Additional committed or planned production capacity could bring the total to about 25,000 short tons U_3O_8 in 1980, and nearly 40,000 short tons in 1985, according to Department of Energy projections. Other estimates suggest that plans for capacity additions are being adjusted to reflect decreased demand and will reach a more modest total of about 28,000 short tons U_3O_8 in 1985.

2.2.2 Supply Outlook From Low-Grade Uranium Resources

In addition to high-grade resources that have been estimated at forward costs up to \$50 per pound U_3O_8 (equivalent to a market price of about \$100 per pound) there are large low-grade and byproduct uranium resources (less than 250 parts U_3O_8 per million parts of ore). Some of these resources are extensions of high-grade conventional sandstone deposits or are contained in the mill tailings from previous production. Additional low-grade resources are known to exist in different types of geological deposits such as the

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Chattanooga shales, coals, and copper. Estimated quantities of these low-grade resources are summarized in Table 2. As shown earlier, current estimates of high-grade domestic production to date have been from high-grade resources, except for uranium produced in byproduct operations. As a result, there is little experience upon which to base supply and cost estimates for lower-grade uranium resources. The estimates given in the table do not imply that this uranium could or would be produced with current technology except at prices considerably higher than today's market price.

Table 2. U.S. Low-Grade Uranium Resources

Resource	Short Tons U_3O_8
Extensions of conventional deposits ^a	461,000
Phosphate byproduct uranium	300,000
Copper leach byproduct uranium	not available
Mill tailings	19,000
Chattanooga shale	5,000,000
Lignite coal ash	30,000
Seawater (world total)	5×10^9

^aWith U_3O_8 content more than 0.01% (January 1979 estimate)

Low-Grade Uranium Resources and Supply Outlooks

Conventional Low-Grade Deposits--Low-grade deposits occur either around higher-grade deposits or as separate entities. They have not previously been used as resources because of their high production costs. Department of Energy-Division of Resource Assessment Operations estimates of total material in deposits that exceed minimum mining thickness and contain at least 100 ppm U_3O_8 were made from drilling data supplied by uranium producers. The forward cost of producing this uranium is estimated at between \$50 and \$100 per pound U_3O_8 or a market price between \$100 and \$200 per pound. This

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cost practically eliminates economic incentive to produce uranium from these low-grade resources at the present time, and ore is not currently produced from them.

Phosphate Byproduct Uranium--Most marine phosphate deposits contain some uranium. The United States has large deposits of phosphate rock, up to 5 billion tons. Uranium is present in concentrations ranging from 50 to 200 ppm U_3O_8 (Reference 5). The uranium can be economically recovered from phosphate that is commercially processed to phosphoric acid, but not from other phosphate processes. Most of the U.S. phosphoric acid production is used to make fertilizers. Current U.S. production capacity is about 9.6 million short tons per year; production at this rate could yield about 4,200 short tons per year of U_3O_8 . A small part of this potential is actually recovered at three operating plants, but production will increase with completion of four additional uranium-recovery units now in the design or construction stage. A typical recovery facility is capable of producing 150 to 600 short tons of U_3O_8 per year at a cost of \$20 to \$25 per lb U_3O_8 , as part of a phosphoric acid production facility producing 0.3 to 1.4 million short tons of phosphoric acid per year. A study by Earth Sciences Incorporated for the Department of Energy-Grand Junction Office (Reference 6) concluded that with a price at \$40 per pound U_3O_8 , about 88 percent of the uranium in current U.S. phosphoric acid production could be recovered economically if the plants were large enough. The study also projected byproduct uranium recovery as constant or decreasing slightly after the year 2000, although the phosphoric acid production after 1985 was projected to be relatively constant or slightly expanded; this is a result of the depletion of higher uranium content phosphate deposits. An estimate by the Department of Energy - Division of Resource Assessment Operations for the INFCE Working Group 1 projected a maximum production rate of 7,000 short tons U_3O_8 per year in the year 2000 and 40,000 short tons U_3O_8 per year in 2025. These estimates were based on recovery of uranium from all phosphoric acid production and a 7 percent annual production growth rate. An environmental benefit may be realized from the removal of uranium from the phosphoric acid, because it would otherwise appear in fertilizers and would slightly increase population exposures from the uranium radioactive decay products.

Copper Byproduct Uranium--Certain copper ore deposits contain only a few parts per million of uranium, but a very large amount of such ore is mined. About one-sixth of the ore is treated to recover the copper by leaching with acid. The uranium could in some cases be economically recovered from the leach solution as a byproduct.

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Table 3. Potential Supply From Low-Grade Uranium Resources

Resource	Range in Annual Production Short Tons U_3O_8	
	Year 2000	Year 2025
Conventional-type deposits ^a	0	b
Phosphate byproduct uranium ^c	5,000 to 7,000	5,000 to 40,000
Copper leach byproduct uranium ^c	500 to 1,500	1,000 to 3,000
Mill Tailings ^c	1,000 to 1,500	0
Chattanooga shale byproduct uranium	0 to 3,000 ^d	5,000 to 35,000 ^d
Coal	0	0
Seawater	0	0
Totals	7,000 to 13,000 (rounded)	11,000 to 78,000

^aWith U_3O_8 costs > \$50 but < \$100/lb

^bEstimate not available

^cThese sources are presently viable and yield limited amounts of U_3O_8 at today's prices

^dMaximum production estimate by DOE-RA for long-range projection used in INFCE Working Group 1

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One production facility is currently in operation in Utah, and others are under study. Production cost is not well defined but appears to be less than \$30 per pound U_3O_8 . The Department of Energy-Resource Assessment Operations estimates that about 20,000 short tons U_3O_8 might ultimately be recoverable by this means through the year 2000. This assessment assumed 1,000 short tons U_3O_8 per year in 2000 with an uncertainty of ± 50 percent; the production rate in the year 2025 was assumed to be double the production of 2000 as a result of increased copper production.

Mill Tailings--During the processing of uranium ores, a portion of the uranium contained therein is not recovered and is left in the mill tailings piles. Some of the early processing plants had lower uranium recovery efficiency than do newer plants. As uranium prices increase and technology improves further, there will be an economic incentive to reprocess such tailings to recover an additional portion of the uranium, and to operate the mills at increased recovery efficiency.

At the beginning of 1977, an estimated 19,000 short tons of U_3O_8 was contained in mill tailings. This quantity is expected to grow with future operations. In view of the uranium grades and metallurgical characteristics of these tailings it is estimated that only 35 to 40 percent of the uranium content could be recovered. Estimated cost of recovery for this material is \$60 per pound. Two plants are already processing tailings, and other tailing piles are under study for future recovery operations. Annual production of 1,000 to 2,000 short tons has been assumed in this analysis to be reached in the late 1990's and to continue through 2010, when the last of the current mill tailings stockpiles will have been reworked.

Chattanooga Shale--The Chattanooga shale in Tennessee is the major potential source of uranium shale in the United States. A large portion of the uranium-bearing shale contains an average of 60 ppm uranium. About 4 million tons of U_3O_8 are contained in shales that are sufficiently defined to be classed as reserves, and another 1 million tons of potential resources are estimated to be contained in shale associated with these reserves.

A recent study (Reference 7) for the Department of Energy focused on the economics and feasibility of producing uranium from Chattanooga shale. The study indicates that uranium could be produced economically at a price of \$50

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to \$100 per lb U_3O_8 as a byproduct of shale-oil recovery with oil priced at \$18 per barrel or higher; if the U_3O_8 were produced as the sole product the price would increase to \$180 to \$260 per lb U_3O_8 . There are three major obstacles to overcome if uranium is to be recovered from Chattanooga shale: (1) the environmental and social impacts of large mining and milling operations, (2) the need to dispose of large amounts of waste since about 15 tons of Chattanooga shale would have to be mined to produce 1 pound of U_3O_8 compared to 1/3 ton per pound of U_3O_8 for the high-grade ore mined today, and (3) the uncertainty of attractive financial return from the multi-billion dollar investment. About 0.8 ton of waste tailings would be produced for each ton of shale feed; 70 percent of the waste tailings could be back-filled into the mine excavation. The remaining 30 percent would require surface disposal because the volume of the tailings is greater than the shale feed. A capital investment of more than \$2 billion would be needed to obtain about 50,000 barrels per day of oil and 1,200 tons per year of U_3O_8 from 100,000 short tons per day of shale. Because solid waste disposal requirements under the Resource Conservation and Recovery Act of 1978 have not yet been confirmed, these costs should be viewed as optimistic. In addition, a large infrastructure, work force, and supplier organization would be required for such operations. Given the scale of such operations, the environmental impact of mining, processing, and waste disposal for such large quantities of material would have to be carefully investigated and planned for. Implementation of such a project would take many years, and would not take place until such time as adequate shale oil prices and environmental costs are perceived and assured. The current outlook for technology, economics, and leadtime make it unlikely that much, if any, uranium production from shales could be expected before 2000.

The Department of Energy-Division of Resource Assessment Operations estimated for INFCE Working Group 1 that an accelerated development of Chattanooga shale could result in production of about 2,400 short tons U_3O_8 from two plants in the year 2000 and 35,000 short tons U_3O_8 from 29 plants in 2025. A delayed scenario was also considered, resulting in 1,200 short tons from one plant in 2000 and 29,000 short tons from 24 plants in 2025. In this report an even more delayed scenario was used, because of the major uncertainties associated with completing the development needed for large-scale plants and overcoming the institutional requirements for mitigating environmental impacts. This lower estimate assumes that the first large shale plant comes online in 2005 after a development and demonstration period beginning in the early 1980's. A production of 5,000 tons U_3O_8 annually is forecast from four plants in 2025.

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Coals--The coals now used in steam-generating plants contain only about 1 ppm uranium and are not feasible sources of uranium. Certain deposits of coal, however, particularly some of the thinner lignitic beds in the western United States, contain higher concentrations of uranium. U_3O_8 could possibly be recovered directly from the lignite or from ash after burning. These uraniferous coals have higher ash contents and much lower heating values than nonuranium-bearing coals, which detracts from their attractiveness as fuels. For this reason, and because of the greater availability of better-quality coal, very little uranium-rich lignite ash is expected to become available for uranium recovery through the year 2025.

Seawater--The oceans and seas of the world contain a virtually inexhaustible source of uranium. The concentration, however, is slight - 0.003 ppm - and enormous volumes of seawater would have to be treated to obtain useful quantities of uranium. A recent study by the Exxon Nuclear Company for the Department of Energy estimated that 0.5×10^9 cubic meters per day (about 0.1 cubic mile per day) of seawater would have to be treated to produce 550 short tons of U_3O_8 per year. The Exxon study assumed a 70 percent uranium absorption efficiency, and a plant capital cost of \$6.2 billion. The resulting cost of the U_3O_8 product was \$600 to \$3,600 per pound. Other studies at the Massachusetts Institute of Technology and by the Japanese Atomic Energy Agency estimate costs as low as \$300 per pound U_3O_8 . The research is at an early stage, the engineering difficulties are very formidable, and costs are likely to be extremely high. For this reason, no U_3O_8 production from seawater is forecast for this analysis.

Summary of Low-Grade Supply

The potential for supplying uranium from low-grade resources is estimated at between 7,000 and 13,000 short tons of U_3O_8 annually by the year 2000, and between 11,000 and 78,000 short tons U_3O_8 annually by the year 2025. As a point of comparison, total U.S. installed capacity, including plants under construction, and being designed for recovery of uranium from low-grade resources, was about 2,500 short tons U_3O_8 in 1978. In terms of total estimated low-grade reserves, production rates are expected to be modest, but production is highly dependent on strong market price incentives to attract the necessary investments. Actual supply will probably be limited by economics, Government regulations, and available manpower, much as in the high-grade uranium case. The supply-price outlook is that uranium will probably

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not be produced before the year 2025 as a primary product from phosphate or Chattanooga shale, but as a byproduct limited by the demand for primary products such as phosphoric acid and shale oil.

2.2.3 Institutional Considerations

Expansion of uranium supply is affected by institutional considerations as well as by technical factors. Some of these are analyzed below.

Market Conditions

The market outlook at present is that the expected growth in future uranium requirements will be substantially reduced from that estimated 2 or 3 years ago. Delays and cancellations of nuclear projects by utilities, which reflect basic uncertainties in the long-term nuclear future and electric energy demand, have been further compounded by the Three Mile Island accident. These uncertainties will affect industry's plans for exploration and resource development, particularly if uranium prices decline.

The history of the uranium market has been characterized by instability, as illustrated by the price history in Table 4. From 1948 to 1958, the Government-guaranteed purchases at attractive prices led to vigorous expansion of uranium supplies. This program was phased out starting in 1958, with fewer purchases made through 1970. Lacking an equivalent commercial market, the result was a price decline to a level barely sufficient to cover costs. Despite large commitments to nuclear power plants beginning in 1967, the utilities delayed purchases of uranium, and the market price of uranium remained low until 1973. From 1973 to 1976, prices quadrupled as a result of utility purchases to cover needs and attempts by a reactor manufacturer to cover speculative selling not backed by firm supply sources.

Before 1970, uranium price was almost exclusively set by contract price with some provision for inflation. By 1974, price was largely set by floor price or current market price at time of delivery. By 1976, most new contracts involved utility financing, often keyed to new mine/mill ventures and linkage to future market price.

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Table 4. Uranium Price History Summary

	Actual	$\$/\text{lb } \text{U}_3\text{O}_8$ Value in 1979 \$
Government supported prices average, 1948 to 1970	9.21	21
Government price, 1969 to 1970	5.77	10
Utility price, 1968 to 1972	6 to 7	10
1976 price	40	47
1979 price	43	43
Average delivered price, 1977	19.75	21

Since 1977, the deferrals and cancellations of nuclear projects, coupled with more flexible Government enrichment contracts that permit delay in product delivery, have led to gradual downward drift in price. The present average price is only about twice the former Government average price in 1979 dollars, which seems reasonable considering that the grade of the ore has decreased about 50 percent (from 0.3 percent in 1950 to 0.13 percent today) and that costs to meet new safety and environmental standards are much higher. Another factor, illustrated in Table 4, is that present delivered prices are considerably lower than present contract prices because deliveries are generally made under old contracts. This low price has a negative impact on industry profits and their ability to finance expansion.

Federal Trade Commission (FTC) data for 1965 to 1975 show that the average annual pretax return on assets in the uranium mining and milling industry was 5.6 percent, far below the normal yield of mining and energy companies. This gap has been narrowing slightly since 1975 because of higher uranium prices, but still exists. The relatively low profitability is the result of several historical factors: profits were depressed in the early 1970's when operations were at 60 percent capacity, and have not yet fully recovered; the current price is low because it is delivered under old contracts; costs have increased faster than price adjustments on set-price contracts; and disproportionately high expenditures have been required for exploration and plant expansions in relation to production. Present exploration and plant expansion activity is the result of the 1973-76 price rise and the perception of

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the future market that existed when commitments were made for exploration expansion. Also, there is competition for exploration funds for oil and gas exploration within some companies, and the perception of market and profit potential will govern future decisions. Thus, while there is strong industrial base for future expansion, if the market turns bleak, retrenchment could occur at a rapid pace.

Industry Structure and Outlook

The beginnings of the uranium industry were characterized by many small to moderate-sized producers and independent mining ventures. With the formation of partnerships and the entry of larger organizations, especially metal production and oil companies, into the uranium industry, the present structure is characterized by relatively few integrated producers. The current structure of the industry, and that projected for 1985, is shown in Table 5. As can be seen, the structure of the industry is expected to be fairly stable through the mid-1980's.

In addition to those companies accounted for in Table 5 there are a dozen more involved in the production of small amounts of uranium from unconventional resources (byproduct uranium, solution mining, etc.) and about 40 utilities have entered partnerships with producers. One utility has taken over a producing company so that it effectively supplies its own uranium needs.

Table 5. Industry Production Distribution

<u>Year</u>	<u>Number of Companies Accounting for Production from High Grade Resources</u>		
Percentage of Production	<u>50</u>	<u>75</u>	<u>100</u>
1977	4	7	19
1985	5	11	23

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Regulatory Constraints

There are increasingly significant regulatory constraints on uranium supply expansion. Exploration is hindered or prevented by the closure of some Federal, State, and Indian lands to exploration or development. Recent Federal actions to suspend exploration on Bureau of Land Management land in Alaska and other States in order to inventory wilderness areas provide a good illustration of the problem. The distribution of \$30 per pound U_3O_8 forward cost resource ownership is shown in Table 6.

Table 6. Distribution of \$30/lb U_3O_8 Resource Ownership

<u>Location</u>	<u>Reserves</u>	<u>Potential Resources</u>	<u>Total</u>
Federal Lands	59%	40%	47%
State Lands	11	15	15
Indian Lands	3	6	5
Private Lands	27	35	33
Other Lands	0	4	0

Other regulatory constraints include overlapping Federal, State, and local jurisdictions; lengthening times for permits and licenses; regulations for mill tailings; and requirements of the National Environmental Policy Act (NEPA) and its counterpart in the various States.

Imports

Present Federal policy will eliminate existing import restrictions on a phased basis by 1984. Commitments for future net imports as of January 1, 1978, totaled about 30,000 short tons U_3O_8 through 1990 at an average rate of about 2,500 short tons per year. This represents about 6 to 7 percent of the median demand during the period. There is potential for substantial future

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near-term imports, principally from Canada and Australia. If these foreign supplies were to be vigorously exported to the United States during the next 10 to 20 years, there is the possibility that marginal, high-cost domestic producers might cease production. Foreign governments have generally been reluctant to allow their exports to undersell U.S. domestic production. Beyond the year 2000, however, the present foreign supply-demand outlook does not indicate that a large percentage of U.S. demand will be filled by imports.

2.2.4 Estimates of Total U_3O_8 Supply Used in the NASAP Analysis

The two ranges of total U_3O_8 supply considered in the NASAP analysis are detailed in Table 7 and are summarized in Figure 2. These ranges are compared with demand scenarios described in Chapter 3 of this report to evaluate possible supply-demand imbalances. The lower band in Figure 2 illustrates the range of the Stoller Corporation estimates of production capability of high-grade and NASAP low-grade resources. The upper band in Figure 2 shows a range of Department of Energy-Resource Assessment operating estimates. The dashed lower line illustrates the Department of Energy-Resource Assessment Administration estimates of maximum production capability from high-grade resources. The middle line shows the Department of Energy-Resource Assessment Administration estimates of total high- and low-grade resources under a low-resource delayed case, while the upper line shows the Department of Energy-Resource Assessment Administration estimates of total high- and low-grade resources under a high-resource accelerated case.

The supply source in the Department of Energy-Resource Assessment Administration forecast of potential production capability would be mainly from high-grade resources through about 2010 and thereafter would come increasingly from phosphate production and Chattanooga shale, which would together furnish 60 percent of annual supply by 2025 in the upper level of the Department of Energy forecast. As discussed previously, the timing of the decline in production from high-grade resources will depend on actual production to meet demand. The lower level of the Department of Energy forecast derives 40 percent of the supply in 2025 from low-grade resources. This dependence on low-grade resources, which are economically producible only as byproducts of phosphate production or Chattanooga shale oil production, creates a great deal of uncertainty about the ability to actually achieve these levels of production.

Table 7. U.S. Uranium Supply Outlook

	<u>2000</u>	<u>2025</u>	<u>2000</u>	<u>2025</u>
<u>High-grade Resource Supply</u>	<u>SMSC</u>		<u>DOE-RA</u>	
Annual, thousand tons U_3O_8	42 ^a to 60 ^b	57 ^a to 77 ^b	73 ^c to 79 ^d (peak of 86,000 in 2010)	30 ^c to 48 ^d
<u>Low-grade Resource Supply</u>	<u>NASAP</u>		<u>DOE-RA</u>	
Phosphate byproduct	5	5	7	15 to 40
Chattanooga shale byproduct	0	5	0 to 3	29 to 35
Other	<u>2</u>	<u>1</u>	<u>0^e</u>	<u>0</u>
Total low-grade production, annual thousand tons U_3O_8	7	11	9 ^c to 13 ^d	45 ^c to 78 ^d
<u>Total Annual Supply (Rounded)</u>				
Thousand tons U_3O_8	50 ^a to 65 ^b	70 ^a to 90 ^b	80 ^c to 90 ^d	75 ^c to 125 ^d

^aConservative estimate^bOptimistic estimate^cLow resource base-delayed development^dHigh resource base-accelerated development

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Figure 2. Total Annual U_3O_8 Supply Capability Estimates

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The range of the high-grade resources estimated by the S.M. Stoller Corporation combined with the NASAP estimate of low-grade resources was used for a lower range of the estimate.

2.2.5 The Department of Energy Stockpile

The estimates used in the NASAP report include only those available from commercial sources. In addition to these sources, the Department of Energy maintains inventories of natural and enriched uranium which are used as operating stocks for enrichment plants and as stockpiles of enriched product for future needs. In addition to this resource, there is a stockpile of over 250,000 tons of depleted uranium at various U-235 assays from the enrichment plant tails. Some enriched uranium has been accumulated as "preproduction," that is, production to meet future needs. This policy of preproducing enrichment has been adopted to more fully utilize the existing enrichment-plant capacity and to delay the addition of new capacity. It is currently planned to operate the Department of Energy enrichment capacity in such a manner that all excess U.S. Government-owned natural uranium inventories are used by the mid-1990's. In addition, it is planned to reduce the enriched uranium inventory to a steady state level which would contain 14 million separative work units. This inventory includes 5 million separative work units which could be available for international fuel assurance purposes. This amount of enriched uranium would be the equivalent of 10,200 short tons of natural U_3O_8 and would be sufficient to fuel about 50 GW-years of standard light-water reactor reload requirements.

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3. COMPARISON OF U.S. URANIUM DEMANDS WITH U.S. PRODUCTION CAPABILITY FORECASTS

3.1 INTRODUCTION

This chapter compares the uranium requirements for several potential evolutions of the U.S. nuclear power system with uranium production capability forecasts. The purpose is to indicate when and under what conditions of energy demand, uranium supply and technology implementation imbalances between uranium supply and demand might occur. These possible evolutions of the nuclear power system represent potential changes in nuclear technology and the introduction of new reactors and fuel cycles. (This type of analysis, which is based on possible courses of events or scenarios, is referred to as scenario analysis.) For each scenario, the demands for uranium, separative work, spent-fuel storage, reprocessing, thorium, and heavy water were calculated, as well as plutonium and U-233 inventories. The demands for thorium, heavy water, and fuel cycle services are discussed in Chapter 5. Details of nuclear system calculations are reported in Reference 8. Characteristics of individual reactors and fuel cycles are summarized in the Appendix of this volume and are reported in more detail in Volume IX.

This analysis compares today's estimate of future annual demands with today's estimate of future annual production and, where appropriate, cumulative consumption with cumulative production capability. Wide ranges of supply and demand are considered because of large uncertainties. The analysis recognizes that the important issues are the timing and effort required to expand uranium production, although the comparison of cumulative consumption with today's knowledge of resources is also an important indicator of the ability to sustain supply over the long term. The analysis further recognizes that, ultimately, supply potential is a function of price and that the amount of uranium produced will be determined by economic factors. Furthermore, over the long term, supply and demand are always in balance. Either additional supplies would be brought about by much higher prices, or demand would be reduced, or a combination of both would take place. Additionally, other technologies might be introduced to meet the demand for energy. The term "supply/demand imbalance" used in the subsequent discussion is a short-hand term for short-term conditions, fully recognizing that in the strict sense the term does not actually represent long-term situations.

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The analyses begin with a consideration of various reactor types on the once-through fuel cycle, comparing resource utilization and various technical improvements to reactors under that regime. Light-water reactors are considered first, followed by fuel utilization improvements to the light-water reactor and then advanced converters. These same reactor types, together with alternative reactors and advanced concepts, are then compared under a recycle regime. This approach was chosen because it better identifies the decision-points along the once-through/recycle continuum, and indicates when pressures to begin recycle might occur. This approach is also consistent with the NASAP conclusion that no alternative which could be deployed in the next few decades offers more proliferation resistance than the light-water reactor on the once-through cycle, provided that the enrichment process and spent-fuel facilities are adequately controlled.

3.2 ONCE-THROUGH FUEL CYCLES, INTERIM STORAGE OF SPENT FUEL

3.2.1 Continuation of the Present System of Light-Water Reactors

The first scenario, which analyzed a continuation of the present system of light-water reactors operating on the once-through fuel cycle, made two assumptions. First, no changes will be made in fuel-utilization performance. Second, enrichment plants will continue to operate at a tails assay of 0.20 percent U-235. The requirements for U_3O_8 resulting from this scenario were calculated for the three nuclear-growth projections made in January 1978 by the Department of Energy.

Since the January 1978 nuclear growth projections were made, a substantial reduction in expected nuclear growth through the year 2000 has occurred. The Department of Energy - Energy Information Administration Report to Congress (Ref. 15) in July 1979 contained a new set of projections which are compared in Table 8 with the January 1978 forecast.

The January 1979 revision of nuclear growth projections by the Energy Information Administration extends to the year 2000. The preliminary information upon which the post-2000 forecast in Table 9 is based was made by extending the mid-range total energy forecast, while assuming limits on the capabilities of non-nuclear alternatives to meet electrical energy demand and the

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Table 8. Installed Nuclear Capacity Projections

Installed Capacity Year's End, GW	January 1978 Projection			January 1979 Projection		
	High	Median ^a	Low	High	Median	Low
1980	66	64	62	66	63	60
1985	122	111	100	118	110	102
1990	192	175	157	171	157	142
1995	275	238	200	225	206	186
2000	395	325	255	300	260	235
2005	480	378	275	(375) ^b	(315)	(285)
2010	590	443	295	(455)	(375)	(340)
2015	690	498	305	(565)	(440)	(400)
2020	800	558	315	(675)	(510)	(460)
2025	910	615	320	(810)	(580)	(530)
Average Growth Rate, 2000 to 2025, GW/year	20.6	11.6	2.6	20.4	12.8	11.8

^a Average of high and low

^b Preliminary information in parentheses based on Energy Information Administration Long-Range Assessment Program for Series C and Mid-Range Energy Marketing Model

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continuation of nuclear power as the lowest cost option for large electrical power plants. There are major uncertainties which could lead to a continued reduction in nuclear growth below the values in the 1979 forecast shown in Table 8, or that could lead to the high growth projection. The uranium demands for the current light-water reactor once-through cycle system were calculated for the 1978 growth projection and the 1979 growth projection. These demands are compared in Figure 3. The results based on the 1978 high nuclear growth projection are included only to provide insight into the effects of a return to high nuclear growth in the post-2000 period; the post-2000 average growth rates for the 1978 and 1979 high projections are essentially equal. The calculations indicate that the 1978 median and low projections are representative of the 1979 forecast ranges, and this assessment emphasizes these results.

The uranium demands corresponding to the 1978 median and low nuclear growth projections are shown in Table 9 and are compared in Figure 4 with the uranium supply capability previously discussed in Section 2.2.4. With the 1978 median nuclear demand scenario, the largest estimated supply capability from both high- and low-grade resources, as estimated by the Department of Energy, would have to be achieved to meet demand through 2025. Considering the activities necessary for maximum production from both high- and low-grade resources, however, the supply-demand imbalance would probably occur sooner than 2025. The task of mining and milling the quantities of uranium required would be formidable. In particular, large-scale production from Chattanooga shale would be required beginning in the year 2000 or earlier, and would have to increase rapidly thereafter. If production from the shales were not achieved, and production were limited to maximum development of high-grade resources and modest production from low-grade by-product resources, a shortfall would be possible by 2015. The maximum development of high-grade resources is the most likely occurrence because an increase in demand would result in higher prices and induce a supply expansion which could use

Table 9. Annual U.S. U_3O_8 Requirements for the Present System of Light-Water Reactors on the Once-Through Fuel Cycle (thousands of short tons)

	<u>Year</u>					
<u>Nuclear Growth</u>	<u>1980</u>	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
1978 Low	15	32	48	56	60	62
1978 Median	16	37	64	88	110	121
1978 High	17	42	79	119	159	181

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Figure 3. Estimates of Annual U_3O_8 Demand Using the Current LWR on the Once-through Fuel Cycle Based on the DOE 1978 and 1979 Nuclear Growth Projections

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Figure 4. Comparison of U_3O_8 Supply Capability and Demand Using the Current LWR of the Once-Through Fuel Cycle

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well-established technology in order to produce from these resources. The likelihood that a large expansion from low-grade resources would take place might be limited by environmental impacts and technical problems.

The 1978 low nuclear demand scenario would not be constrained by uranium supply to any great extent, although even meeting this projected demand of 62,000 short tons U_3O_8 in 2025 would require a tripling of the current production rate. Since a uranium supply/demand problem for the 1978 low nuclear demand appears unlikely, this will receive limited further discussion.

As discussed above, the 1978 high nuclear growth projection through the year 2000 has a very low probability of occurring. However, if a high growth rate of 20 GW/year were to resume in the year 2000, a supply/demand imbalance might develop after 2010.

There is an inherent defect in the comparison of annual potential supply with annual demand. The actual annual supply will closely follow annual demand, except for accumulation of inventories in advance of need, which is neglected in this analysis. Ideally, the uranium production forecast should be closely matched with each demand forecast, but this approach was not feasible within the context of the NASAP work. Thus, the comparisons of supply and demand show large production capability surpluses in the early years which are not counted as available for later production, even though production capability from high-grade resources is declining in the high supply capability projection by the Department of Energy - Division of Resource Assessment Operations. In the high supply comparisons, this could lead to a date for the decline of production from high-grade resources that is too early and an overstatement of the need to rapidly expand production from low-grade resources. Comparisons with the low supply projections are not affected because production from high-grade resources would not decline through the year 2025.

To remedy this inaccuracy, the time at which a supply/demand imbalance would occur was defined as either the time when the demand would exceed the maximum production capability using high- and low-grade resources or the time when the cumulative demand exceeded cumulative production, whichever occurred last. This is not to imply that the U_3O_8 would be produced and stockpiled before needed, but that the uranium not needed and therefore not produced in early years would be available in the ground to sustain the peak production level from high-grade resources in later years.

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Thus, for the 1978 median nuclear demand scenario, the cumulative demand would begin to exceed the cumulative production from high-grade resources between 2015 and 2025, as illustrated in Table 10, and annual production from these sources would begin to decline in this period.

Table 10. Comparison of Cumulative Demand and Production Capability*
(thousand short tons U_3O_8)

Year	Cumulative Demand	Cumulative Production Capability
2010	1,630	1,810 to 1,910
2015	2,100	2,190 to 2,320
2020	2,630	2,500 to 2,670
2025	3,210	2,700 to 2,940

*1978 median nuclear growth and continuation of light-water reactor once-through fuel cycle is assumed.

Annual production from high-grade resources was estimated by the Department of Energy - Division of Resource Assessment Operations to reach a maximum of between 80,000 and 86,000 short tons U_3O_8 per year in the period between 2015 and 2025, since the high-grade resource production centers, as a whole, would not be depleted, and there would be adequate time (over 35 years) to expand production. (Figure 1 indicates that a minimum of about 25 years is needed to reach maximum production.) Annual demand in 2015 would be 99,000 short tons U_3O_8 , would increase to 110,000 short tons in 2020, and in 2025 would amount to 121,000 short tons. Therefore, annual supply from low-grade resources would have to reach at least 13,000 short tons U_3O_8 in 2015 and rise to over 35,000 short tons by 2025. Thus, a uranium shortfall is possible in about 2015 if production from low-grade resources is limited to about 13,000 short tons U_3O_8 , but could be delayed beyond 2025 if much higher production levels are achieved by such means as rapid expansion of supply from Chattanooga shales.

In summary, if a nuclear growth to about 300 GW in the year 2000 occurs and growth continues at a rate of 12 GW/year thereafter, a uranium supply/demand

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imbalance might occur as early as 2005 based on the S.M. Stoller maximum supply capability estimate and as late as 2025 based on the Department of Energy maximum estimate unless there were large-scale development of low-grade uranium resources. This further assumes that the present light-water reactors continue to operate on the once-through fuel cycle with current fuel-utilization efficiency and that enrichment plants operate at a tails assay of 0.20 percent U-235.

3.2.2 Improvement of Light-Water Reactor Fuel Utilization

Light-Water Reactor, Once-Through Cycle

A number of techniques have been proposed to improve the fuel utilization of light-water reactors operating on a once-through fuel cycle. These improvements can be grouped into changes to fuel design and management, and the reduction of enrichment plant tails assay. The technical details are described in Volume IX. Two levels of fuel design and management improvements were analyzed for this report:

- A 15 percent improvement in light-water reactor fuel utilization, available in 1990 and backfitted into all light-water reactors over the following decade.
- An additional 15 percent improvement in light-water reactor fuel utilization for a total of 30 percent improvement, introduced in all new plants beginning in the year 2000.

In addition to the fuel design and management improvements to the light-water reactors, three levels of enrichment plant tails assay were analyzed:

- The 0.20 percent U-235 tails assay that is currently used in enrichment plants.
- A 0.10 percent U-235 tails assay which would result in the lowest cost enriched uranium product if the U_3O_8 price reaches about \$160/lb and the cost of enrichment service is \$100/SWU; the reduction of tails assay from

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0.20 percent U-235 would reduce annual uranium requirements by about 13.4 percent and increase separative work requirements by 39 percent. This could be achieved with current gaseous-diffusion or gas-centrifuge technology.

- A 0.05 percent U-235 tail assay which would result in the lowest cost enriched uranium product if the enrichment services charge were \$40 per separative work unit and the U_3O_8 price were \$100/lb; some advanced isotope-separation techniques show promise of a \$40 per separative work unit charge. The reduction of tails assay from 0.20 percent separative work U-235 to 0.05 percent would reduce annual uranium requirements by 18.6 percent and increase separative work by 82 percent. The advanced isotope separation techniques are assumed to be introduced over a 10-year period beginning in 2000 to include all enrichment plant feed.

The U_3O_8 requirements for improved light-water reactors are presented in Table 11 for three enrichment plant tails assays.

Light-Water Reactor, 15 Percent Improved

For the 1978 median growth projection, a supply/demand imbalance appears possible late in the first quarter of the next century, even with implementation (beginning in 1990) of a 15 percent improvement in fuel utilization of light-water reactors as indicated in Figure 5. Such an imbalance could be avoided only with production from low-grade resources. If the gross nuclear capacity increased at about 12 GW/yr to 580 GW in 2025, the annual uranium demand would reach 98,000 short tons U_3O_8 , and this demand would require maximum production from high-grade resources and moderate production from low-grade resources (10,000 to 15,000 short tons U_3O_8 /year). However, production from the Chattanooga shales probably would not be required until after 2025. A 13 percent reduction in U_3O_8 requirements to about 83,000 short tons U_3O_8 would delay the need for production from shales by about 5 to 10 years and could be achieved by reducing enrichment tails assay to 0.10 percent U-235 and the construction of 40 percent more enrichment capacity.

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Table 11. Annual U.S. U_{308} Requirements for the Light-Water Reactor
on the Once-Through Fuel Cycle (thousands of short tons)

	Nuclear Growth					
	1978 Low			1978 Median		
	2000	Year 2010	2025	2000	Year 2010	2025
- No Improvement - 0.20% Tails	48	56	62	64	88	121
-15% Improvement - 0.20% Tails	41	48	52	54	75	103
- 0.10% Tails				47	65	
- 0.05% Tails*				44	61	84
-30% Improvement - 0.20% Tails	41	45	44	54	69	88
- 0.10% Tails				47	60	76
- 0.05% Tails*				44	56	72

*Reduced from 0.10 percent to 0.05 percent over period 2000 to 2010 for 10 percent of feed/yr.

If a high growth rate (20 GW/yr) were resumed in the year 2000, the full implementation of the 15 percent improvements in light-water reactor fuel utilization, a reduction in enrichment plant tails assay to 0.10 percent U-235, and maximum production from high-grade resources with rapid development of low-grade resources would be required. Large-scale production from Chattanooga shale would not be required until after the year 2015.

The 1978 low demand scenario is shown in Figure 5 to indicate that the 1979 median demand through the year 2000 is slightly higher; a uranium supply/demand imbalance would not occur with the 15 percent-improved light-water reactors, even with the lowest supply capability projection, if the 1979 nuclear growth trend were to continue. The low nuclear growth cases do not present a uranium-supply problem.

Figure 5. Comparison of U_3O_8 Supply Capability and Demand Using the 15% Improved LWR on the Once-Through Fuel Cycle

Light-Water Reactor, 30 Percent Improved

An additional 15 percent reduction in uranium requirements, bringing total fuel utilization improvements to 30 percent, might be implemented in the year 2000 and used in all new light-water reactors by 2010.

As shown in Figure 6, the 1978 median demand projection is not likely to result in a uranium shortfall until after 2025. If reduction of tails assay to 0.05 percent U-235 using advanced isotope-separation techniques were also successful, a supply/demand imbalance before 2025 is even less likely. However, this tails assay reduction would require about 82 percent more enrichment capacity than is required with 0.20 percent U-235 tails. If the post-2000 nuclear growth rate were 12 GW/year and the enrichment plant tails assay were reduced to 0.10 percent U-235, uranium supply would be adequate through 2025. Should high nuclear growth of about 20 GW/yr resume in the year 2000, a uranium supply/demand imbalance might be avoided through the year 2025 with maximum production from high-grade resources (about 80,000 to 85,000 short tons U_3O_8 /year), modest production from low-grade resources (about 10,000 to 15,000 short tons U_3O_8 /year) and a tails assay reduction to 0.05 percent U-235. If a tails assay reduction of only 0.10 percent U-235 were possible, then another 5,000 short tons U_3O_8 /year would have to be produced from low-grade resources.

In summary, if the 30 percent reduction in light-water reactor fuel requirements is successfully implemented and is coupled with a reduction in enrichment plant tails assay to 0.10 percent, the uranium requirement for a median growth rate of about 12 GW/yr in the post-2000 period could be met through 2025. The uranium requirements for a high-growth rate of 20 GW/yr beginning in the year 2000 could be met with maximum development of high-grade resources, moderate development of low-grade resources, and successful development of advanced isotope separation techniques to achieve a reduction of tails assay to 0.05 percent U-235. Even with these developments, however, a shortfall might occur soon after 2025 if high nuclear growth continued.

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Figure 6. Comparison of U_3O_8 Supply Capability and Demand Using the 30% Improved LWR on the Once-Through Fuel Cycle

3.2.3 Advanced Converter Reactors

Advanced converter reactors, such as the heavy-water reactor and the high-temperature gas-cooled reactor, use uranium more efficiently than the current light-water reactor on the once-through fuel cycle; an individual heavy-water reactor uses 42 percent, and a high-temperature gas-cooled reactor uses 30 percent less uranium over a 30-year operating lifetime. The effect of any individual reactor on the uranium consumption of the total nuclear system, however, is dependent on its ability to penetrate the market. For this analysis, it is assumed the advanced converter reactor would be introduced in 2003, and would capture an increasing fraction of capacity additions plus replacements each year thereafter, but not all new capacity additions plus replacements until about 30 years after its introduction. The annual U_3O_8 requirements for the nuclear systems into which advanced converter reactors have been introduced with these assumptions are presented in Table 12 for the 1978 median nuclear growth and an enrichment plant tails assay of 0.20 percent U-235. The introduction of advanced converters on the once-through cycle following a 15 percent improvement in light-water reactor fuel utilization would reduce uranium demand by about 10 percent, as shown in Figure 7. This alternative would not be as effective as the potential 15 percent further improvements to the light-water reactor.

Table 12. Annual U.S. U_3O_8 Requirements for Systems Containing Advanced Converters on the Once-Through Fuel Cycle*
(thousands of short tons)

Reactor	Year		
	2000	2010	2025
Heavy-water reactor	54	74	91
High-temperature gas-cooled reactor	54	74	94
Light-water reactor-15% improved	54	75	103
Light-water reactor-30% improved	54	69	88

*1978 median nuclear growth; 0.20 percent tails assay.

Figure 7. Comparison of U_3O_8 Supply Capability and Demand Using the Introduction of Advanced Converters into a System of 15%-Improved LWR's on the Once-Through Cycle

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3.3 RECYCLE

3.3.1 Light-Water Reactor, Recycle

The uranium requirements of an individual light-water reactor, with fuel utilization improvements which reduce its uranium requirements by 15 percent on the once-through cycle, would decrease by 21 percent if its spent fuel were reprocessed and the recovered uranium and plutonium were recycled (i.e., "self-generated recycle"). When compared to current light-water reactor once-through cycle fuel utilization, this represents a reduction in uranium requirements of 33 percent. The rate at which this reduction is realized by the nuclear system is, however, dependent upon the availability of reprocessing capacity. Since the effect of recycle can be realized by all operating reactors, it can be considered a retrofittable improvement.

Recycle of spent fuel has not occurred in the United States for a variety of technical, economic, and political reasons, although the technology has been developed for large-scale reprocessing plants. The current U.S. policy is to defer commercial reprocessing. If this policy were changed and the economics were attractive, reprocessing and recycle might begin about 1990 if the Allied General Nuclear Services plant is used and major design changes are not required. In this analysis, reprocessing was assumed to begin in 1990, and reprocessing capacity is limited to the designed capacity of 1,500 tons/year for the following 10 years. Additional reprocessing capacity is assumed to be added during the next decade, until all light-water reactors operate with self-generated recycle by the year 2010.

The annual U_{308} requirements for a system of 15 percent improved light-water reactors in which self-generated recycle is initiated are summarized in Table 13 and compared with the requirements for once-through light-water reactors. The 1978 median nuclear growth and an enrichment plant tails assay of 0.20 percent U-235 were assumed in all cases.

These annual U_{308} requirements are also compared in Figure 8. The annual U_{308} demand for the recycle system is about 21 percent lower than the once-through system with a 15 percent improvement and 7 percent lower than the 30 percent improved once-through light-water reactor system. It should be noted

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Table 13. Annual U.S. U_3O_8 Requirements for the Light-Water Reactor on the Once-Through Cycle or on Self-Generated Recycle*
(thousands of short tons)

Reactor	Year		
	2000	2010	2025
Once-Through			
-15% Improved	54	75	103
-30% Improved	54	69	88
Self-Generated Recycle	51	61	82

*1978 median nuclear growth; 0.20 percent U-235 enrichment plant tails assay.

that the annual uranium demand for all these systems can be further reduced by 13 percent if the enrichment tails are reduced from 0.20 percent U-235 to 0.10 percent U-235 and by 18 percent if the tails are reduced from 0.20 percent U-235 to 0.05 percent U-235. It does not appear that self-generated recycle in light-water reactors has a significant effect on uranium requirements as compared to the maximum improvements considered in this analysis for the light-water reactor once-through fuel cycle.

3.3.2 Advanced Converters, Recycle

Further improvements in fuel utilization are possible if advanced converters recycle spent fuel. In general, advanced converter reactors using recycled fuel are expected to use the thorium fuel cycle. The thorium fuel cycle involves the production of U-233 which is, from a physics standpoint, a better fuel for these reactors than uranium enriched in U-235. Two approaches to the making of U-233 were analyzed: use of enriched (20 percent and 93 percent) U-235 uranium/thorium fuel in light-water reactors; and use of plutonium/thorium fuel, also in light-water reactors. It was assumed that either fuel type could be used in light-water reactors beginning in 1990, and that U-233/thorium fuel would be used in the advanced converters.

The annual U_3O_8 demands of the system of light-water reactors and advanced converters for these two alternative approaches are summarized in Table 14 and are compared with the self-generated recycle in the light-water reactor previously discussed. The high-temperature gas-cooled reactor was used to represent advanced converters.

Figure 8. Comparison of U_3O_8 Supply Capability and Demand Using Self-generated Recycle of 15%-Improved LWR Spent Fuel

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Table 14. Annual U_3O_8 Demand for Advanced Converters on the Thorium/U-233 Cycle Versus Light-Water Reactor Self-Generated Recycle*
(thousands of short tons)

	<u>1978 High Growth</u>		<u>1978 Median Growth</u>	
	<u>2010</u>	<u>2025</u>	<u>2010</u>	<u>2025</u>
HGTR thorium/U-233 cycle via enriched uranium/thorium route in LWR's	159	59	118	48
Denatured HTGR thorium/U-233/U-238 cycle via enriched uranium/thorium U-235/thorium route in LWR's	160	66	118	38
HTGR thorium/U-233 cycle via plutonium/thorium route in LWR's	60	88	41	54
Denatured HTGR thorium/U-233/U-238 cycle via plutonium/thorium route in LWR's	60	91	41	56
LWR self-generated recycle	81	123	61	82

* All scenarios are with 0.20 percent enrichment plant tails assay.

When the U-233 is produced by fueling reactors with U-235 and thorium, large initial inventories of enriched uranium are required. As U-233 is produced and recycled, uranium demands diminish. As shown in the table, U_3O_8 demand in 2010 is nearly twice that for self-generated recycle in light-water reactors. With either the 1978 median or high growths there would be a supply/demand imbalance during the initial deployment stage. By 2025, uranium requirements would be significantly reduced, but the earlier high requirements could preclude rapid deployment of this fuel cycle.

These scenarios assume that uranium/thorium-fueled light-water reactors are deployed in the 1980's to support rapid deployment of high-temperature gas-cooled reactors beginning in about 2003. Should advanced converters penetrate the market at a slower rate, peak uranium demand is avoided but the longer

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term uranium demand is higher than the demand with a more rapid market penetration. This problem of the market penetration rate and a peak in uranium demand is analyzed for the light-water breeder reactor in the next section. The results are generally applicable to the heavy-water reactor and the high-temperature gas-cooled reactor.

Using plutonium obtained by reprocessing spent fuel from light-water reactors and combining it with thorium in light-water reactors to produce U-233 could avert uranium supply/demand imbalances through the year 2025, even with rapid introduction of advanced converter reactors. These advanced converter reactors could begin operation fueled with U-233 and thorium without recourse to U-235 from mined uranium. For both 1978 high and median growth, the annual U_3O_8 supply would be adequate or nearly adequate before 2025 if the large backlog of light-water reactor spent fuel were to be used as a source of plutonium. Once this source is consumed, probably shortly after 2025, the annual uranium demand would begin increasing, and within about a decade or two extensive use of low-grade resources would be required.

Advanced converter reactors using the thorium cycle could also produce U-233 themselves by either of the two means described above. This would result in a lesser impact on uranium requirements than that of the approach analyzed.

3.4 WATER-COOLED BREEDER REACTOR

The water-cooled breeder reactor has been advanced as a reactor system that would significantly reduce future uranium consumption. Two types have been proposed by the Department of Energy - Division of Naval Reactors: a light-water cooled breeder reactor design and a heavy-water cooled breeder reactor design. The light-water cooled breeder reactor type was used for the study as representative of the two types.

The light-water breeder reactor has the potential for making slightly more fuel than it consumes. It would also make extensive use of current light-water reactor technology and would possess the safety characteristics of water-cooled and moderated reactors. However, the good fuel utilization of the light-water breeder reactor depends upon the use of thorium/U-233 fuel recycle, and large amounts of U-233 are needed for the initial breeder reactor fuel loading. In subsequent years, potentially no additional U-233 is needed.

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The U-233 needed for the initial breeder reactor fuel loading must be made in prebreeder reactors that are light-water reactors with thorium-fuels. The prebreeder fuel can be either thorium and uranium enriched in U-235 or thorium mixed with plutonium.

A typical light-water breeder reactor strategy consists of two phases: (1) a prebreeder phase and (2) a light-water breeder reactor (or high-gain converter) phase. These phases are frequently reflected in two separate reactor designs, but in some cases, a single reactor design with two sequential fuel types is used in the strategy. The rate of deployment of the prebreeders in the system determines the U_{308} consumption if the prebreeder uses a uranium/thorium fuel with a relatively high U-235 enrichment. However, if a plutonium/thorium fuel is used in prebreeders, there is no U_{308} requirement for those reactors, assuming the plutonium is obtained by reprocessing of light-water reactor spent fuel. The U-233 produced by prebreeders is used to fuel reactors in the light-water breeder-reactor phase, so the breeder has little or no requirement for U_{308} . Although light-water breeder reactors generate new U-233 at approximately the same rate that they consume it, some portion of a growing system must always consist of prebreeders. These prebreeders must furnish the additional U-233 to make up for losses, and provide for system expansion. For this analysis, it was assumed that the light-water breeder reactor concept was introduced into a system of 15 percent improved light-water reactors. A seed/blanket type of light-water breeder was used for the uranium/thorium fueled scenarios and a high-gain converter was used for the plutonium/thorium fueled scenarios. These and other light-water breeder reactor concepts are described in Volume IX.

If rapid deployment of a light-water breeder reactor system based on initial production of U-233 in thorium-fueled prebreeders took place, uranium supply problems similar to those discussed for advanced converters with recycle might develop. If the prebreeder reactors are deployed more slowly, the peak in U_{308} demand associated with rapid deployment could be avoided. This would result in the deployment of fewer light-water breeder reactors by 2025 and, consequently, higher long-term annual and cumulative uranium consumption. For this analysis, a range of deployment rates was considered by varying the fraction of new and replacement reactors which are prebreeders. It was found for the 1978 median growth that the large peak in demand during deployment could be avoided, if 30 percent of new reactors are prebreeders. With this lower rate of deployment, the long-term demand in 2025 would be higher, however. The annual U_{308} requirements for two deployment rates are presented in Table 15. The prebreeders are deployed into a system of 15 percent improved light-water reactors beginning in 1990. Figure 9 compares the U_{308} demands with the supply capability estimates for the scenarios. The rapid deployment

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Table 15. Annual U_{38} Demand for Systems of Light-Water
Reactor Prebreeders and Breeder Reactors^a
(thousands of short tons)

	<u>1990</u>	<u>2000</u>	<u>2005</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>
Rapid deployment (begin deployment 1990, 100% of market by 2000)	52	66	83 ^b	45	34	33
Moderate deployment (begin deployment 1990, 30% of market by 2010)	50	56	66	79 ^b	77	73

^a 1978 median nuclear growth, 0.20% enrichment plant tails assay.

^b Peak value of demand.

scenario requires a rapid increase in annual uranium production in the 1990's. In the first decade after 2000, this scenario would require expansion of the supply capability at the maximum rate projected as feasible by the Department of Energy and at a rate faster than considered achievable by the S.M. Stoller projection of supply capability. After 2005, uranium demand begins to rapidly decline as the thorium/U-233 fueled light-water breeder reactors come on-line in increasing numbers. It would be possible to alleviate this front-end peaking of demand by using the enrichment plant preproduction stockpile discussed in Section 2.2.5 and by reducing enrichment plant tails assay if adequate capacity were made available.

A more practical strategy might be to reduce the deployment rate of the prebreeders to reduce demand as shown in Figure 9 for moderate deployment at 30 percent of new reactors annually. It appears to be feasible with this strategy to avoid the possibility of a uranium supply/demand imbalance through 2025 and for several decades thereafter, if the nuclear growth is about 12 GW/year or less; somewhat higher growth rates of 12 to 15 GW/year also appear to be supportable if the maximum supply capability projected by the Department of Energy can be achieved and adequate enrichment plant capacity is built to allow tails assay reduction to 0.10 percent or lower.

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Figure 9. Comparison of U_3O_8 Supply Capability and Demand for a System with LWBR's Deployed with U/Th Fueled Prebreeders

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In summary, it is possible to use enriched uranium in a uranium/thorium pre-breeder to make the transition to a U-233/thorium-fueled light-water breeder reactor without encountering a uranium supply/demand imbalance through 2025 and for several decades thereafter. However, aggressive uranium resource development, improvement in the fuel utilization of light-water reactors, and reduction in enrichment plant tails assay are required; otherwise, the deployment rate of prebreeder reactors will be constrained and light-water breeder reactors will have marginal impact on uranium requirements during the period through 2025. It appears to be feasible to support nuclear growth rates of 12 to 15 GW/yr with this strategy.

A uranium supply/demand imbalance can also be avoided with prebreeder light-water reactors using plutonium/thorium fuel. Figure 10 illustrates this approach for a high-gain converter type of light-water breeder reactor (the high-gain converter may be the most economic type during the pre-2000 period.) If plutonium-fueled reactors are introduced by 2000, a supply/demand imbalance can be avoided for 1978 median nuclear growth. Alternately, if the expected light-water reactor improvements are realized, the introduction of plutonium-fueled reactors can be delayed until at least 2010 and a supply-demand imbalance is still avoided beyond 2025 with a median growth rate. If a high nuclear growth rate resumed after 2000, supply would not appear to be a problem until about 2025.

It appears that the plutonium/thorium strategy leading to the light-water breeder reactor can sustain a growth rate of about 12 to 15 GW/yr; a growth of 12 GW/yr could be sustained with a production of about 50,000 to 65,000 short tons U_3O_8 /yr for about 50 years after light-water breeder reactor introduction.

3.5 FAST BREEDER REACTOR

The fast breeder reactor does not depend on the mining of new uranium after starting but requires plutonium recovered from light-water reactor fuel, or enriched uranium from mined uranium ore, to provide initial inventory of fuel. This reactor can also produce an excess of fuel over its lifetime and thereby fuel new reactors in a growing nuclear power system without the need to mine uranium. Thus, electric-power generating systems which employ significant numbers of fast breeder reactors would require substantially less mined uranium than systems which do not. On the other hand, reprocessing to obtain plutonium from spent-fuel is absolutely essential.

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Figure 10. Comparison of U_3O_8 Supply Capability and Demand for a System with LWBR's Deployed with Pu/Th LWR's

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The commercial assessment in Volume IV concludes that the liquid-metal fast breeder reactor could be deployed in the United States beginning in the year 2006. This scenario requires that a specific set of assumptions be met, including an aggressive research, development, and demonstration program; acceptance of financial and technical risk; a median to high nuclear growth; a U_3O_8 price rising to \$120-200/lb; and a capital cost for the breeder no more than 30 percent higher than that of the light-water reactor. Under alternative conditions of a lower financial and technical risk program, the liquid-metal fast breeder reactor might be deployed about 2014. The commercial assessment also concludes that the fast breeder reactor could eventually capture 100 percent of the nuclear market about 30 years after commercial introduction, if uranium prices rise to \$120-200/lb U_3O_8 . In addition, the capital cost of the fast breeder is only about 30 percent higher than that of the light-water reactor.

The commercial assessment also concluded that the gas-cooled fast breeder reactor could be deployed in the United States beginning in 2014 with an aggressive research, development, and demonstration program pace and acceptance of financial and technical risk by the program participants. A less aggressive and lower risk program would lead to gas-cooled fast reactor deployment beginning in 2024. The following analyses were based on the characteristics of the liquid-metal fast breeder reactor and the appropriate range of deployment dates. Specific analyses were not made for the gas-cooled fast reactor. However, characteristics of this reactor are similar enough to the liquid-metal fast breeder reactor that the effects on uranium demand can be inferred from these analyses for either system. If the liquid-metal fast breeder reactor were deployed as well as the gas-cooled fast reactor, the effects of gas-cooled fast reactor deployment on uranium demand would depend on the relative deployment dates and the market penetrations of the two types of fast breeder reactors. If the risk-balanced gas-cooled fast breeder reactor program were undertaken and resulted in deployment in 2024, the effects on uranium demand would occur after 2025.

The principal factors considered in the system analyses of fast breeder reactor introduction were: (1) the time of introduction--either 2006 or 2014; (2) the type of breeder core and blanket--which governs the type of excess fuel bred--either plutonium or U-233; and (3) the other reactors associated with the fast breeder reactor--either improved light-water reactors on the once-through cycle, light-water reactors with self-generated recycle, or the high-temperature gas-cooled reactor.

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Time of Introduction

The introduction of the fast breeder reactor into a system of 15 percent improved light-water reactors on the once-through cycle results in a leveling off and then a decline in annual U_{38} demand; the peak of the annual demand occurs within about 10 years after introduction, as illustrated in Figure 10 and Table 16.

Table 16. Effect of Fast Breeder Reactor Time of Introduction on Annual U_{38} Demand
(thousands of short tons U_{38} /year)

	<u>1990</u>	<u>2000</u>	<u>2005</u>	<u>2015</u>	<u>2020</u>
<u>1978 High Growth</u>					
2006 Introduction	72	83	89	73	49
2014 Introduction	74	87	100	110	95
<u>1978 Median Growth</u>					
2006 Introduction	56	61	64	55	42
2014 Introduction	57	64	71	76	74

*Introduced into system of 15 percent-improved light-water reactors, 0.20 percent U-235 tails assay

This effect depends on the rate of introduction of the breeder, which in turn is dependent on the rate of reprocessing undertaken to obtain the plutonium for the initial breeder inventory. The uranium recovered from the reprocessed light-water reactor spent fuel contributes substantially to the reduction in uranium demand. In the high-growth case, about 21 GW of breeders would be introduced between 2006 and 2015; uranium demand would peak in about 2015, and reprocessing requirements would have to increase to about 7,600 t/yr by that time, the equivalent of the annual spent-fuel discharge from about 500 15-percent improved light-water reactors. With breeders in 2014, a peak in demand occurs in 2021, or about 7 years after introduction.

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With the 1978 high growth demand and with fast breeder introduction in 2014, a peak annual demand in excess of 100,000 short tons U_3O_8 /yr would develop and would last about a decade. This would require production of 15,000 to 25,000 short tons U_3O_8 /yr from low-grade resources, a production level that might have to be partially supplied from Chattanooga shale. If the breeder were introduced in 2006, annual uranium supply requirements would not exceed 90,000 tons U_3O_8 per year, and production from shale would not be needed. Thus, with a high nuclear growth, early fast breeder introduction would be an alternative to large-scale development of low-grade resources.

To further reduce uranium requirements should a high nuclear growth occur, the fuel utilization of the light-water reactor once-through fuel cycle might be improved more than 15 percent, and the enrichment plant tails assay could be reduced. Also, high- and low-grade uranium resources could be exploited to the maximum. Since the fast breeder reactor will tend to significantly decrease the demand for enriched uranium within 10 years after its introduction, however, maximum development of uranium-supply facilities and added enrichment plant capacity for reduced tails assay might result in surplus facilities before the end of their useful lives. Thus, a rapid deployment of fast breeder reactors may reduce the incentives to invest in uranium mining and enrichment facilities.

For the 1978 median nuclear demand and fast breeder introduction in either 2006 or 2014, uranium supply should not be a problem, and in either case annual demand would be declining by 2025 as shown on Figure 11. The resource conservation incentives for introducing the fast breeder reactor stem from its being seen as a source of electrical energy which draws upon an essentially inexhaustible resource base.

Thus, the fast breeder reactor and the associated reprocessing of light-water reactor spent fuel to provide initial cores would be an effective way to cap rising uranium demand. A moderate rate of introduction for the first 10 years could have a substantial effect, because of the reprocessing needed for initial fast breeder reactor inventories and recycle of recovered uranium into light-water reactors. Initially, the dominant effect would come from uranium recycle because reprocessing of light-water reactor spent fuel for a fast breeder's first core would recover enough uranium for five to six annual reloads for a light-water reactor.

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Figure 11. Comparison of U_3O_8 Supply Capability and Demand for a System with LMFBR's and 15% Improved LWR's – Effect of Breeder Introduction Date and Nuclear Growth

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Type of Breeder Core and Blanket; Type of Recycle

A liquid-metal fast breeder reactor, with a plutonium-uranium core and uranium blankets used in conjunction with light-water reactor self-generated recycle is more effective in reducing the peak U_3O_8 demand as compared with the use of thorium in breeder blankets and denatured U-233 fuel in light-water reactors. This is illustrated in Table 17 for the high nuclear demand and fast breeder reactor introduction in 2006 into a system of 15-percent improved light-water reactors on the once-through cycle, using an enrichment plant tails assay of 0.20 percent U-235.

The scenario with thorium blankets in breeders and no plutonium recycled in the light-water reactors has 10-percent higher U_3O_8 requirements because the U-233 must be bred in the breeders, and the recycle of denatured U-233/thorium fuel is limited by the rate at which U-233 is made in the breeders; whereas the self-generated recycle of uranium and plutonium has more recycle fissile materials available at the decade following the breeder introduction. More detailed descriptions of these alternatives can be found in Section 1.6.1.2 of Volume IX of the NASAP report.

Table 17. Use of Uranium Versus Thorium in Fast Breeder Blankets
(thousand tons U_3O_8 /Year)

Type of Breeder	2005	2010	2015	2020	2025
Uranium-plutonium core, uranium blanket, LWR self- generated recycle	84	94	93	87	39
Uranium-plutonium core, uranium blanket, LWR recycle of denatured U-233/thorium fuel	84	97	103	81	46

Thus, the thorium scenario is hampered by the availability of denatured U-233 fuel, if it does not allow for plutonium recycle in light-water reactors to produce U-233.

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Effect of Other Thermal Reactors Coupled with the Fast Breeder Reactor

The other reactors in a system including breeders can have an effect on reducing the peak annual U_3O_8 demand because nonbreeders will continue to make up a large part of the system, particularly if breeder introduction were delayed. With the delayed breeder deployment, beginning in 2014, breeders are less than 5 percent of the U.S. system by 2025. As shown in Table 18, the peak annual U_3O_8 demand for a system of 30 percent improved light-water reactors into which fast breeders are introduced is 19 percent less than for fast breeder introduction into a system of 15 percent improved light-water reactors; self-generated recycle in the latter system has slightly less effect than the 30 percent improvements in the light-water reactor fuel utilization on the once-through cycle. Thus, improved once-through cycles in conjunction with the fast breeder can be effective in reducing the peak uranium demand.

Table 18. Effect of Thermal Reactors Coupled with the Fast Breeder on Peak Annual U_3O_8 Demand

	Peak Annual U_3O_8 Demand* (thousand tons)	
	<u>1978 High Growth</u>	<u>1978 Median Growth</u>
<u>FBR uranium-plutonium core, uranium blanket plus</u>		
15%-Improved LWR; FBR recycle only	110 (in 2020)	76 (in 2020)
30%-Improved LWR; FBR recycle only	89 (in 2025)	61 (in 2020)
15%-Improved LWR; FBR and LWR recycle	93 (in 2015)	67 (in 2020)

*0.10% U-235 tails assay

A system consisting of a high-temperature gas-cooled reactors using denatured U-233/thorium fuel with the U-233 coming from fast breeder reactors having thorium blankets is compared in Table 18 with a system consisting of light-water reactors, also using denatured U-233 fuel supplied from fast breeder

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reactors with thorium blankets. Both systems introduce fast breeders using uranium-plutonium cores and thorium blankets in 2006. The comparison shows that there is essentially no difference between the two systems.

Table 19. Annual U_{308} Demand for Fast Breeder Reactors Coupled with Light-Water Reactors or High-Temperature Gas-Cooled Reactor (thousand tons)

<u>System*</u>	1978 High Growth			1978 Median Growth		
	<u>2010</u>	<u>2015</u>	<u>2025</u>	<u>2010</u>	<u>2015</u>	<u>2025</u>
LWR + FBR	97	103	46	71	74	45
HTGR + FBR	97	103	49	71	73	47

*Enrichment tails assay 0.20 percent U-235

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4. ESTIMATES OF FOREIGN URANIUM RESOURCES AND SUPPLY

The foreign uranium supply/demand situation is quite different than that of the United States. Current estimates show that the United States has the largest known uranium resources as well as the highest uranium demand of all countries in the world. With only a few exceptions, the other major sources of uranium supply are located in countries without large nuclear programs, and many of the countries with large nuclear power programs have limited domestic uranium resources. For many countries, the uranium situation is similar to the petroleum situation--there are large mismatches between suppliers and users. Therefore, this analysis considers the supply/demand situation from both an aggregated global viewpoint and from the perspective of several nations.

4.1 CURRENT ESTIMATES OF WORLD URANIUM RESOURCES

The principal source of data on the global resource base at forward costs up to \$50/lb U_3O_8 for reserves and probable resources¹ is the December, 1977, report (Reference 14), "Uranium Resources, Production, and Demand," by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, and the International Atomic Energy Agency. This report was prepared by a Joint Nuclear Energy Agency/International Atomic Energy Agency Working Party on Uranium Resources from data officially supplied by the various countries. The People's Republic of China, U.S.S.R., and associated Eastern European countries have not provided data and are therefore not included in these estimates.

The Nuclear Energy Agency/International Atomic Energy Agency Working Party recognized that additional possible and speculative resources exist beyond those included in their report on reserves and probable potential resources. Data on these more speculative resources have recently become available through the International Uranium Resource Evaluation Project. In general, the foreign uranium resource picture is less well defined than that of the United States.

¹Nuclear Energy Agency/International Atomic Energy Agency uses the terms "reasonably assured" and "estimated additional" resources for reserves and probable resources, respectively. They also use cost categories of \$80 and \$130/kg uranium which are equivalent to \$30 and \$50/lb U_3O_8 .

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4.1.1 Reserves and Probable Potential Resources

The Department of Energy resource classifications used to describe domestic uranium sources in earlier sections of this volume will also be used to describe foreign resources. The Nuclear Energy Agency/International Atomic Energy Agency-based estimates of foreign resources at a forward cost of up to \$50/lb U_3O_8 are presented in Table 18. Excluding U.S. resources, the estimates total about 2 million short tons U_3O_8 for reserves and an additional 1.4 million short tons for probable potential resources. Nearly 83 percent of these resources are in Australia, Canada, Niger, South and Southwest Africa, and Sweden.

4.1.2 Additional Resource Potential

The Nuclear Energy Agency/International Atomic Energy Agency Working Party and others recognized that additional possible and speculative potential resources exist beyond those included in probable potential resources, since that category includes only those resources associated with known deposits. Canada has a comprehensive systematic program similar to our National Uranium Resource Evaluation program that seeks to assess undiscovered resources. Argentina, France, India, Brazil, Iran, Portugal, and Spain also have national assessment programs. However, few other countries have such programs.

To overcome these uncertainties, the Nuclear Energy Agency/International Atomic Energy Agency has implemented the International Uranium Resource Evaluation Project to develop a more complete appraisal of world resources. Studies are now being made for 185 countries, including the United States, covering general geography, geology in potentially favorable uranium-bearing areas, past exploration, uranium occurrences and past production, present status of exploration, and the potential for new discoveries. Areas that are believed to be favorable for the discovery of uranium beyond the resources previously reported by Nuclear Energy Agency/International Atomic Energy Agency have been identified in this first phase.

For each of the 185 countries, a judgment has been made by the International Uranium Resource Evaluation Project representatives of the extent of the additional potential resources, based on the geological favorability for the

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Table 18. World Uranium Resources by Continent*
(thousands of short tons U_3O_8)

	Reserves		Probable Potential	
	<\$30/lb U_3O_8	<\$50/lb U_3O_8	<\$30/lb U_3O_8	<\$50/lb U_3O_8
<u>North America</u>	920	1180	1,550	2,340
U.S.	689	891	1,014	1,395
Canada	224	246	525	918
Mexico	6	6	3	3
Greenland	0	35	0	21
 <u>Africa</u>	 690	 740	 200	 260
South & SW Africa	400	452	44	94
Niger	208	208	69	69
Algeria	36	36	65	65
Gabon	26	26	7	13
C.A.R.	10	10	10	10
Zaire	3	3	3	3
Somalia	0	8	0	4
Madagascar	0	0	0	3
 <u>Australia</u>	 380	 380	 70	 70
 <u>Europe</u>	 80	 490	 70	 120
France	48	68	31	57
Spain	9	9	12	12
Portugal	9	10	1	1
Yugoslavia	7	9	7	27
U.K.	0	0	0	9
Germany	3	3	4	5
Italy	1	1	1	1
Austria	3	3	0	0
Sweden	1	390	4	4
Finland	1	3	0	0

*As of 1977., Excludes People's Republic of China, U.S.S.R., and associated countries.

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Table 18. World Uranium Resources by Continent^a
(Continued)

(thousands of short tons U₃O₈)

	<u>Reserves</u>		<u>Probable Potential</u>	
	<u><\$30/lb U₃O₈</u>	<u><\$50/lb U₃O₈</u>	<u><\$30/lb U₃O₈</u>	<u><\$50/lb U₃O₈</u>
<u>Asia</u> ^b	<u>20</u>	<u>60</u>	<u>1</u>	<u>30</u>
India	5	39	1	30
Japan	10	10	0	0
Turkey	5	5	0	0
Korea	0	4	0	0
Philippines	0	0	0	0
 <u>South America</u>	 <u>50</u>	 <u>60</u>	 <u>20</u>	 <u>20</u>
Brazil	23	23	10	10
Argentina ^b	25	35	4	6
Chile	0	0	7	6
Bolivia	0	0	0	1
 Total (Rounded)	 2,140	 2,910	 1,910	 2,840

Source "Uranium Resources, Production, and Demand"; Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency and International Atomic Energy Agency, December 1977. Except United States.

^a As of 1977. Excludes People's Republic of China, U.S.S.R., and associated countries.

^b Revised since OECD report.

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existence of uranium deposits that, if discovered now, could be exploited at costs less than \$50/lb U_3O_8 . The sums of these possible and speculative potential resources for the free world range from about 8.5 to 19.2 million short tons U_3O_8 as is shown in Table 19. Data for individual countries have not been disclosed by the Nuclear Energy Agency/International Atomic Energy Agency report on the International Uranium Resource Evaluation Project. The conversion of these potential resources into reserves will require very large exploration and drilling programs similar in magnitude to those previously described for the U.S. resources. In addition, the International Uranium Resource Evaluation Project estimates that total resources in planned-economy nations, including resources and probable resources, are in the range of 4.3 million to 9.5 million short tons of U_3O_8 .

Table 19. Speculative Resources Listed by Continent

Continent	Number of Countries	Speculative Resources (million short tons U_3O_8)	Percent of Total
Africa	51	1.6 - 5.2	18-27
America, North	3	2.7 - 4.7	32-24
America, South and Central	41	0.9 - 2.5	11-13
Asia and Far East ^a	41	0.3 - 1.3	3- 7
Australia and Oceania	18	2.6 - 3.9	31-20
Western Europe	<u>22</u>	<u>0.4 - 1.7</u>	<u>5- 9</u>
	176	8.5 -19.2	
Eastern Europe, U.S.S.R, People's Republic of China	9	4.3 - 9.5 ^b	

^aExcluding People's Republic of China and the eastern part of USSR

^bThe potential shown here is "Estimated Total Potential" and includes an element for reserves and probable potential resources although those data were not separately available.

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The distinctions drawn between the reserves and probable potential resources and the speculative resources based on differing degrees of geological evidence make it essential that each category be regarded as a discrete entity for the purpose of estimating supply potential.

Parts of North America, Australia, Africa, and Europe have been most extensively explored for uranium. These regions contain most of the current low-cost uranium resources. Furthermore, these areas are also considered the most favorable for discovery of additional resources. However, there are other regions identified in the International Uranium Resource Evaluation Project study with little or no past exploration that appear geologically favorable and merit additional work. In assessing speculative resources, the International Uranium Resource Evaluation Project believes that the highly subjective nature of the exercise and a number of other factors should be emphasized. In particular, it is emphasized that the totals are not meant to indicate ultimate resources of uranium since the perspective was restricted by current knowledge, which is itself severely limited in many areas of the world.

Figure 12 presents a historical summary of reserves and probable potential resources prepared from Nuclear Energy Agency/International Atomic Energy Agency reports. Although the forward-cost grouping of these reserves was changed in 1975, the report judged that these changes have not made a significant impact on the estimates. The 30 percent increase in reserves between 1976 and 1977 represents a real increase due to exploration and development. For this reason, judgments of possible and speculative resources are expected to increase as cumulative knowledge increases, just as estimates of other resources such as oil have increased based on further exploration. Worldwide uranium exploration activity, concentrated in a few areas, has increased substantially in recent years to a level of about \$400 to \$500 million per year.

However, these estimates do not guarantee that the uranium will be discovered or made available during the time period of interest. Serious constraints may well arise in many of the same areas discussed in the section on U.S. resources; that is, production limitations due to shortages of capital and/or labor, timelags in the start of mining ventures, etc.

Figure 12. Historical Estimates of World* Reasonably Assured Resources of Uranium
(Source: NEA/IAEA Reports) \$ per Kg of Uranium

*(EXCLUDES PEOPLES REPUBLIC OF CHINA, USSR, & ASSOCIATED COUNTRIES)

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4.2 FOREIGN SUPPLY OUTLOOK FROM HIGH-GRADE URANIUM RESOURCES

The uranium production capability of foreign countries (WOCA excluding the United States) was estimated to be about 30,000 short tons U_3O_8 in 1978, an increase of about 5,400 short tons over 1977. Canada, France, Gabon, Niger, South Africa, and Namibia accounted for over 90 percent of this capacity. About 40 percent of the total capacity in WOCA, including the United States, is currently in the United States.

4.2.1 Near-Term Outlook: 1979 to 1990

Estimates of future WOCA production capability, as projected by the Nuclear Energy Agency/International Atomic Energy Agency report in December 1977, are presented in Table 20. The production through 1985 is primarily from resources with forward costs less than \$30/lb U_3O_8 , although some resources up to \$50/lb are included. Foreign production capability is expected to reach about 40,000 short tons in 1980 and, potentially, about 72,000 short tons in 1985. The increase in production capability is principally due to expansions in Canada, South Africa, Namibia, Niger, and Australia. The production capacity for 1980 is largely under construction or committed, while for 1985 the additional capacity is either planned or projected from known resources and is the maximum that could be in place under favorable economic and political conditions.

The Nuclear Energy Agency/International Atomic Energy Agency projection is that WOCA production capacity, excluding the United States, could be increased to about 83,000 short tons U_3O_8 by 1990. A very significant point is that one country, Australia, is projected to account for 93 percent of the potential increase between 1985 and 1990. This observation indicates that known resources are an insufficient basis upon which to justify projections of increased production in other countries, and reflects the inherent difficulty and long leadtime in discovering new uranium deposits at greater depths and in more inaccessible areas. For instance, there are physical constraints limiting further expansion of both Canadian and South African conglomerate deposits. In addition to these physical constraints, there are political and environmental constraints in some areas. Sweden has uranium resources of almost 400,000 short tons U_3O_8 in black shales, but use of this resource is uncertain because of political and environmental factors.

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Table 20. Uranium Production Forecast from High-Grade Resources in
World Outside Centrally-Planned Economy Areas (WOCA)^a
(short tons U₃O₈/year)

	<u>1977</u>	<u>1978</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>
Total WOCA	38,600	48,200	66,300	111,800	138,200
U.S.	<u>14,900^c</u>	<u>18,500^c</u>	<u>26,900</u>	<u>39,500</u>	<u>54,500</u>
Rest of WOCA	<u>23,700</u>	<u>29,700</u>	<u>39,400</u>	<u>72,300</u>	<u>83,700</u>
Canada	7,500	8,800 ^b	9,900	16,200	16,200
Mexico	0	30	220	710	710
Argentina	170	360	650	780	780
Brazil	0	0	500	500	500
South Africa & Namibia	8,700	11,400	15,200	16,200	16,200 ^b
Niger	2,100	3,100	5,300	11,700	11,700
Gabon	1,040	1,560	1,560	1,560	1,560
Central African Empire	0	0	0	1,300	1,300
Australia	500	650	650	15,300	26,000
France	2,900	3,000 ^b	3,700	4,800	5,200
Spain	250	250	880	1,650	1,650
Portugal	110	110	120	350	350
Italy	0	0	160	160	160
Germany, F.R.	130	130	130	260	260
Yugoslavia	0	0	0	230	600
India	260	260	260	340	340
Japan	40	40	40	40	40
Turkey	0	0	130	170	170
Philippines	0	0	50	-	-

^a"Uranium Resources, Production, and Demand," Organization for Economic Cooperation and Development Nuclear Energy Agency and the International Atomic Energy Agency, December 1977.

^bRevised based on INFCE Working Group 1 inputs.

^cAdjusted to reflect 1977 production and 1978 estimate by the Department of Energy.

4.2.2 Post-1990 Outlook: Through 2025

Key Factors

Although there appears to be a large potential global resource base, increases in world production capacity in the 1990's and beyond will depend on successful conversion of potential resources into the reserve category through exploration and development. To assure that a given production rate can be maintained, a forward reserve equivalent to a number of years of future production needs to be established. A forward reserve of at least 10 to 15 years is believed to be necessary; that is, the present reserves should be sufficient to supply needs through 1990 or 1995. Canadian policy is even more cautious, and requires that national reserve levels be sufficient to provide for the lifetime requirements of all reactors operating or planned within a 10-year forward period before any uranium can be exported. Some countries require that a particular uranium production facility operate for 20 to 25 years and thus limit the rate of production from the reserves associated with the mine and mill. This policy may be reasonable where new towns and transportation must be built, as it takes into consideration the great influence such activity has upon the social and economic development of the area.

The leadtime between the commencement of an exploration program and first production from a successful discovery has been 8 to 12 years. The leadtime is likely to be at least 15 years and possibly much longer in remote areas, or where political issues must be resolved. Lower grade resources, which require larger mine, mill, and support infrastructure, are likely to require more time and larger investment to develop. Thus, the pace of exploration in the early 1980's needs to be matched to the needs foreseen in the 1990 to 1995 period.

The pace of exploration and development activity that occurs will depend on many factors, but especially on the presence of a strong market demand with attractive prices. Stable, positive, long-range government planning and policies will also be very important in attracting the necessary large investment for these long-term activities. Access to favorable exploration areas on equitable terms will promote development.

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Key differences between the United States and several other countries with major nuclear programs such as Japan, the Federal Republic of Germany, and the United Kingdom are that the United States has large uranium resources, has control of their development, and all domestic users have free market access to the supply. This is not the case with these other nations, all of whom have limited indigenous uranium resources, no political control of the development of resources in other countries, and, consequently, must rely on the world market for supplies of uranium. The policies of the major uranium suppliers are critical to these major importing countries.

The Department of Energy - Division of Resource Assessment Operations estimated the production capability of the WOCA nations covering the period through 2025. Four production capability schedules were developed which considered two resource levels, a "high" and a "low," and two resource development rates, an "accelerated" and a "delayed." The high and low resources derive from the upper and lower range of the International Uranium Resource Evaluation Project speculative resource estimates (8.5 and 19.2 million short tons U_3O_8). The accelerated and delayed development rates are estimates of the range of rates for converting resources to reserves and the range in installation rates of production capacity for uranium recovery. The ranges of these estimates for high-grade resources are shown in Table 21 and Figure 13. Reserves and potential resources in the $\leq \$50/lb$ U_3O_8 forward cost categories were included. In addition, uranium recovered as a by product from phosphate production and black shale was estimated; production from Swedish black shale has been included in Table 21, but production from other shales and phosphate is included with low-grade resources. The production capability projections were considered as the maximum feasible scenarios, that is, the upper bounds of achievable production from presently estimated resources under specific assumptions.

The projections for the $\leq \$50/lb$ reserves and probable potential categories were developed by considering the expansion of production from existing or projected production centers (uranium processing plants and tributary mines and resources). In the accelerated production scenario, startup of new production centers was assumed to occur in the 1990 to 1995 period; in the delayed scenario, new production centers were delayed until 2000.

The estimate of production from speculative resources involved more complex assumptions. The resources were categorized by country and the expected geologic type of deposit. Leadtimes and resource development rates were

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Table 21. WOCA Production Potential from High-Grade Resources*
(thousands tons $U_{38}O_{10}$ per year)

Scenario	Region	Year					
		1980	1990	2000	2010	2020	2025
Accelerated Development and Low/High Resource Base	WOCA	66	138	195-211	232-307	212-357	194-362
	U.S.	27	55	79	83-86	50-62	42-48
	WOCA minus U.S.	39	83	116-132	149-221	162-295	152-314
Delayed Development and Low/High Resource Base	WOCA	66	134	171-189	195-265	184-314	172-320
	U.S.	27	55	73-74	80-83	51-61	29-42
	WOCA minus U.S.	39	79	98-115	115-182	133-253	143-278

* Conventional resources at <\$50/lb forward cost plus the Swedish black shales containing 250 to 380 ppm uranium

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Figure 13. Estimate of WOCA Annual U_3O_8 Supply Capability from High-Grade <\$50/lb Resources

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then specified for each geologic type and for the situations in various countries, depending on the level of industrial development and past activity in uranium exploration and development. Leadtimes from the start of exploration to start of production ranged from 17 to 24 years for foreign countries which now have developed uranium resources; for developing countries with limited or no uranium exploration, leadtimes ranged from 28 to 41 years.

Figure 13 indicates that a uranium supply capability of 90,000 to 100,000 short tons U_3O_8 per year could be reached in the early to mid-1990's in WOCA countries, excluding the United States. However, this production rate could not be sustained for more than a few years unless possible and speculative potential resources are developed in the 1980's. By the period 2005 through 2010, the majority of supply from high-grade resources would have to come from these potential resources. Discovery and development of these resources at the projected rates are subject to many uncertainties and reflect long leadtimes.

4.3 FOREIGN SUPPLY OUTLOOK FROM LOW-GRADE URANIUM RESOURCES

This section summarizes the supply potential from low-grade uranium resources for the foreign WOCA nations. The general types of low-grade resources are the same as discussed in the chapter on U.S. resources and supply. Overall, the foreign outlook for supply is similar to that projected in the United States; that is, low-grade resources will probably provide a relatively small percentage of the uranium supply through 2000. As in the United States, there is much uncertainty associated with economically producing uranium from most of the low-grade resources. The foreign supply outlook from low-grade resources is summarized in Table 22.

4.3.1 Conventional Low-Grade Deposits (forward cost $>\$50/\text{lb } U_3O_8$)

As in the United States, foreign high-grade uranium deposits in sedimentary type formations can be expected to have low-grade resources associated with them. There is little information on these resources. If the same ratio of low-grade to high-grade resources exists in foreign countries as in the United States, they could add about 10 percent to the high-grade resources, that is,

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Table 22. Foreign Annual Supply Outlook from Low-Grade Resources
(short tons U_3O_8 /year)

	<u>2000</u>	<u>2025</u>
Conventional deposits (>\$50/lb)	0	0
Phosphate byproduct uranium	7,500 to 14,000	16,000 to 70,000
Shales (excluding Sweden)	0	0
Other sources	<u>500</u>	<u>1,000</u>
Total	8,000 to 15,000 (rounded)	17,000 to 71,000

an additional 1 to 2 million short tons. These resources would be produced at forward costs over \$50/lb U_3O_8 , and are not likely to provide a significant supply during the period through 2025, unless there are constraints on development or lack of access to the lower-cost supplies from high-grade resources.

4.3.2 Phosphate Byproduct Uranium

From the foreign standpoint, phosphate byproduct uranium is expected to be the major source of supply from low-grade resources. The major phosphate resources are distributed as follows: 65 to 75 percent in Morocco, 10 to 14 percent in the United States, 5 percent in Australia, 4 percent in the U.S.S.R. The remaining 10 percent is distributed among at least 20 other nations. World phosphate resources contain a reported 20 million short tons of U_3O_8 . At least half of this is in northern Africa, and 20 percent is in the United States. Uranium concentration ranges from 60 to 150 ppm U_3O_8 . A recent study by Earth Sciences, Inc. for the Department of Energy (Reference 6) concluded that use of this resource during the next 50 years will be limited by economics to recovery of uranium as a byproduct from that part of the phosphate production which is converted into phosphoric acid for "triple-superphosphate" fertilizers. World phosphoric acid annual capacity is 24 million tons of equivalent P_2O_5 of which 40 percent is in the United States. This phosphoric acid production is estimated to contain about 9,200 short tons of U_3O_8 of which about 4,200 short tons would be in the U.S. production. About 42 percent of the 5,000 short tons of U_3O_8 in foreign production is estimated to be economically recoverable at a price of \$40/lb U_3O_8 . About 20

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other countries could recover uranium from phosphates and several countries are planning to do so. Annual uranium byproduct in foreign countries is projected in Reference 6 to increase from 2,500 short tons U_3O_8 in 1980 to 5,000 short tons in 1990, to 7,500 short tons in 2000, and 16,000 short tons in 2025.

A higher range of potential uranium byproduct production from phosphate was estimated by the Department of Energy - Division of Resource Assessment Operations. The Department of Energy projected a growth rate of 5 percent per year through the year 2000. Following the year 2000, production from phosphates was estimated to expand at a rate of 7 percent per year for the accelerated development scenario and at 3 percent per year in the delayed development scenario. Full capability for uranium byproduct recovery was assumed to be reached in 1990. The U_3O_8 byproduct resulting from these assumptions in the year 2000 was 14,000 short tons and 29,000 to 70,000 short tons in the year 2025.

4.3.3 Shales

The richest known uranium-bearing shale is in Sweden and contains about 400,000 short tons of U_3O_8 in concentrations of 250 to 380 ppm. This resource is estimated to be producible at a forward cost of <\$50/lb and has been included with the high-grade foreign resources. Uranium-bearing shales have also been reported in other countries; little data is available, but at least several million tons of U_3O_8 are involved. There is not likely to be much uranium produced from these shales during the period through 2025, however, except possibly as a byproduct of oil recovery from shale.

4.3.4 Mill Tailings

Canadian uranium mill tailings are estimated to contain at least 7,800 short tons U_3O_8 and 20,000 tons of ThO_2 . This material would probably not be used until the price approached \$100/lb U_3O_8 .

In South Africa, existing gold mine tailings contain about 160,000 short tons U_3O_8 of which 38 percent is considered recoverable. Two plants currently

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plan to recover about 850 short tons of U_3O_8 per year from this source. As the prices of gold and uranium increase, more of this material will become economic to rework.

4.3.5 Copper Ores

A small amount of uranium might be recovered from copper leach solutions from porphyry-copper ore mining in Chile. The potential supply from this source is small.

4.3.6 Coal and Lignite

Some lignites in Canada and Spain contain over 100 ppm uranium, and the ash can be processed to recover this material, although there is some difficulty in doing so. Spanish resources include 104,000 short tons U_3O_8 in reserves and 83,000 short tons in probable potential resources, but recovery costs are over \$50/lb. Little production is expected from this source through 2025.

4.3.7 Seawater

As discussed for potential low-grade U.S. resources, several nations are performing research on ways to recover uranium from seawater. The technology and engineering difficulties are formidable, however, and the costs are likely to be extremely high. For this reason, no significant production is forecast from seawater through 2025.

4.4 TOTAL ESTIMATES OF WOCA U_3O_8 PRODUCTION CAPABILITY USED IN THE NASAP ANALYSIS

As in the U.S. analysis, estimates of supply from high- and low-grade resources have been added to provide projections of total foreign WOCA U_3O_8 potential production capability. These estimates were then combined with the

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corresponding estimates of total United States U_3O_8 potential production capability to obtain projections for WOCA countries including the United States. Figure 14 shows the range of supply capability projections which result from combining the previously described high-grade and low-grade projections for WOCA countries excluding the United States. Figure 15 shows the range of supply capability projections for WOCA countries including the United States.

The upper pair of curves shows the high-grade resources for accelerated resource development and high resource base assumptions combined with the higher estimates of supply from low-grade resources. The lower pair of curves shows the high-grade resources for delayed resource development and low resource base combined with the lower estimates of low-grade resources. Together, these curves represent upper and lower bounds of potential uranium supply based on current knowledge of foreign resources.

The high supply for foreign WOCA countries projects a production capability of 147,000 short tons of U_3O_8 in 2000 and 385,000 short tons of U_3O_8 in 2025; the supply is 90 percent and 82 percent respectively from high-grade resources. The low supply for foreign WOCA countries projects production capability of 106,000 short tons of U_3O_8 in 2000 and 160,000 short tons of U_3O_8 in 2025; the supply is 92 percent and 89 percent respectively from high-grade resources.

The high supply for WOCA countries including the United States projects a production capability of 235,000 short tons of U_3O_8 in 2000 and 508,000 short tons of U_3O_8 in 2025; the supply is 90 and 71 percent respectively from high-grade resources. The low supply for WOCA countries including the United States projects a production capability of 192,000 short tons of U_3O_8 in 2000 and 247,000 short tons U_3O_8 in 2025; the supply is 89 and 68 percent respectively from high-grade resources.

As noted previously, the majority of high-grade uranium supply after the 2005 to 2010 period would have to come increasingly from uranium currently in the possible and speculative resources categories. Production of uranium from these categories is highly uncertain, and this situation is complicated by the long leadtimes associated with exploration, reserves delineation, and mine/mill development in a variety of overseas areas.

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Figure 14. Estimates of Total Foreign (WOCA Minus U.S.) Annual U_3O_8 Supply Capability Used in NASAP

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Figure 15. Estimates of Total WCCA Annual U_3O_8 Supply Capability Used in NASAP

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Uranium byproduct from phosphoric acid production is expected to be the only significant source of supply from low-grade resources through 2025, and as such the uranium production rate will depend on the rate of phosphoric acid production.

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5. COMPARISON OF FOREIGN URANIUM DEMANDS WITH FOREIGN PRODUCTION CAPABILITY FORECASTS

5.1 INTRODUCTION

Analyses of international nuclear reactor deployment strategies were performed as part of NASAP in support of the United States participation in the International Nuclear Fuel Cycle Evaluation (INFCE). This chapter draws upon analytical work done for a U.S. submission to INFCE Working Group 8 and reported in Reference 12.

An approach similar to that of Chapter 3 was used: a comparison of potential uranium demand with potential production capability was made to indicate when and under what conditions of demand, production capability, and technology implementation, imbalances between uranium supply and demand might occur.

The supply/demand comparison will be made first on aggregated basis as follows: for foreign WOCA nations excluding the United States, and then for WOCA nations including the United States. The analyses must be viewed with the understanding that except for a few countries, the major potential suppliers of uranium are not the same countries with large demands for nuclear fuel due to nuclear power programs. As a result, such analyses provide a general view of the adequacy of the world's resources, but do not provide full insight into the supply situation as it may be perceived by the major consumer nations. Therefore, comparisons of demand and resources for individual nations are also provided. The demands for thorium, heavy water, and fuel cycle services are discussed in Chapter 6.

The two nuclear power growth assumptions used for the INFCE scenario analysis are shown in Table 23. The U.S. growth range in the table is presented in Chapter 3 as the 1978 Department of Energy projections.

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Table 23. Installed Nuclear Capacity in WOCA Nations (GW)

<u>Year</u>	<u>INFCE Low Nuclear Growth</u>				<u>INFCE High Nuclear Growth</u>			
	<u>WOCA</u>	<u>U.S.</u>	<u>Foreign WOCA</u>	<u>HWR Users*</u>	<u>WOCA</u>	<u>U.S.</u>	<u>Foreign WOCA</u>	<u>HWR Users*</u>
1978	103	52	51	6	103	52	51	6
1985	245	100	145	11	274	122	152	14
1990	373	157	216	21	462	192	270	26
1995	550	200	350	37	770	275	495	51
2000	850	255	595	64	1,200	395	805	90
2005	1,100	275	825	82	1,650	480	1,170	124
2010	1,300	295	1,005	97	2,150	590	1,560	162
2015	1,450	305	1,145	109	2,700	690	2,010	203
2020	1,650	315	1,335	124	3,350	800	2,550	252
2025	1,800	320	1,480	135	3,900	910	2,990	293
<u>Average Growth Rate (GW/year)</u>								
1978 to 2000	34.0	9.2	24.7	2.6	49.9	15.6	34.3	3.8
2000 to 2025	38.0	2.6	35.4	2.8	108.0	20.6	87.4	8.1
1978 to 2025	36.1	5.7	30.4	2.7	80.8	18.3	62.5	6.1

*Included in foreign WOCA nations.

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These nuclear growth forecasts may be summarized as follows:

- INFCE High Growth. A nuclear growth in foreign WOCA countries averaging 63 GW/yr from 1978 through 2025, leading to 805 GW in 2000 and 2,990 GW in 2025. In WOCA including the United States, growth would average 81 GW/yr leading to 1,200 GW in 2000 and 3,900 GW in 2025.
- INFCE Low Growth. A nuclear growth in foreign WOCA countries averaging 30 GW/yr from 1978 through 2025 leading to 595 GW in 2000 and 1,480 GW in 2025. In WOCA including the United States, growth would average 36 GW/year, leading to 850 GW in 2000 and 1,800 GW in 2025.

A more recent forecast of installed nuclear capacities based on January 1979 data in WOCA countries was reported by the Department of Energy - Energy Information Administration in July 1979 (Reference 15) which takes into account the reduction in electricity demand and significant changes in some national programs (e.g., Iran, Brazil) since the INFCE projections were made. This update leads to the following forecast for WOCA excluding the United States:

Table 24. Installed Nuclear Capacity in Foreign WOCA Nations (GW)

Year	Foreign WOCA	WOCA	U.S.
1978	51	103	52
1985	114 to 129	216 to 247	102 to 118
1990	163 to 205	305 to 376	142 to 171
1995	232 to 296	418 to 521	186 to 225

Average Growth Rates 1978 to 1995 (GW/year)

10.6 to 14.4 18.5 to 24.6 7.9 to 10.2

Comparison of Table 24 with Table 23 shows that the more recent Department of Energy-Energy Information Administration forecast through 1995 is between 34 and 40 percent below the range of the INFCE forecast. Thus, the subsequent analysis of supply and demand imbalances will only consider the INFCE low growth.

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Two Department of Energy estimates of uranium supply for foreign WOCA countries and for WOCA countries including the United States are summarized as follows:

- High Supply. Maximum total foreign WOCA potential production capability of 147,000 short tons U_3O_8 in 2000 and 385,000 short tons in 2025; the supply is 90 to 82 percent respectively, from high-grade resources. In WOCA countries including the United States, maximum potential production capability could grow to 235,000 short tons in 2000 and 508,000 short tons in 2025; the supply is 90 and 71 percent, respectively, from high-grade resources.
- Low Supply. Total foreign WOCA potential production capability of 106,000 short tons of U_3O_8 in 2000 and 160,000 short tons in 2025; the supply is 92 and 89 percent, respectively, from high-grade resources. In WOCA countries including the United States, maximum potential production capability could grow to 192,000 short tons in 2000 and 247,000 in 2025; the supply is 89 and 68 percent, respectively, from high-grade resources.

The analysis begins with the present nuclear reactor and fuel cycle system and assumes its continuance without change. The supply/demand outlook is considered first for the foreign WOCA countries as a group; then for WOCA countries including the United States as a group; and then for individual countries. Improvements to the present system are then considered for all foreign light-water reactors as a group, and then for WOCA countries including the United States. Finally, deployment of the breeder is considered in the group of nations which currently have major breeder programs. The impact of this change is analyzed for the foreign WOCA countries as a group, excluding the United States, and then for the WOCA countries including the United States. The analyses summarized in this report are described in more detail in Reference 12.

5.2 CONTINUATION OF THE PRESENT SYSTEM

The present system for most nations with nuclear capacity consists of light-water reactors, with some nations using heavy-water reactors. A small number of other types of reactors are included with the light-water reactors.

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Heavy-water reactors currently supply about 5 percent of world nuclear capacity. It was assumed that this fraction would grow to 7.5 percent by 2000 and remain constant thereafter. Continuation of this system would imply that no fuel utilization improvements were made to the reactors and that enrichment plant tails assays remain at 0.20 percent U-235. Uranium demand in foreign WOCA countries and in WOCA as a whole would increase as is shown in Table 25 for the current system of light- and heavy-water reactors on the once-through cycle. Supply and demand are compared in Figure 16 for foreign WOCA countries and in Figure 17 for WOCA countries including the United States.

Table 25. Annual U_3O_8 Demands for WOCA Nations:
Current Light-Water Reactor and Heavy-
Water Reactor Systems*
(thousand short tons)

	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
Foreign WOCA Countries, INFCE Low Growth	50	125	196	259	290
U.S., 1978 Median Growth					
	<u>37</u>	<u>64</u>	<u>88</u>	<u>110</u>	<u>121</u>
Total WOCA	87	189	284	369	411

*Light-water reactor with 30,000 MW/t burnup fuel, 0.20 percent U-235 tails assay; heavy-water reactor with natural uranium fuel; all reactors on the once-through cycle.

A uranium supply-demand imbalance might occur in the late 1990's if the INFCE low-growth occurred in foreign WOCA countries, a median growth occurred in the United States, and a low-supply capability developed in the WOCA countries. This is a possibility, moreover, whether or not the United States is included in the WOCA group. As mentioned previously, however, the current trend through 1995 is 34 to 40 percent below the INFCE low growth and, if this trend persists an imbalance will probably not occur before the year 2010. If the high supply were achieved, an imbalance could be avoided beyond 2025. However, it should be recalled that after the year 2000, both supply projections are based on rapid expansion of production from resources currently in the "possible" and "speculative" potential categories, both of which are characterized by considerable uncertainty. Thus, if the production from these resources is limited, a shortfall might occur in the first decade after 2000.

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Figure 16. Comparison of Foreign WOCA Annual U₃O₈ Supply Capability and Demand for Current LWR's and HWR's

Figure 17. Comparison of WOCA Annual U_3O_8 Supply Capability and Demand for Current LWR's and HWR's

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The foregoing analysis treats supply and demand as aggregated for all WOCA countries. An aggregated analysis is appropriate if there is adequate uranium supply, a free market, and all nations have access to uranium on equal terms. In a long-term scarcity situation such as might occur after the year 2000 should there be a lag in developing new reserves, each country will be most concerned with its own supply and demand situation. As an example, some consumer countries are taking steps to protect their source of supply by acquiring interests in the development of uranium resources in supplier countries. Conversely, some supplier countries are establishing restrictive export policies. Thus, some nations might be concerned that a free market with access by all countries on equal terms may not occur in the future. As is shown in Table 26, uranium resources occur in a large number of countries; but in many instances, the resources currently known with high confidence, that is the reserves and probable resource categories, are small in relation to potential demand.

The totals of the <\$50/lb U_3O_8 reserves and probable potential resources previously presented in Table 18 are compared in Table 26 with estimates of cumulative U_3O_8 demand for various countries during the 1980 to 2000 time period. The percentage of demand that could be provided from indigenous resources is shown, independent of any considerations regarding the ability to develop those resources as needed. The nuclear power demands are based on projections made by the Nuclear Assurance Corporation (Reference 13) and are, in general, about 15 to 20 percent above the low projections by INFCE for individual countries. (The INFCE national projections were not publicly available at the time.) However, use of the more recent projections would not change the conclusions drawn.

Of the countries which have extensive uranium resources, only Canada is projected to have a fairly large installed nuclear system by the year 2000. Australia and South Africa have the potential to become significant uranium exporters.

In contrast, many of the countries with aggressive plans for expanding their nuclear power capabilities have little uranium. Some of these uranium-poor countries, such as the United Kingdom, the Federal Republic of Germany, and Japan have substantial nuclear capacity in operation or under construction and are currently importing significant quantities of uranium.

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Table 26. U_3O_8 Resources and Projected Demand: Individual Nations

Country	Projected Nuclear Capacity in 2000	Reserves + Probable Potential Resources	Uranium Demand (1980-2000)	Ratio of Resources to Demand
	GW	(1,000 Short Tons U_3O_8)	(1,000 Short Tons U_3O_8)	(%)
Argentina	6	36	9	>100
Australia	4	450	6	>100
Canada	54	1,164	94	>100
India	7	43	9	>100
Mexico	15	231	23	>100
South and S.W. Africa	10	546	15	>100
Yugoslavia	10	36	18	>100
Brazil	31	33	52	64
Finland	6	3	13	23
F.R. Germany	59	8	99	8
France	91	125	210	60
Italy	33	2	62	3
Japan	71	10	120	8
Philippines	3	0	6	0
The People's Republic of China	14	0	33	0
Republic of South Korea	20	4	38	11
Spain	17	21	51	41
United Kingdom	36	9	72	13

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5.3 IMPROVEMENTS IN LIGHT-WATER REACTOR FUEL UTILIZATION

A 15 percent improvement in all foreign light-water reactors, accompanied by an enrichment plant tails assay reduction to 0.10 percent, would lower annual demand by about 26 percent for those reactors in subsequent years. It was assumed for this analysis that both these improvements in light-water reactor fuel utilization would be implemented in the early 1990's in the United States, and the late 1990's in foreign WOCA countries; also new heavy-water reactors would be fueled with 1.2 percent enriched U-235 fuel after the year 2000. The annual U_3O_8 demands for this scenario, are shown in Table 27 for the INFCE low growth in foreign WOCA countries and the 1978 median growth projections in the United States. These demands are compared with the range of potential supply capability projections in Figure 18 for foreign WOCA countries and in Figure 19 for WOCA countries including the United States.

Considering only the foreign WOCA countries as a group, the implementation of a 15 percent improvement in light-water reactor fuel use and a reduction in tails assay to 0.10 percent would delay a supply-demand imbalance until after 2000 if the INFCE low growth occurred. If the current growth trend persists, a supply/demand imbalance could be forestalled until 2020. The demand in 2025 would be about 38 percent greater than the low supply, which is about the same amount as the current growth trend is below the INFCE low growth. If the WOCA nations including the United States are considered as a group the outlook is about the same. Again, it should be noted that the supply in the post-2000 period would be increasingly tied to production from speculative high-grade resources and low-grade resources.

Assuming the adoption of the 15 percent improved light-water reactor and tails reduction to 0.10 percent in the year 2000 were followed by adoption of a 30 percent reduction in U_3O_8 requirements and a reduction in tails assay to 0.05 percent U-235 by the year 2010, and that these improvements were applied to all new reactors, annual demands would be lowered by about 43 percent in subsequent years as compared to the system with current light- and heavy-water reactor fuel utilization technology. The annual U_3O_8 demands for this scenario are shown in Table 27 for the foreign WOCA countries and the United States. Potential supply capability is compared with demand in Figure 18 for foreign WOCA countries and Figure 19 for WOCA countries including the United States. Considering the foreign WOCA countries as a group, a supply capability about 20 percent greater than the low supply would avoid an imbalance until 2025 with these additional improvements in light-water reactor fuel

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Table 27. Annual U_{308} Demands: Foreign WOCA Nations,
Using Improvements in Light-Water Reactor and
Heavy-Water Reactor Fuel Utilization
(thousand short tons)

	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
<u>LWR-15% Improved</u>					
<u>0.10% Tails Assay^a</u>					
Foreign WOCA countries,					
INFCE Low Growth	50	96	148	195	220
U.S., 1978 Median Growth	<u>32</u>	<u>47</u>	<u>65</u>	<u>81</u>	<u>89</u>
Total WOCA	82	143	213	276	309
 <u>LWR-30% Improved,</u>					
<u>0.05% Tails Assay^b</u>					
Foreign WOCA Countries,					
INFCE Low Growth	50	96	137	173	191
U.S., 1978 Median Growth	<u>32</u>	<u>46</u>	<u>56</u>	<u>66</u>	<u>72</u>
Total WOCA	82	142	193	239	363

^aTails assay reduction implemented 1990 in U.S., late 1990's in foreign WOCA countries.

^bTails assay reduction from 0.10 to 0.05 percent implemented in 2000 in U.S. and in next decade in foreign WOCA countries.

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Figure 18. Comparison of Foreign WOCA Annual U_3O_8 Supply Capability and Demand for Improved LWR's and HWR's

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Figure 19. Comparison of WOCA Annual U_3O_8 Supply Capability and Demand for Improved LWR's and HWR's

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utilization. If the WOCA countries including the United States are considered as a group, the supply capability would have to be only 5 percent greater than the lowest capability projection to be adequate through 2025. If the current growth trend which is 34 to 40 percent below the INFCE low growth projection persists, a supply/demand imbalance would not occur until after 2025.

In summary, improvements to reduce uranium requirements for light-water reactors by about 15 percent and a reduction in enrichment plant tails assay to 0.10 percent could probably avoid a supply-demand imbalance through at least 2020, if uranium supplies are considered as an aggregated resource for the WOCA countries and the current nuclear growth trend persists. Additional improvements to light-water reactor uranium utilization could provide further assurance that demand would not exceed the lowest projection of supply capability through 2025. However, expansion of foreign uranium supply is a much more critical need for foreign countries than for the United States if a once-through scenario is to be followed. An expansion of U.S. production capability for export could alleviate supply shortfalls in foreign WOCA countries, if they occur.

5.4 FAST BREEDER REACTORS

As shown in the previous section, the outlook is favorable for avoiding a uranium supply-demand imbalance through 2025 if uranium supplies are considered an aggregate resource for WOCA countries and nuclear growth proceeds at the current pace, provided improvements in light-water reactor once-through fuel utilization and enrichment technology are deployed beginning in the 1990's. As noted previously, however, there is a mismatch between uranium suppliers and users, and therefore, some countries perceive incentives to pursue alternatives to the once-through cycle. The major alternatives being considered are advanced converter reactors, light-water reactor recycle, and fast breeder reactor recycle.

As demonstrated in Chapter 3 for U.S. demand, advanced converter reactors offer limited advantages over improved light-water reactor once-through cycles, in part because the incremental reduction in uranium requirements is relatively small compared to the improved light-water reactors, and in part because there are limits to how quickly these systems could penetrate the current nuclear market once they are commercially introduced after the year 2000. This applies even to the heavy-water reactors which are already in

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commercial use. The impact on total foreign uranium demand would be similar to that for the United States; that is, about an additional 10 percent reduction in demand by 2025.

Reprocessing and recycle are being pursued in a number of nations for both thermal reactors and fast breeder reactors. The primary objective of these programs, as stated by some of those nations participating in them, is to develop recycle for the deployment of fast breeder reactors. The liquid-metal fast breeder reactor is the system receiving the most development attention overseas and in the United States. Demonstration plants are operating in several nations and commercial breeder introduction is planned prior to the year 2000. In particular, the liquid-metal fast breeder reactor is being developed in large industrial nations with small or negligible uranium resources and substantial ongoing nuclear power programs, i.e., France, the United Kingdom, the Federal Republic of Germany, and Japan. The stated goal of these nations is to rapidly develop and deploy a technology that will eventually reduce the requirements for imported uranium. This analysis focuses on these four countries and considers first the impact of breeder deployment on total foreign uranium demand, and then the impact of breeder deployment in these four countries and in the United States on total uranium demand in the WOCA countries.

The critical factors in breeder reactor deployment are the time of introduction and the rate at which they can be introduced into the system. For this analysis it was assumed that commercial deployment in the four foreign WOCA nations would begin in 2000, and the breeder would be introduced into a system consisting primarily of 15 percent improved light-water reactors using an enrichment tails assay of 0.10 percent U-235. The time of introduction is consistent with the current plans of these nations. Two scenarios were assumed, one leading to liquid-metal fast breeder reactor deployment of about 10 percent of installed foreign capacity by 2025 in what was considered a slow scenario and another leading to an installed foreign capacity of 20 percent in what was considered a rapid scenario. If all breeders were deployed in these four WOCA nations, the liquid-metal fast breeder reactor market penetrations in these four nations would be about 25 or 50 percent of total nuclear capacity in 2025, respectively, for the two scenarios. The annual $U_{38}O_{10}$ demands for these two scenarios are shown in Table 28 for foreign WOCA nations.

The effect of these two liquid-metal fast breeder reactor deployment rates on foreign uranium demand is shown in Figure 20. For the INFCE low growth rate,

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Table 28. Annual U_{308} Demands: Foreign WOCA Nations
Introducing the Fast Breeder Reactor in Four Nations
With 15 Percent Improved Light-Water Reactors*
(thousand short tons)

	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
Rapid fast breeder reactor deployment	50	96	128	160	192
Slow fast breeder reactor deployment	50	96	136	180	208

*INFCE low growth; fast breeder reactor introduced in the year 2000 into a system of 15 percent improved light-water reactor, with 0.10 percent tails assay; rapid deployment, 20 percent of capacity in 2025; slow deployment 10 percent of capacity in 2025.

achievement of a uranium supply which is about 20 percent above the low-supply capability would be adequate if the liquid-metal fast breeder were deployed at the faster rate. Thus, the impact through 2025 of fast breeder reactor deployment would be about the same as that for the 30 percent improved light-water reactor on the once-through cycle with 0.05 percent tails assay. The deployment of the fast breeder would have greater impact after 2025. The slower deployment rate for the fast breeder reactor would lead to a uranium demand in the year 2025 about 30 percent larger than the low production capability projected in that year. The difference between the slow and rapid breeder reactor deployment rates does not appear to be significant in view of the current nuclear trend through 1995, which is 34 to 40 percent below the INFCE low growth projection. Since the four nations most likely to deploy breeders are uranium-poor, there may still exist incentives in those nations to deploy the liquid-metal fast breeder reactor even if overall nuclear power growth is low.

Two factors related to fast breeder reactor deployment would be at work to reduce uranium demand. Initially there are very few breeders in the system, so they would displace only a small percentage of the system's light-water reactor requirements for uranium. However, large quantities of spent fuel must be reprocessed to separate enough plutonium for the liquid-metal fast breeder reactor's first cores and at least one or two reloads. Therefore, there is a significant amount of uranium to be recovered which can be re-enriched and recycled in light-water reactors. Enough uranium can be recovered from the spent fuel reprocessing needed for one liquid-metal fast breeder reactor's initial core to replace the annual U_{308} requirements for about five or six light-water reactors. This latter effect will be important as long as the light-water reactor spent fuel stockpile is reprocessed for liquid-metal fast breeder reactor initial cores.

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Figure 20. Comparison of Foreign WOCA Annual U_3O_8 Supply Capability and Demand for a System with FBR's, 15% Improved LWR's and 0.10% Tails

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As with advanced converters, deployment constraints limit the impact of a new technology until it achieves a significant share of the market. For the above cases, 90 and 80 percent of the foreign nuclear system would be on the light-water reactor once-through fuel cycle in 2025. Irrespective of plans for the liquid-metal fast breeder reactor, there will still be strong incentives for once-through improvements because such a large part of the WOCA capacity is still on that cycle. This will be especially true if liquid-metal fast breeders are deployed in a limited number of nations. The annual foreign WOCA U_3O_8 demands for the deployment of the fast breeder reactor into a system of 30 percent improved light-water reactors with an enrichment plant tails assay of 0.05 percent U-235 are presented in Table 29.

Table 29. Annual U_3O_8 Demands for Foreign WOCA Nations
Introducing the Fast Breeder Reactor in Four Nations with
30 Percent Improved Light-Water Reactors*
(thousand short tons)

	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
Rapid fast breeder reactor deployment	50	96	124	148	160
Slow fast breeder reactor deployment	50	96	132	160	175

*INFCE low growth; fast breeder reactor introduced in 2000 into a system of 30 percent improved light-water reactors with 0.10 percent tails assay; rapid deployment, 20 percent of capacity in 2025; slow deployment 10 percent of capacity in 2025.

Figure 21 shows the effects of achieving this additional improvement in light-water reactor fuel utilization together with either a rapid or a slow liquid-metal fast breeder deployment rate. By 2025 annual uranium demand would be at about the level of the low production capability projected in that year. The deployment of the fast breeder reactor would reduce demand in 2025 either 16 or 8 percent, respectively, below that for the 30 percent improved light-water reactors on the once-through cycle using 0.05 percent U-235 tails assay. Thus, achieving the maximum improvements in light-water reactor uranium utilization on the once-through cycle could reduce the urgency in these four countries for the rapid deployment of the fast breeder reactor to avoid supply-demand imbalances through 2025, if uranium supply and demand are considered on an aggregated basis. Rapid deployment of the fast breeder reactor would be more important for higher growth rates and for the long-term needs beyond 2025.

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Figure 21. Comparison of Foreign WOCA Annual U_3O_8 Supply Capability and Demand for a System with FBR's, 30% Improved LWR's and 0.05% Tails

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The foregoing analysis does not show the ultimate effects of breeder deployment. In those four countries assumed to have early and aggressive liquid-metal fast breeder deployment, a decrease in uranium demand would occur in about 10 years or less if breeders were introduced at a moderate rate. Moreover, those countries would represent 45 percent of foreign nuclear capacity in the year 2000, about 35 percent in 2025, and less than 35 percent in subsequent years. Thus, the annual uranium demand would tend to increase after 2025 for the foreign nations as a group if nuclear growth continues at a faster pace in the countries with once-through light-water reactors than it would in the four countries with breeders, assuming breeders were to be restricted to these four countries.

If the fast breeder reactor is deployed in the United States as well as the four large industrial WOCA nations (i.e., France, the United Kingdom, the Federal Republic of Germany, and Japan), the aggregated demand in WOCA countries will be further reduced. The annual U_3O_8 demands for these scenarios are presented in Table 30. For a rapid breeder deployment rate leading to 19 percent of U.S. capacity in 2025, an introduction date of 2006 was assumed. For the slow deployment rate, an introduction date of 2014 was assumed while breeder capacity grew to 5 percent of total U.S. capacity by 2025.

Figure 22 compares the WOCA supply capability and demand for the two breeder introduction scenarios in a system of 15 percent improved light-water reactors. If these results are compared with the scenarios in which breeders are only introduced into the four foreign WOCA nations mentioned, it is apparent that the introduction of the fast breeder reactor into the United States would further reduce the possibility of a supply-demand imbalance. Also, rapid fast breeder reactor deployment in the United States would keep demand below the minimum estimated supply capability for WOCA. Figure 23 compares the WOCA supply capability and demand for the two breeder introduction scenarios in a system of 30 percent improved light-water reactors. The achievement of the maximum level of light-water reactor fuel utilization improvements in WOCA countries would keep the demand below the low supply capability even with slow fast breeder reactor deployment.

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Table 30. Annual U_{308} Demands for WOCA Nations
Introducing the Fast Breeder Reactor in
Four Foreign Nations and the United States*
(thousand short tons)

	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2025</u>
<u>FBR Introduction into</u>					
<u>15% Improved LWR,</u>					
<u>0.10% Tails Assay System</u>					
Rapid FBR Deployment	87	143	189	215	234
Slow FBR Deployment	87	143	200	256	282
<u>FBR Introduction into</u>					
<u>30% Improved LWR,</u>					
<u>0.05% Tails Assay System</u>					
Rapid FBR Deployment	87	143	178	190	204
Slow FBR Deployment	87	143	188	225	238

*INFCE low growth; fast breeder reactor introduced in foreign WOCA nations in 2000; rapid deployment 20 percent of capacity by 2025; slow deployment 10 percent of capacity by 2025. Fast breeder reactor introduced in the United States in 2006 and reaching 18 percent of capacity by 2025; for slow deployment, introduction is in 2014 and fast breeder reactor capacity of 4 percent in 2025.

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Figure 22. Comparison of WOCA Annual U_3O_8 Supply Capability and Demand for a System with FBR's, 15% Improved LWR's and 0.10% Tails

Figure 23. Comparison of WOCA Annual U_3O_8 Supply Capability and Demand for a System with FBR's, 30% Improved LWR's and 0.05% Tails

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Figure A-1. U_3O_8 Resource Utilization for Once-Through Cycles Relative to Current PWR

(Current PWR Requires 5717 Tons of U_3O_8 per GWe-30 Yr Life at 70% Capacity Factor, 0.2% Enrichment Tails)

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6. WORLD SUPPLY AND DEMAND FOR OTHER RESOURCES AND FUEL CYCLE SERVICES

Currently there is a commercial-scale demand for the following fuel cycle services: uranium enrichment, spent-fuel storage, and, to a limited extent, heavy water and reprocessing. Thorium would be required in some alternative reactor and fuel cycle systems. Supply and demand are first analyzed for enrichment and spent-fuel storage services, and then for potential reprocessing services. Finally, heavy-water supply and demand relationships for current systems and some assumed scenarios, and thorium supply and demand for future alternatives, are analyzed.

For the next 10 to 20 years, uranium supply appears to be the critical item in assuring the security of nuclear fuel supply to other nations. Although any element of the nuclear fuel cycle that is not directly accessible to a nation may be viewed as a critical supply item to that nation, uranium appears to be the item of most concern to other nations.

Of the other items considered here, only significant quantities of uranium enrichment services and spent-fuel storage are known to be required with any degree of certainty. The demand for heavy water and thorium reprocessing will be dependent upon the use of particular reactor and fuel cycles. For these items, global supply is difficult to assess because, where required, they will often be supplied by the user country or through bilateral agreements. Thus, where supply is handled on a case-by-case basis, global supply has limited meaning.

6.1 ENRICHMENT

WOCA Nations

Since between 90 and 95 percent of projected world nuclear generating capacity will be produced by light-water reactors between now and the year 2000, there will be a continuing and growing world demand for enrichment services. Furthermore, after the year 2000, demand will remain strong because, even with low nuclear growth and the introduction of the fast breeder reactor, the demand for enriched uranium fuel would increase through the year 2025.

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Until recently, the United States has held a virtual monopoly on the supply of commercial enrichment services for the world's reactors. Through 1980, the United States will have supplied more than 90 percent of total separative work for uranium enriched to 3 percent U-235 or less, with the Soviet Union providing much of the rest. This situation will change over the next decade, as a number of new enrichment plants, most of them in Europe, begin operation. As shown in Table 31, foreign capacity will be comparable to U.S. capacity during the early and mid-1980's, and by 1990, U.S. capacity is projected to be about 40 percent of total world capacity.

The status of major enrichment facilities is summarized as follows:

British Nuclear Fuels, Ltd., United Kingdom - The 400,000 SWU/yr diffusion facility at Capenhurst has been supplying Britain's Advanced Graphite Reactor program for the past ten years. It is expected that this facility will be phased out in the 1980's as Urenco comes into full production.

Commissariat a l'Energie Atomique, France - Separative work shown in Table 31 is to be supplied to Cogema in 1979 from the Pierrelatte plant. The actual capacity is greater than the Cogema commitment and is about 400,000 SWU/yr. The balance of the capacity is used primarily for government purposes.

Eurodif, S.A., France - The Eurodif facility at Tricastin began commercial deliveries of enriched uranium in April 1979, and is scheduled to reach full capacity by 1982.

Compagnie De Realisation D'Usines De Diffusion Gazeuse, France - The partners of Coredif have reportedly made a firm decision to begin production in the mid-1980's. The first stage of production of two to four million SWU is planned for 1986, and by 1990 production would reach ten million SWU. This is subject to change, however, depending on reactor demand and commercial considerations.

Empresas Nucleares Brasileria, S.A., Brazil - The Brazilian organization, Nuclebras, is planning a 250,000-SWU capacity enrichment plant for the mid-1980's utilizing a jet nozzle process under development in the Federal Republic of Germany. Construction of the plant is dependent upon the operational success of current development work.

Power Reactor and Nuclear Fuel Development Corporation, Japan - Japan's planned centrifuge demonstration plant should be completed by 1984. The capacity is expected to reach over one million SWU in 1988, and four million SWU annually by the early 1990's.

Table 31. Enrichment Plant Capacities Available For Commercial Enrichment
(millions of SWU/year)

Facility	Site of Facility	Type of Plant	1978	1980	1982	1984	1986	1988	1990
BNFL	UK	Diffusion	0.4	0.4 ^a	-	-	-	-	-
CEA	France	Diffusion	0.2	0.4 ^a	-	-	-	-	-
Eurodif	France	Diffusion	0	6.0	10.8	10.8	10.8	10.8	10.8
Coredif	France	Diffusion	-	-	-	-	2.0 ^e	6.0	10.0
Nuclebras	Brazil	Jet Nozzle	-	-	-	-	0.2 ^e	0.2	0.2
PNC	Japan	Centrifuge	-	-	0.05	0.15	0.55	1.35	2.5
Techsnab	USSR	Diffusion	(2.4) ^b	(3.9)	(4.0)	(3.4)	(3.2)	(3.2)	(2.4)
		Total USSR	5.0	8.0	10.0	10.0	10.0	10.0	10.0
UCOR	South Africa	Stationary walled Centrifuge	0.006	0.006	0.006	0.006	0.3 ^e	0.3	0.3
Urenco	UK, Netherlands, FRG	Centrifuge	0.3	0.5	1.0 ^e	2.0	4.0	7.0	10.0
US DOE	USA	Diffusion	12.2 ^c	10.0 ^f	21.1	23.1	25.1	25.1	25.1
		Centrifuge	-	-	-	-	-	0.9	4.0
TOTAL ^d			18.1	25.3	43.0	46.1	53.0	61.7	72.9

^aFacilities may be used for government requirements or shutdown when new facilities come on line.

^bCommitments to Western Countries in 1978 and subsequent years.

^cCapacities based on planned power purchases through 1990; does not include 0.5 million SWU/year for government requirements 1978 through 1990.

^dIncludes Techsnab total.

^eMay be delayed or reduced.

^fPower limited.

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Vsesojuznoje Exportno-Importnoe Objedinenije, USSR - Techsnabexport's ability to supply enrichment service is unknown. The quantities shown in the first line for Techsnabexport in Table 31 are based on its nominal commitments to Western countries. If the estimated requirements for all its customers are included, Techsnabexport's ability to supply enrichment services may approach 10 million SWU annually. This estimate is shown on the second line under Techsnabexport.

Uranium Enrichment Corporation of South Africa, LTD., South Africa - In 1977, South Africa completed a pilot plant at Valindaba estimated to be about 6,000 SWU capacity. Plans have been announced to expand this pilot facility to guarantee the South African electricity industry independence from foreign supplies. Although the size of the plant has not been announced, it is probably planned to be 200,000 to 300,000 SWU annually. This would be enough to support the planned South African Koeberg nuclear station (two 900 MW reactors). South Africa has indicated that it may expand its capacity for the export market in the future.

Uranium Enrichment Company, Ltd., United Kingdom, Netherlands, and the Federal Republic of Germany - It is expected that both the Almelo plant in the Netherlands and the Capenhurst plant in the United Kingdom would reach 200,000 SWU/yr capacity each by 1979. They are expected to reach a combined production capacity of 2 million SWU annually by 1984 to 1986, or later if reactor delays so dictate. Urenco's planned capacity additions generally will be related to contractual commitments. Nevertheless, there is an unknown minimum capacity addition needed annually in order to sustain machine manufacturing. However, if justified by demand, Urenco is currently capable of expanding at the rate of 500,000 SWU/yr, and could increase this rate to 1.5 million SWU without major capital investments.

United States Department of Energy, United States - The available capacities shown in Table 31 for the Oak Ridge, Paducah, and Portsmouth diffusion plants are based on the existing facilities, the schedule to complete the two programs currently in progress to improve and upgrade these plants, and the planned power purchases. The diffusion plant design capacity after completion of improvements in 1985 will be 27.3 million SWU/yr; the maximum operating capacity based on the expected annual average power supply is 25.6 million SWU/yr. The quantities shown in the table do not include U.S. Government requirements of 0.5 million SWU/yr. Additional centrifuge capacity of 2.2 million SWU/yr is under construction at Portsmouth, Ohio, and additional capacity of 6.6 million SWU/yr will be added as needed.

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The United States is expected to remain a major supplier of enrichment services, but the principal foreign users will become less dependent on the United States. Japan will fulfill its enrichment needs with purchases from the United States and Eurodif through 1990, but plans to become self-sufficient thereafter. As of 1978, the European Economic Community countries depended on the United States and the U.S.S.R. for 99 percent of commercial enrichment requirements, but it is projected that two-thirds of their needs will be met internally by 1980 and 75 percent by 1985. In addition to the Japanese and the European ventures, Brazil and South Africa plan to construct enrichment facilities.

Almost all of the present commercial enrichment capacity uses the gaseous diffusion process, and almost all of the new capacity through the mid-1980's will be gaseous diffusion as well. Thereafter, all new capacity is expected to be filled by more advanced types, primarily gas centrifuge. Also, a number of more advanced techniques are being developed, including the Becker nozzle process in the Federal Republic of Germany, and plasma and laser processes in the United States. These processes are discussed in Volume IX, Chapter 2. Over the next 10 to 20 years, therefore, the number of enrichment suppliers, as well as the number of viable enrichment technologies, are expected to increase.

Current estimates indicate that excess enrichment capacity will exist in the WOCA countries until the early 1990's. Current reactor requirements in 1979 are about 20 million SWU/yr compared to global capacity of about 25 million SWU/yr. This current overcapacity is one reason that U.S. enrichment plants will be operated at less than full capacity for the next several years. By 1990, reactor requirements are expected to reach 40 to 50 million SWU/yr, which compares to a projected supplier capacity of over 70 million SWU/yr. If the overcapacity reaches this level, supply will not be a problem through at least the mid-1990's. This situation will probably lead to several of the following: delays in capacity additions, cutbacks in plant operations, some stockpiling of enriched uranium, and a reduction of tails assay.

For the INFCE low-growth case, annual enrichment requirements would increase from about 90 million SWU in the year 2000 to 200 million SWU in 2025, requiring annual additions of about 4 to 5 million SWU, if tails assay remains at 0.20 percent and no improvements are made to light-water reactor fuel utilization technology. By comparison, announced additions for the period 1985 to 1990 average about 4 million SWU of new capacity per year. Considering the number of suppliers and technologies, the slightly increased rate of annual

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capacity additions over the long-term for the low-growth case appears to be technically reasonable. In general, any improvement to reactor utilization technologies will reduce enrichment requirements, and any reduction in tails assay will increase them.

The crucial factor in future enrichment capacity expansion is the rate at which new capacity can be added. The project time for enrichment capacity additions is shorter than the project time for new reactors, and thus, the market can be defined before commitments are made to construct new facilities. There appears to be no technical factor constraining the rate of expansion; the only limit on expansion is the extent to which Government and private investors are willing to construct new facilities.

United States

The United States is currently the major supplier of enrichment services in the world for foreign civilian nuclear power programs, as well as the supplier of all enrichment services for domestic reactors. All uranium enrichment in the United States is performed in facilities owned and managed by the Department of Energy to enrich uranium provided by the customer.

Through the 1990 to 1995 time period, U.S. enrichment capacity appears adequate to meet both U.S. and some foreign requirements, in addition to those already contracted for. In fact, at this time there is an excess of enrichment capacity, and the Department of Energy plans to operate the enrichment plants at less than full capacity during the next several years. An excess of capacity has existed for a number of years, and, as discussed in Section 2.2.4, this has resulted in the Department of Energy producing a large stockpile of enriched uranium, which provides an assurance of supply to customers. Current plans are to increase the stockpile during the early 1980's and to use it during the late 1980 and early 1990's to meet anticipated demand.

Prior to the ongoing capacity expansion programs, U.S. enrichment capacity was about 17.2 million SWU/yr. Programs now underway will increase the design capacity of the three existing gaseous diffusion plants to 27.3 million SWU/yr by 1981. The maximum operating capacity based on expected annual average

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power supply will then be 25.6 million SWU/yr. An expansion of the uranium enrichment plant at Portsmouth, Ohio, is also underway and will add 2.2 million SWU/yr of gas centrifuge capacity in about 1988. An additional 6.6 million SWU/yr of gas centrifuge capacity is to be added at Portsmouth as required. The current Department of Energy plan for operating these facilities through 1990 was shown in Table 31.

Completion of these U.S. expansion plans would result in 36 million SWU/yr of rated design capacity in the mid-1990's. By comparison, domestic requirements in 1995 are estimated to be 30 million SWU for the 1978 median nuclear-growth case. The United States will have adequate capacity to meet not only domestic requirements, but enough to be a reliable supplier of a portion of foreign requirements through the mid 1990's. Expansion of enrichment supply capacity beyond the mid-1990's will depend upon commitments for new U.S. nuclear generating capacity made in the 1980's and beyond, and foreign contracts for enrichment services.

Annual enrichment requirements for several alternative scenarios in the United States are compared on Table 32 for the 1978 median nuclear growth projection. Several trends are shown. Annual capacity additions for continuing the light-water reactor once-through system would average 1.3 to 1.8 million SWU/yr. This rate of expansion is believed to be feasible but would require annual investment of several billion dollars. The near-term improvement of light-water reactors will have a very small impact on enrichment demand, reducing demand by about 5 percent if the tails assay is held constant and increasing demand by 31 percent if the tails assay is reduced to 0.10 percent U-135. Compared to the improved light-water reactor once-through system, the high-temperature gas-cooled reactor once-through system would have very small impact on enrichment demand. The 1.2 percent enriched heavy-water reactor, however, would have about 25 percent lower demand than the improved once-through light-water reactor systems. A major increase in long-term requirements would result if a lower tails assay were to be used. Going to 0.10 percent U-235 tails assay from 0.20 percent U-235 tails assay increases long-term demand by 39 percent and going to 0.05 percent U-235 tails assay increases demand by 82 percent. Introduction of the fast breeder reactor would reduce requirements soon after introduction.

Enrichment requirements for the 30 percent improvement in light-water reactor once-through fuel utilization are not given, since the technical details of the total improvement are not sufficiently defined to allow the calculation to be made.

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Table 32. Annual Enrichment Requirements for Alternative
Reactor Scenarios, 1978 Median Growth
(millions SWU/year)

<u>Reactor Scenario/Tails Assay</u>	<u>Annual Enrichment Requirements</u>			<u>Average Annual Increase</u> <u>2000-2025</u>
	Year			
	<u>2000</u>	<u>2015</u>	<u>2025</u>	
Current LWR/0.20%	38	52	72	1.4
15%-Improved LWR/0.20%	36	49	68	1.3
15%-Improved LWR/0.10%	50	68	94	1.8
HWR+15%-Improved LWR/0.20%	36	48	51	0.6
HTGR+15%-Improved LWR/0.20%	36	50	70	1.4
15%-Improved LWR- Self Generated Recycle/0.20%	32	44	61	1.2
LWBR (Type 1)+15%-Improved LWR/0.20%	42	51	65	0.9
FBR+15%-Improved LWR/0.20%	36	48	45	0.4

6.2 SPENT-FUEL STORAGE

Foreign WOCA Nations

At the present time, the management of spent fuel is a problem of radioactive waste management which each country with commercial nuclear power is facing. A discussion of the proliferation concerns of storing spent fuel is provided in Volume II, section 3.2. In most cases the spent fuel is held at reactors or, in a few cases, in central facilities. A few countries are proceeding with reprocessing of spent fuel, which causes proliferation concerns. These concerns are discussed in Volume II. There are no national or international facilities for permanent spent-fuel disposal. Although spent fuel has been placed in interim storage for over 20 years in some countries, there is no demonstrated technology for permanent disposal. Each country is developing its own approach to the problem. In a recent report (Reference 9) the Nuclear Regulatory Commission estimated that 78 percent of all reactor spent fuel in the United States would still be stored at reactor sites in the year 2000. The United States has plans to demonstrate spent-fuel disposal technology and has offered to accept spent fuel from foreign countries for interim storage on an emergency basis where this would promote nonproliferation objectives. The Federal Republic of Germany has recently announced a policy of long-term storage of spent fuel while it considers the disposal of either high-level waste or spent fuel. France and the United Kingdom are reprocessing some domestic spent fuel and have made commitments to reprocess spent fuel from Japan and the Federal Republic of Germany. In summary, the facilities for spent-fuel storage consist primarily of the spent-fuel storage pools at the reactor sites in the various countries, the receiving pools at the reprocessing plants in France and the United Kingdom, and the receiving pools at the shut-down or incomplete reprocessing plants in the United States.

The requirements for spent-fuel storage will depend on the choices made by the individual nations in their nuclear programs. A forecast of spent fuel arisings in WOCA countries excluding the United States is shown in Table 33. This forecast, developed by INFCE Working Group 6, on spent fuel from data furnished by the countries, appears to be too high based on recent trends. Spent-fuel storage is beginning to be a problem in several countries, however, as the storage pools at reactor sites are becoming filled. Most reactors have been constructed with storage capacity for 1 to 1 1/2 reactor cores; that is, storage capacity for 5 to 6 years after startup. (Canadian heavy-water reactors have 10 years storage.) Reactor operators usually wish to maintain available storage for one full core discharge, in the event reactor or fuel

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Table 33. Cumulative Spent-Fuel Arisings in 1978 and
Projected to 1980, 1985, and 2000
(tons of uranium)

Country	1978	1980	1985	2000
Argentina	----	620	1,890	15,290
Austria	----	----	110	440
Belgium	64	196	764	3,702
Brazil	----	----	92	7,600
Canada	2,366 ^a	2,500	8,310	65,300
Denmark	----	----	----	680
Egypt	----	----	92	373
Finland	----	56	396	2,014
France	----	----	2,900	19,000
Federal Republic of Germany	165	655	3,065	21,490
Greece	----	----	----	461
India	50	210	876	7,900 ^d
Iran	----	----	361 ^d	6,697 ^d
Italy	51	73	344	1,592 ^e
Japan	720 ^b	1,000 ^f	3,900	30,000
South Korea	----	16	347	7,663
Mexico	----	----	80	2,740
Morocco	----	----	----	221
Netherlands	18	53	140	1,767
Philippines	----	----	33	462
Portugal	----	----	----	1,202
South Africa	----	----	72	1,592 ^e
Spain	^e	60 ^c	737	1,592 ^e
Sweden	120	420	1,400	1,592 ^e
Switzerland	252	320	787	2,164
United Kingdom	100	300	1,000	8,400
Total	3,906	6,479	27,691	207,158

^a Canada, 1976

^b Japan, 1976

^c Spain, 1977

^d Excluded from total due to uncertainty in plans

^e Not available

^f Not available; estimated

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malfunction requires an unscheduled core unloading. Most storage pools can be modified to provide additional storage. This storage problem will worsen in the 1980's and 1990's as the amount of spent fuel builds up. Unless those nations with recycle and breeder programs are successful and offer reprocessing services to other countries, spent fuel storage will be a large and growing problem after the year 2000.

Assuming a continuation of the present light- and heavy-water reactor once-through systems, the spent-fuel storage requirements in away-from-reactor facilities for the high growth case in WOCA exclusive of the United States would grow to about 90,000 tons in the year 2000, about twice that projected for the United States. As was assumed for the United States assessment, spent fuel will remain at reactor sites for seven years after exposure and prior to being sent to away-from-reactor storage. For the INFCE low growth, spent-fuel storage would increase to about 70,000 tons in the year 2000, and about 0.75 million tons in 2025. If the improved light-water reactor is introduced in the 1990's, spent fuel discharged from each reactor will be reduced by about 40 percent, and the away-from reactor storage for the system will be reduced by about 25 percent in the year 2025. If the liquid metal fast breeder reactors were introduced around the year 2000 in conjunction with light-water reactor improvements, the aggregate impact on requirements would be much greater, since each fast breeder started up requires the plutonium recovered from reprocessing 28 to 40 GW years of light-water reactor spent fuel. For the rapid fast breeder reactor introduction rate discussed in Chapter 5 and the INFCE low growth, storage requirements would be about 0.4 million tons in 2025, a further reduction of 35 percent. For the slower fast breeder reactor deployment rate, spent-fuel storage requirements would reach a level of about 0.5 million tons in 2025.

United States

The current U.S. policy is to store spent fuel for an indefinite period while re-examining the benefits and risks of proceeding with reprocessing and recycling of plutonium.

If the ban on reprocessing is continued indefinitely, provision will have to be made for the long-term storage and/or permanent disposal of spent fuel. A presidential policy on the interim management of spent fuel was announced in October 1977. Under this policy, the Federal Government would offer to take

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title to and provide interim storage for spent fuel from U.S. power reactors and spent fuel from foreign reactors, where this would contribute to nonproliferation goals. Approaches for storage and disposal are under study and development by the Department of Energy (References 10 and 11). As of this time, no final decision has been made on how spent fuel will be managed once it leaves reactor sites. Over the near term, there is concern that some reactors will have to shut down in the mid-1980's, because their spent-fuel storage basins will become full unless some fuel can be transferred to other sites or new onsite storage is built within the next few years.

Estimates of the quantities of spent fuel which must be managed in the United States for alternative reactor and fuel cycle scenarios are presented in Table 34 in terms of the requirements for away-from-reactor storage.

For this analysis it was assumed that fuel discharged from the reactor core remains at the reactor site for 7 years and then is transferred to away-from-reactor storage. However, the current trend is to increase storage capacity at the reactor site by high-density racks in the reactor storage basins and by addition of new facilities. The outlook is that spent fuel will be retained at the reactors for longer than 7 years. Away-from-reactor storage is assumed to be a temporary measure lasting an indefinite period of time, and followed by permanent disposal or reprocessing.

In general, once-through fuel cycles will require the annual addition of capacity sufficient to store between 3,000 and 4,000 tons of spent fuel during the period 1990 to 2010. This is equivalent to the addition of about one major away-from reactor facility every 1-1/2 to 2 years at a cost of about \$200 million per addition in 1978 dollars (References 10 and 11). If all reactors are on the once-through fuel cycle, the largest reduction in spent-fuel storage requirements would come from deploying light-water reactor fuel utilization improvements. A light-water reactor using fuel with a 15 percent fuel-utilization improvement could operate on a 5-year cycle rather than today's standard 3-year cycle, so that one-fifth rather than one-third of the fuel is replaced annually. As a result, the annual spent-fuel discharge is reduced by 40 percent. The heavy-water reactor has slightly higher spent-fuel discharges, and the high-temperature gas-cooled reactor has slightly lower discharges than the improved light-water reactor. But due to deployment constraints, advanced converter reactors on the once-through cycle would have only limited impact on storage requirements by 2025.

Table 34. U.S. Away-From-Reactor Spent-Fuel Storage Requirements for Alternative Scenarios and the 1978 Median Growth

<u>Reactor Scenario</u>	<u>Spent-Fuel Storage Requirement</u> (thousands of tons)				<u>Average Annual Increase or Decrease</u>	
	<u>1990</u>	<u>2000</u>	<u>2010</u>	<u>2025</u>	<u>1990 to 2010</u>	<u>2010 to 2015</u>
Current LWR	9	44	112	281	5.2	11.3
15% Improved LWR	9	43	83	185	3.7	6.8
HWR+15% Improved LWR	9	43	83	190	3.7	7.1
HTGR+15% Improved LWR	9	43	83	183	3.7	6.7
LWBR (Moderate Deployment with U-235 Prebreeders)	8	42	77	149	3.5	4.8
LWBR (Deployment with Pu/Th LWRs)	9	43	43	4	1.7	-2.6
FBR+15% Improved LWR	9	43	83	96	3.7	0.9
FBR+15% Improved LWR + Self-generated recycle	9	43	82	48	3.7	-2.3

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With the light-water reactor, light-water breeder reactor, or fast breeder reactor recycle strategies, away-from-reactor storage requirements would be considerably less. Prior to 2010, use of light-water reactor recycle would have the greatest impact on spent-fuel storage; requirements are reduced to one-third of those needed for the 15 percent improved light-water reactor on the once-through cycle. After 2010, the light-water breeder or fast breeder scenarios would greatly reduce spent fuel storage requirements. Annual capacity additions would become very small or, in some cases, away-from-reactor storage capacity might become surplus.

6.3 REPROCESSING

Spent-fuel reprocessing would be required for any of the scenarios which recycle reactor fuel. In addition, fuel refabrication facilities for plutonium and/or fuels that contain U-233 would be required, although these requirements are not discussed in this report. Fuel refabrication facilities are not expected to be as limiting to recycle scenarios as reprocessing facilities will be, except for fuels requiring remote fabrication such as the U-233 fuels, very high burnup plutonium fuels, or fuels that are made radioactive for nonproliferation reasons.

At this time, several nations are operating or are planning to operate plants to reprocess spent fuel from commercial power reactors. The major motivation for reprocessing at this time appears to be to gain experience with the technology and to accumulate separated plutonium for use in fast breeder reactors. There are also some plans for the recycle of recovered plutonium and uranium in thermal reactors. At this time all large-scale reprocessing capacity, planned and operating, is for thermal reactor fuels. Although systems for reprocessing thermal and fast reactor fuels are very similar, separate plants would generally be operated for the two different types of fuels. Until a significant number of breeders become operational, probably after the year 2000, there will be no need for large commercial reprocessing plants for fast breeder reactor fuel. The large quantities of plutonium needed for initial breeder reactor cores will nearly all come from thermal reactor fuels.

Table 35 summarizes the major existing and planned reprocessing capacity in WOCA countries. Only France currently has an operational large commercial-size plant for reprocessing light-water reactor oxide fuel, but seven more

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countries have plans to introduce such plants, and three or four additional countries are expected to use the services of these plants. Most existing and planned commercial reprocessing capacity is in Europe. Japan is developing a large-scale reprocessing industry, and plans to reprocess most of its spent fuel by the year 2000. India has a small-scale capability. Brazil and Belgium are developing reprocessing for their own requirements. France and the United Kingdom have operated reprocessing plants since the 1950's, but these plants were designed for gas-cooled reactor fuels which will play a decreasing role in global nuclear power generation. The new plants which are planned or under construction in these countries will reprocess fuels from light-water reactors, and thus will be compatible with the systems of light-water reactors which dominate most nuclear power systems. The larger facilities in Europe are being developed to meet domestic requirements as well as to provide commercial reprocessing services to other nations.

It is difficult to assess the demand for reprocessing, because as long as world markets are able to supply all requirements for uranium at a reasonable price, there is no overwhelming need for it. As noted above, some reprocessing will be done for thermal recycle, but if fast breeder reactor programs are to be as aggressive as some nations have indicated, much of the plutonium recovered for processing prior to the year 2000 will have to be used for the initial cores of fast breeder reactors. Fast breeders require large inventories of plutonium for their initial cores. For example a 1 GW fast breeder will require the fissile plutonium from about 28 GW years of current-design light-water reactor operation for the first breeder core. Even if breeder reprocessing capacity is available, the early breeders will require about one-half to one-fourth of the first core quantity for at least the first one or two reload batches of fuel because of the lag times involved in cooling, reprocessing, and refabricating fuels. Reprocessing enough light-water reactor spent fuel for the first core of a 1 GW fast breeder will require nearly one-year's operation of a 800 tons/year reprocessing plant such as the two plants that France intends to begin operating in 1985 and 1987. However, the French program does not project reaching a startup rate for fast breeder reactors of 2 GW per year until the late 1990's. For the immediate future, most nations with a need for reprocessing will use their existing capacity to meet their domestic requirements, but the new capacity coming on line in the 1980's will permit an international market in reprocessing.

For the long term, reprocessing requirements are even less certain because they will depend upon the development of the world nuclear power regime. Assuming that reprocessing will be performed primarily to support breeder

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Table 35. Foreign Large-Scale Reprocessing Capacity
(tons heavy metal/year)

<u>Country</u>	<u>Type of Fuel</u>	<u>Operational^a</u>	<u>Planned Additions (Year)</u>
Belgium	metal or oxide	---	150 (1980), 150 (1982)
Brazil	oxide	---	300 (1990)
FRG	oxide	---	1,400 (1990) ^b , 1,400 (late 1990's) ^b
France	metal	1,200	---
	oxide	1,000	800 (1985), 800 (1987)
India	oxide	160	150 (?)
Italy	oxide	---	1,000 to 1,500 (late 1990's)
Japan	oxide	210	1,000 (1990's)
U.K.	magnox	2,500	---
	oxide	---	1,200 (1987)

^aLaboratory and pilot-scale reprocessing facilities are in operation in the FRG (40 t/yr), Italy (5 t/yr), and Spain (2 t/yr); other facilities are shut-down or on-call in Argentina, Belgium, Canada, and Taiwan.

^bAugust 1979 announcement by FRG Ministry for Internal Affairs appears to postpone these plants for many decades.

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deployment, the reprocessing capacity was estimated for the breeder deployment scenario presented in section 5.4. For the slow breeder deployment rate scenario, reprocessing requirements would be about 5,400 t/yr in 2000 which is less than the planned additions shown in Table 35. By 2005 requirements would rise to about 15,000 t/yr but the addition of 10,000 t/yr capacity over a 5-year period does not appear unreasonable since at least four nations will have experience with large reprocessing plants by that time (the U.K., the F.R.G., France, and Japan). After the initial stages of breeder deployment, requirements would drop to about 10,000 t/yr in 2015. For the rapid breeder deployment rate scenario, requirements would be about the same through 2005, but over the following 15 years new capacity would have to be added at the rate of about 1,400 t/yr (i.e. 36,000 t/yr capacity in 2020). Since commercial-scale plants will be in the 1,500 to 3,000 t/yr range, and considering the number of potential suppliers, this expansion also appears feasible.

United States

If Governmental and institutional constraints were removed in the United States, the supply of adequate reprocessing capacity would presumably be determined by industry. If the economics were favorable, supply would be dependent upon the willingness of industry to invest the capital and take the risks. The light-water reactor self-generated recycle scenarios have the lowest requirements because fuel is being reprocessed only as fast as it is being discharged from the reactors in contrast with other scenarios that utilize the spent fuel stockpile and require more rapid buildup of reprocessing capacity.

At this time there are no commercial reprocessing plants operating in the United States. The Allied General Nuclear Services reprocessing facility is partially completed, but further construction work has been suspended, and new facilities would have to be added and modifications made to some existing facilities prior to the issuance of a license for commercial operation. Although, the license application review has been suspended by the Nuclear Regulatory Commission, it is estimated that this work could be completed and the plant put into operation by 1990. The Allied General Nuclear Services facility has a designed annual throughput of 1,500 tons of spent fuel, which represents the scale required for a commercial plant. It appears technically feasible to bring another 1,500 t/yr on line by about the year 2000 based on the Allied General Nuclear Services facility's operating experience. Additional capacity of about 3,000 t/yr could be added in the following decade so that all light-water reactors would be using self-generated recycle by 2010.

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Table 36 presents the reprocessing requirements and the average annual capacity additions for several recycle scenarios. The reprocessing requirements are presented for the 1978 high growth projection as well as for the 1978 median growth projection to indicate the requirements if a growth rate in the median to high range resumes in the post-2000 period. In systems with more than one reactor type, several types of reprocessing facilities would be required. For example, if the plutonium-thorium prebreeder fuels are used the light-water prebreeder reactor and breeder reactor fuels would require separate facilities for the uranium-thorium, plutonium-thorium, and uranium-plutonium fuels. Also, the fast breeder scenarios would require separate facilities for light-water and fast breeder reactor fuels, although if reprocessing of both types of fuel was done at the same plant site, some facilities could be shared.

The average annual capacity additions in the 2000 to 2025 period for light-water reactor self-generated recycle are comparatively modest for either the median or the high growth rate--an annual addition of about 170 to 320 tons, equivalent to about one or two Allied General Nuclear Services - scale plants each decade at a cost in the order of \$600 million per plant (\$1978).

For the light-water breeder scenarios, expansion beyond the Allied General Nuclear Services capacity would be delayed until shortly after the year 2000. An average of about 400 to 700 t/yr of new capacity would be added every year to support the 1978 median to high growth range, that is, about three to five Allied General Nuclear Services-scale plants in each decade. These plants would be more complex than those for processing the light-water reactor uranium-plutonium fuel. The technology for the uranium-thorium and plutonium-thorium fuel reprocessing and fabrication are at an early stage of development. A vigorous technology development and demonstration program during the next 20 years would be required to achieve the recycle facility capabilities for the light-water breeder scenarios.

With fast breeder reactor scenarios, only three to five Allied General Nuclear Services-scale plants would come into operation during the first decade after introduction (2005 to 2015). However, the fast breeder reactor would rapidly capture the nuclear market during the following decade, and large quantities of light-water reactor spent fuel would have to be reprocessed to fuel the rapidly increasing number of fast breeder reactors. For the scenario with fast breeder reactor reprocessing but no light-water reactor recycle, the annual capacity additions during the period 2015 to 2025 would average 2,100 to 3,400 t/yr for the 1978 median and high growth projections, respectively.

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Table 36. Annual Reprocessing Requirements for
for Alternative Scenarios
(thousands of tons)

<u>Growth Projection</u>	<u>Reactor Scenario</u>	<u>Annual Reprocessing Requirements Year</u>			<u>Average Annual Capacity</u>
		<u>2000</u>	<u>2015</u>	<u>2025</u>	<u>2000 to 2025</u>
1978 High	LWR Self-Generated Recycle of 15% Improved LWR fuel	3.0	8.5	11.0	0.32
	LWBR (Moderate Deployment with U-235/Th prebreeders)	0.5	8.1	14.8	0.57
	LWBR (Deployment with Pu/Th LWR's)	1.6	16.3	19.0	0.70
	FBR+15% LWR	0	7.6	41.4	2.07*
	FBR+15% LWR + LWR-Self- Generated Recycle	0.1	11.2	51.0	2.04
1978 Median	LWR Self-Generated Recycle of 15% Improved LWR fuel	3.0	6.0	7.3	0.17
	LWBR (Moderate Deployment with U-235/Th prebreeders)	0.5	6.1	10.9	0.42
	LWBR (Deployment with Pu/Th LWR's)	1.5	11.5	14.5	0.52
	FBR+15% LWR	0	5.2	26.1	1.31*
	FBR+15% LWR + LWR-Self- Generated Recycle	0.4	7.7	31.7	1.25

* Reprocessing initiated in 2005; average for 2005 to 2025

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If light-water reactor self-generated recycle were also implemented, between the years 2015 and 2025, reprocessing capacity additions would be 2,400 to 4,000 t/yr. This pace of reprocessing capacity expansion would be difficult to achieve. Also, in the high growth scenario with light-water reactor recycle, the spent fuel stockpile would be consumed by the year 2025 in order to provide the plutonium needed to support the rapid expansion of fast breeder reactor capacity (about 20 GW/year) during the 2015 to 2025 period. Thus, there would be difficulty sustaining the fast breeder reactor expansion rate beyond 2025 unless self-generated recycle were temporarily discontinued, pending buildup of breeder capacity and the plutonium-generation rate in the total nuclear system. The idling or changeover of capacity for reprocessing light-water reactor fuel to provide for fast breeder fuel reprocessing is a problem that would have to be dealt with in the planning of recycle facility additions.

6.4 HEAVY WATER

Heavy water is used as a moderator and coolant in the Canadian Deuterium Uranium heavy-water reactor. For this assessment, NASAP has considered a modified version of this reactor which would use fuel enriched to 1.2 percent U-235. Details of this design can be found in section 1.2.1 of Volume IX. One important limitation to the increased use of heavy-water reactors is the high cost and limited availability of heavy water. For the initial loading of each reactor, about 780 t/GW are required for a Canadian Deuterium Uranium-type reactor, or 650 t/GW for the modified heavy-water reactor studied under NASAP. An additional 1 percent of initial inventory is required each year to make up for losses. Future demand for heavy water will depend on the commercial acceptance of heavy-water reactors. While this does not currently appear promising in the United States, a forecast by the INFCE Working Group 1 for the other WOCA countries is that 11 to 14 GW by 1985, 21 to 26 GW by 1990, and 64 to 90 GW may be installed by 2000. The ranges in this forecast correspond to the low and high nuclear growth projections, respectively. This would create a heavy-water demand of 8,600 to 11,000 tons in 1985, 16,000 to 20,000 tons in 1990, and 50,000 to 70,000 tons in 2000, based on the Canadian requirements.

As of September 1976, over 9,000 tons of heavy water had been produced worldwide. Current WOCA capacity for production of heavy water is 2,000 t/yr. This capacity may exceed 2,650 t/yr by 1980 and reach nearly 6,650 t/yr by the year 1985. This capacity would be about adequate for the lower demand

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through 1985, if some preproduction occurs. The current heavy-water production plants in the WOCA countries are listed in Table 37 together with their annual production capacity, startup date, and type of extraction process.

It takes about 5 to 6 years from the time of construction commitment to bring new heavy-water production capacity into full production. In foreign countries this compares to 6 to 7 years from the time that a heavy-water reactor is committed until its heavy-water charge is required. Since the lead time for the installation of new heavy-water reactor capacity is longer, it is possible to respond to projected heavy-water shortages prior to need.

There are four major nations that currently have heavy-water plants in operation: the United States, the U.S.S.R., Canada, and Norway. However, India presently has five plants under construction or repair, and all of these are expected to be operating before 1980. In addition, Argentina currently has plans to build heavy-water facilities, while the United Kingdom has expressed some interest in building a production plant at Chapelcross. Reportedly, Egypt has been producing heavy water as a byproduct of a fertilizer plant in Aswan. Little is known about heavy-water production in the U.S.S.R., except that hydrogen distillation plants have been used there for heavy-water production. In 1977, the U.S.S.R. agreed to supply 200 tons of heavy water to India for the operation of its RAPP-II CANDU reactor at Rajasthan.

There is no current demand for heavy water in the United States except for military purposes and a small amount for research and development. A government-owned plant with a capacity of 190 t/yr is in operation at Savannah River, South Carolina.

The heavy-water reactor assessed by NASAP requires an initial inventory of about 650 t/GW and a makeup to about 1 percent/yr. The commercial assessment in Volume IV of the NASAP Report concludes that this reactor could not enter the U.S. market before about the year 2003 and would be limited to a 50 percent market capture, at most. Because of higher capital cost and heavy-water carrying charges, it is not likely that this reactor would enter the U.S. market. However, in Chapter 3 of this Volume, which analyzed alternative systems in the United States, introduction of a heavy-water reactor with 1.2 percent enriched uranium fuel was analyzed. The heavy-water reactor installation rates and the approximate magnitude of heavy-water plant additions are summarized in Table 38.

Table 37. Current Heavy-Water Plant Capacity

<u>Country</u>	<u>Plant</u>	<u>Extraction Process</u>	<u>Plant Size, t/yr</u>	<u>Start-up Date</u>
Canada	Port Hawkesbury	GS ^a	400	1970
	Bruce A	GS	800	1973
	Glaco Bay	GS	400	1976
	Bruce B	GS	800	1979
	La Prade	GS	800	b
	Bruce D	GS	800	b
India	Nangal	Electrolysis/H ₂ Distillation	14	
	Baroda	Monothermal H ₂ /NH ₃ Exchange	67	
	Tuticorin	Monothermal H ₂ /NH ₃ Exchange	71	
	Talcher	Bithermal H ₂ /NH ₃ Exchange	63	1979
	Kota	GS	100	1979
Norway	Rjukan	Electrolysis	20	1934
United States	Savannah River	GS	190	1952

^aGS is the Girdler sulfide process for hydrogen sulfide water isotopic exchange.

^bThese plants are in an advanced stage of construction but completion has been deferred indefinitely. The plants are being maintained in a secure state and could be completed and brought on line within three years of approval to proceed.

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Table 38. Potential Heavy-Water Reactor Growth
and Average Heavy-Water Capacity

	<u>Heavy-Water Reactor Capacity Added, GW</u>	<u>Average Heavy-Water Capacity (thousand t/yr)*</u>
<u>High Demand</u>		
2003 to 2005	3	1.0
2005 to 2015	39	3.2
2015 to 2025	222	15.9
<u>Medium Demand</u>		
2003 to 2005	3	1.0
2005 to 2015	27	2.1
2015 to 2025	141	10.2

*At 650 tons/GW for initial inventory plus 1 percent/yr for makeup.

The leadtime for construction of heavy-water plants in the United States would probably be 7 to 10 years from the time of project initiation; this time is somewhat shorter than the total project time span for reactors. The Canadians, who have the most experience in constructing and operating large heavy-water plants, have constructed plant modules with capacities up to 720 t/yr. Thus, it appears technically feasible to supply heavy water at the rates required.

6.5 THORIUM

Thorium Resources

Thorium is about three times more abundant than uranium in the earth's crust. In the United States, thorium is found in a variety of geologic formations. The largest recoverable thorium reserves are in the form of vein or placer deposits.

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Monazite sands, which are primarily phosphates of the rare-earth elements, are one source of thorium. A few of these deposits have been worked commercially to recover titanium-bearing minerals with monazite containing the rare earths as a secondary product. Another source of thorium in the United States is vein-type deposits. These deposits were estimated at approximately 553,000 short tons of ThO_2 reserves and 2,700,000 short tons potential resources available at a cost of less than \$30/lb by the U.S. Geological Services in 1978. Many other deposits are considered significant but have not been adequately assessed.

In addition to domestic natural deposits of thorium-bearing minerals, there is also considerable thorium impounded in the form of crude thorium hydroxide at the only rare-earth processing facility in the United States, which is at Chattanooga, Tennessee. The rare-earth processing plant has not maintained an inventory of ThO_2 discharged to the impoundment. However, the management at the plant estimates the ThO_2 content at about 15,000 short tons; and additional ThO_2 is currently discharged to the holding pond at a rate of about 250 short tons/yr. Domestic monazite accounts for about 19 percent of the plant throughput, and the remaining 81 percent is from imported monazite. The Federal Government maintains a surplus of monazite sand to build stocks of rare-earth materials.

The largest known world reserves of thorium outside the United States are in the heavy mineral, monazite, in Indian beach sands. The resources reported in Table 39 for Australia, Egypt, India, and Liberia, and some of the resources reported for Brazil, are estimates of the thorium content in their beach sands. Unassessed quantities of monazite also occur in the sands of Bangladesh, Korea, Madagascar, South Africa, Sri Lanka, Thailand, and Uruguay. Because exploration for thorium has not been undertaken in most parts of the world, it is reasonable to expect that a large part of the world's resources have not yet been identified or assessed.

Thorium Supply

Currently, monazite sand is the only commercial source of thorium. The domestic U.S. monazite deposits being mined contain heavy minerals, of which 1 percent is monazite sand containing about 4 percent ThO_2 . The two active operations in Florida currently produce enough for the current demand of about 10 short tons of ThO_2 /yr, but could increase output to about 65 short tons with full operation of modified existing equipment. As previously mentioned,

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the rare-earth processing facility at Chattanooga is discharging about 250 short tons/yr to a holding pond, and this material could be readily recovered; the throughput of this plant, furthermore, could easily be doubled. To extend the production of ThO_2 even further, it would be necessary to process additional monazite, and store or market the additional rare-earth products produced, or to develop other thorium-bearing resources. If additional monazite is processed, it would be necessary to further expand purification capacity and to increase monazite imports and/or domestic placer mining activity. If vein-type thorium-bearing minerals become a source of additional ThO_2 , it would be necessary to develop these resources. A leadtime of 10 years is normally required for mine and mill development.

Foreign imports have been an unreliable source of thorium because national controls and agreements have become a part of the international traffic in monazite. Monazite is a primary source of rare-earth materials and is currently the only commercial source of thorium. The United States, Brazil, India, and the Republic of South Africa have been the chief sources of monazite, but small amounts have come from many other countries. In the past, many of these countries have restricted exports of monazite. In 1944, Australia prohibited shipments of monazite to markets outside the United Kingdom and the United States. The Republic of South Africa has had similar regulations. India restricted exports in 1946. At the beginning of 1951, Brazil ceased the issuance of export licenses, but was, like India, considering offers by foreign firms to process monazite within the country. Rare earths extracted from monazite were to be exported and the thorium retained in the country of origin. Also, in the past the price of monazite has been affected by political controls. Only India and Brazil still maintain embargoes on the export of monazite because of its thorium content.

The potential for satisfying foreign requirements for thorium is not well known. A relatively large resource base exists and there is a potential to greatly expand this resource base through exploration. Large deposits of unassessed monazite sands are believed to exist in a number of developing countries.

The extraction of thorium from monazite and purification of the thorium is generally straightforward. The technology and equipment for these operations could be made available to other countries as an incentive to exporting an upgraded product. With these incentives, expansion of thorium supply is not expected to be a deterrent to thorium fuel cycle deployment.

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U.S. Thorium Demand-Supply Outlook

The potential for satisfying domestic thorium requirements is excellent. A very large resource base has been established for both monazite sands and vein deposits that are scattered across the United States. The current demand for thorium is very small, and crude thorium products, resulting from rare-earth coprocessing, are being stockpiled against future needs. The industry's current production of 10 short tons/yr could be rapidly expanded to several hundred tons/yr. This expanded capacity could supply initial cores for about four reactors per year (at 68 short tons for each initial core and 25 short tons for annual makeup of each GW of reactor capacity, which is typical for light-water reactors with plutonium/thorium fuel). If additional capacity is needed, techniques for milling vein-type ores would have to be developed. Industry could expand to fill requirements with about a 10- to 15-year lead time. The annual requirement for thorium per unit of reactor capacity is only about 15 percent or less of the natural uranium requirement of a reactor which does not use thorium because the thorium is not enriched; in contrast, enriching uranium results in over 80 percent of the feed being sent to tails, potentially as waste or as fertile material for fast breeders. Also, if the thorium fuel cycle is closed, the thorium can be recovered and recycled after about 10 years' storage. Therefore, thorium supply should not be a deterrent to thorium fuel-cycle deployment in the long term and could be sufficient for about four reactors per year in the short term.

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Table 39. Thorium Resources,^a
(tons ThO₂)

<u>Country</u>	<u>Reserves</u>	<u>Potential Resources</u>
Australia	23,000	
Brazil	73,000	4,000
Canada ^b	0	314,000
Denmark	19,000	0
Egypt	18,500	350,000
India	400,000	0
Iran	0	38,000
Liberia	600	0
South Africa	14,000	0
Turkey	600	0
United States ^c	553,000	2,700,000
Total	1,101,700	3,406,000

^a Source (except U.S.): IAEA/OECD Uranium Resources, Production, and Demand.: 1977. Estimates have been rounded.

^b Over half of the total is classified as inferred resources, although associated with reasonably assured resources of uranium; less assured category reflects low degree of reliability for thorium grades and high variability of Th/U ratios.

^c Source: U.S. Geological Survey, 1978. Additional unassessed monazite resources are also known.

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APPENDIX

RESOURCES AND FUEL SERVICES REQUIREMENTS FOR INDIVIDUAL REACTORS

Production of nuclear power is based on the fission of uranium and isotopes derived from uranium and thorium. All nuclear fuel cycles are in some way derived from natural uranium. The amount of natural uranium required to produce a unit of energy varies widely, depending on the characteristics of the reactor and fuel cycle, the fractional recovery of U-235 in the enrichment process, and the degree to which fission products are removed and fissile values are recovered from spent fuel and recycled. These factors are discussed and data are presented in this Appendix for the reactors and fuel cycles assessed in this volume.

The natural uranium requirements for any fuel cycle using enriched uranium can be reduced by controlling the enrichment process to put more U-235 into fuel and less into enrichment plant tails. However, additional separative work is needed to achieve this.

The fuel utilization of once-through fuel cycles can be improved by designing the reactor for higher conversion ratio¹ and in situ burnup of the bred fissile material (plutonium from U-238 or U-233 from thorium), by more complete burnup of the initial fuel charge. Extended exposure cycles in light-water reactors reduce U_{308} consumption through more complete burnup of the initial U-235 charge and in situ burnup of the bred plutonium. Advanced converter reactors such as the heavy-water reactor, high-temperature gas-cooled reactor, and the light-water breeder reactor would have higher conversion ratios than light-water reactors.

¹The conversion ratio is defined as the amount of new fissile material (U-233, U-235, or plutonium) created in the reactor per unit of fissile material consumed; the new fissile material is created by absorption of neutrons in fertile material (uranium or thorium).

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Fuel reprocessing and recycle reduces natural uranium consumption by recovering uranium fissile values left in the spent fuel for recycle after re-enrichment or for blending into new reactor fuel, by recovery of plutonium for recycle into the reactor of origin or into a more efficient cycle such as a breeder, and by removing fission product "poisons" from the fuel. Thorium is introduced into some of these fuel cycles as an alternative to U-238. The major benefit gained by the use of thorium is the improved conversion ratios obtained through recycle of U-233 in thermal reactors.

Most of the reactors and fuel cycles discussed in this volume are either already in use worldwide, under active development, or appear to be technically feasible. These include:

Reactor Systems

- Light-water reactors of the pressurized-water reactor and boiling-water reactor type.
- Heavy-water reactors.
- High-temperature gas-cooled reactors.
- Light-water breeder reactors/high-gain converters.
- Fast breeder reactors.

In this volume, the pressurized-water reactor is used to represent the light-water reactor; analyses are generally applicable to boiling-water reactors and to the mixture of two-thirds pressurized water reactors and one-third boiling-water reactor that now exists.

Fuel Systems

- Low-enriched uranium--LEU5 (<20 percent U-235/U-238 mixtures).
- Plutonium-uranium--Pu(U).
- Plutonium-thorium--Pu(Th).

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- Uranium-thorium--U-233(Th).
- Denatured uranium-thorium--MEU5(Th) (<12 percent U-233/U-238 mixed with thorium).

A.1 URANIUM, FISSILE MATERIAL, AND SEPARATIVE WORK REQUIREMENTS FOR SELECTED REACTORS AND FUEL CYCLES

A.1.1 Once-Through Fuel Cycles (Figure A-1)

Analyses of evolutionary improvements to once-through fuel cycles show that substantial reductions in natural uranium requirements are possible. A reduction in the 30-year U_{30} requirements of over 40 percent from the current light-water reactor seems plausible by the year 2000. Specific conclusions are:

- Reducing enrichment tails assay from 0.20 percent to 0.10 percent U-235, which can be achieved using current technology, saves 13.4 percent of the U_{30} used in the current light-water reactor cycle but requires 39 percent more separative work.
- Reducing the tails assay from 0.20 percent to 0.05 percent U-235, which may require advanced technology to be economical, saves 18.6 percent of the U_{30} , but requires 82 percent more separative work.
- Combining increased fuel burning and other fuel management changes to achieve a 15 percent improvement in light-water reactor fuel utilization and reducing enrichment tails assay to 0.10 percent U-235 saves about 27 percent of the U_{30} used in the current light-water reactor cycle; a further reduction to 0.05 percent U-235 tails assay would save 31 percent.
- The target 30 percent improved light-water reactor combined with tails assay reduction to 0.10 percent U-235 would save about 40 percent of the U_{30} and, combined with 0.05 percent U-235 tails assay, would save 43 percent.

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Figure A-1. U_3O_8 Resource Utilization for Once-Through Cycles Relative to Current PWR

(Current PWR Requires 5717 Tons of U_3O_8 per GWe-30 Yr Life at 70% Capacity Factor, 0.2% Enrichment Tails)

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- The once-through high-temperature gas-cooled reactor cycle uses 5 percent less uranium as compared to the 30 percent improved light-water reactor when both cycles employ 0.20 percent U-235 tails assay; the high-temperature gas-cooled reactor uses 8 percent less when both cycles employ 0.05 percent U-235 tails assay.
- The once-through heavy-water reactor with lightly enriched (1.2 percent U-235) UO_2 fuel is 18 percent better than the 30 percent improved light-water reactor when enrichment tails assays are at 0.20 percent U-235. If tails assays are at 0.05 percent U-235, the advantage of the heavy-water reactor drops to only 9 percent.

A.1.2 The Impact of Improved Once-Through Light-Water Reactor Cycles on Uranium Utilization in a Recycle Mode (Figure A-2)

Since the spent fuel from all light-water reactors contains unfissioned U-235 and plutonium, reprocessing and recycle of fissile materials lead to improved fuel utilization in both standard and increased fuel-burnup cycles. However, increased fuel burnup cycles reduce the relative benefits of reprocessing, since more of the plutonium and uranium are burned up in situ. Specific observations include:

- Uranium-only recycle in the current light-water reactor reduces U_{308} requirements by about 19 percent as compared to the once-through current light-water reactor and about 5 percent as compared to a light-water reactor with increased fuel burnup. Uranium-only recycle in a light-water reactor with increased fuel burnup reduces U_{308} requirements to 6 percent less than those of the current light-water reactor with uranium-only recycle.
- Recycling uranium and plutonium in the spent fuel from current light-water reactors will reduce the 30-year-lifetime U_{308} requirements by 40 percent, as compared to the current light-water reactor on the once-through cycle.

Figure A-2. U₃O₈ Resource Utilization for Extended Exposure LWR Cycles Relative to Current PWR
(Current PWR Requires 5717 Tons of U₃O₈ per GWe-30 Yr Life at 70% Capacity Factor, 0.2% Enrichment Tails)

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- Recycling uranium and plutonium in the spent fuel from light-water reactors with increased fuel burnup reduces U_3O_8 requirements by 33 percent as compared to the current once-through light-water reactor.
- Increased fuel-burnup cycles in the uranium-plutonium recycle mode are almost as resource efficient as recycle of current light-water reactor spent fuel; thus, if improvements that increase fuel burnup are implemented on once-through cycles as an interim measure, and the fuel recycled at a later time, there would be a 7 percent loss in resource efficiency, as compared to the current light-water reactor with full recycle.

A.1.3 Uranium and Plutonium Recycle in Fast Breeder Reactors and Light-Water Reactors (Figure A-3)

Introduction of the fast breeder reactor has a much more favorable impact on uranium utilization than any of the thermal reactor options. Reactor fuel-cycle scenarios involving the use of recycle plutonium in fast reactors offer the potential of eventual independence from uranium mining. The fast-breeder reactor is the only type of reactor that can produce a significant excess of fissile material and, therefore, is the type best suited to sustain high nuclear-growth rates. Symbiotic combinations of fast and thermal reactors could be self-sustaining or growing without additional requirements for natural uranium. One fast-breeder reactor produces enough surplus plutonium to support about one-half of a light-water reactor fueled with plutonium (a plutonium burner).

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Figure A-3. Recycle of Pu and U

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A.1.4 Uranium-Thorium Recycle Systems (Figure A-4)

Uranium-only recycle in thermal reactors has been proposed as a fuel-cycle option that would minimize proliferation risks from plutonium fuels. Both denatured and high-enriched uranium cycles have been evaluated in NASAP. Specific observations include:

- The denatured U/Th cycle (uranium-only recycle) reduces U_{308} requirements by 32 percent in the light-water reactor, relative to the current once-through light-water reactor cycle.
- Advanced converters on the denatured U/Th cycle can be significantly more efficient than the denatured light-water reactor in overall U_{308} requirements. This corresponds to a reduction in U_{308} from the standard once-through cycle of 42 to 72 percent.
- The high-enriched uranium/thorium (HEU-Th) cycle is about 20 percent more resource efficient in the high-temperature gas-cooled reactor than the denatured uranium-only recycle option; the corresponding advantage of the HEU-Th cycle (uranium-only recycle) in the light-water breeder reactor high-gain converter is 40 percent.
- In terms of resource efficiency, the apparent attractiveness of the advanced converter uranium-only systems is offset by the increased amounts of U_{308} required for the initial cores.

*ALL OF THESE SYSTEMS REQUIRE AN EXTERNAL SOURCE OF HIGH ENRICHED U-233 FOR MAKEUP

Figure A-4. Recycle of Th and U*

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A.1.5 Uranium-Plutonium and Thorium Recycle Systems (Figure A-5)

Cycles combining recycle of uranium, plutonium, and thorium generally combine one set of plutonium-consuming, U-233-producing reactors with a symbiotic set of U-233/Th recycle systems. While fast or thermal reactors can be used for either function, plutonium is the preferred fuel for fast breeder reactors and U-233 the preferred fuel for thermal reactors. Specific observations include:

- Denatured thermal reactor systems combining plutonium with uranium recycle (full recycle) are more resource efficient than the corresponding denatured uranium-only recycle systems; for example, 10 percent better in the light-water reactor and 25 percent better in the light-water breeder reactor high-gain converter.
- Denatured thermal reactor cycles based on plutonium obtained from light-water reactor spent fuel (Pu/Th transmuters producing U-233) are not quite as resource efficient as the denatured systems based on U-235. However, they do not suffer from the need for increased amounts of U_3O_8 in the initial cores.
- One plutonium-fueled fast breeder reactor containing thorium blankets produces nearly enough surplus fuel to support one denatured light-water reactor or high-temperature gas-cooled reactor or two denatured light-water breeder reactor high-gain converters. The liquid-metal fast breeder reactor would produce denatured U-233 makeup for the thermal reactors and would in turn accept plutonium produced in the denatured cycle. Such a system of symbiotic reactors requires only thorium and U-238 addition at equilibrium.
- A system consisting of 80 percent light-water breeder reactor high-gain converters, and 20 percent liquid-metal fast breeder reactors can be supported by additions of U-235 equivalent to only 8 percent of the U_3O_8 requirements of the current once-through light-water reactor.
- A substantial net breeding gain can be achieved using denatured U-233/U-238-fueled liquid-metal fast breeder reactors in symbiosis with uranium-plutonium-fueled liquid-metal fast breeder reactors.

Figure A-5. Recycle of U, Pu and Th

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A.1.6 Impact of Front-End Loading in U-235-Fueled Reactors (Figure A-6)

The effect that alternative reactors and fuel cycles have on U_{308} supply requirements depend not only on the integrated 30-year lifetime U_{308} requirement but also on the front-end loading, i.e., the initial core(s) needed to reach steady-state fueling requirements. Cycles with high front-end U_{308} loading requirements may present U_{308} supply problems relative to less efficient cycles (such as the current light-water reactor) that have comparatively low initial inventory. Some observations based on Figure A-6 are as follows:

- The denatured uranium-thorium-fueled light-water reactor requires 63 percent more initial loading than the current light-water reactor.
- The light-water breeder reactor high-gain converter prebreeder requires 90 percent more initial loading than the current light-water reactor. The net U_{308} consumption of 1,300 tons over 30 years may be compared to the initial inventory of 772 tons.
- The light-water breeder reactor requires supply of 1,900 tons of U_{308} for the prebreeder, 772 tons in the first core. Of this total, the net consumption of U_{308} over 30 years is only 200 tons representing the total of net fissile production and losses to waste in the fuel facilities.

A.1.7 Mass Flow and Separative Work Data Base

This section provides estimates of the heavy-metal mass flows and separative work requirements for the reactors discussed in the resource analyses in this volume and the economic analysis in Volume V. The estimates given here are approximations to the base line information presented in Appendix B of Volume IX. Additional reactors and fuel cycles are discussed in Volume IX. The U_{308} and separative work requirement estimates given in Section A.1.1 through A.1.6 of this appendix are based on these additional data as summarized in Tables B.3 through B.7 of Volume IX.

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Figure A-6. U_3O_8 Resource Utilization in U-235/U-223 Fueled Systems
(70% Capacity Factor, 0.2% Enrichment Tails)

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The estimates presented here and in Volume IX provide a basis for comparing the resource requirements of the various fuel cycles. This is summary data, and using it to conduct independent analyses may lead to incorrect results because in some cases the system analyses have used more detailed data reflecting the year-to-year differences in mass flows.

All of the reactor/fuel cycle combinations are assumed to operate with a constant 70 percent capacity factor. Enrichment tails are assumed to be 0.2 weight percent. A 1 percent material loss due to fuel fabrication was included in the charge requirements, and a 1 percent material loss due to reprocessing was deducted from the discharge credits. A 0.5 percent material loss due to the U_3O_8 to UF_6 conversion process was included in the charge requirements for those fuel cycles that require enriched uranium. For systems such as the heavy-water reactor, which do not employ annual refueling, the annual equilibrium charge and discharge quantities were defined as the equilibrium charge (or discharge) divided by the equilibrium cycle length. Table A-1 shows U_3O_8 requirements, Table A-2 shows enrichment requirements, and Table A-3 shows the fissile material and heavy-metal mass flows. In Table A-3, discharged Pa-233 is included with the discharged U-233 because Pa-233 has a relatively short half-life (27 days, and after 1 year nearly all (99.99 percent) of the protactinium will have decayed to U-233 prior to reprocessing. In that same table fissile plutonium is defined as the sum of the Pu-239 and Pu-241 isotopic concentrations.

The tables include 30-year lifetime values as well as annual equilibrium values. Initial core charge requirements and final core discharge quantities are also reported, since these values can vary significantly from the annual equilibrium charge and discharge values. The 30-year lifetime uranium and enrichment requirements are the sum of the initial core, final core, and 28 equilibrium core annual requirements. The average annual uranium and enrichment requirements are the 30-year lifetime values divided by 30. Also shown are the equilibrium and first core enrichment requirements. The following are brief descriptions of each of the reactor types listed in the tables:

Explanation of Reactor Types

PWR-LEU Current, OT -- A current-technology once-through light-water reactor of the pressurized-water type that uses low-enriched uranium (about 3.0 percent U-235) fuel to achieve an average burnup of 30 MWd/kg.

Table A-1. U_3O_8 Requirements (short tons/GW)*

Reactor Type	Initial Core		Annual Equilibrium		Final Core		Annual Average		30-Year Lifetime			% Enrichment (Initial Core, if Different)
	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge	Discharge	Net	
PWR-LEU Current, OT	405	33	184	40	184	231	191	45	5,717	1,363	4,354	2.9(2.2)
PWR-LEU 15% Imp., OT	405	20	153	18	153	318	162	28	4,845	852	3,993	4.1(2.2)
PWR-LEU 30% Imp., OT	448	22	123	0	123	255	134	16	4,016	277	3,739	4.0(2.4)
PWR-LEU Current/LEU SGR	405	31	137	35	137	181	153	39	4,590	1,170	3,420	2.4(2.2)
PWR-LEU Current/LEU X, SGR	469	19	137	18	133	181	149	23	4,476	658	3,818	3.8(2.5)
PWR-Pu(Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
PWR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
HWR-LEU, OT	235	0	106	0	106	0	111	0	3,295	0	3,295	1.2(.8)
HTGR-MEU5 (Th), OT-Opt	250	29	123	5	123	126	126	10	3,813	298	3,515	19.8
HTGR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
HTGR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
LWBR-MEU5 (Th)-WR1	746	63	232	63	232	379	249	74	7,478	2,208	5,270	93.0
LWBR-MEU3 (Th), Recycle HGC	0	0	0	0	0	0	0	0	0	0	0	-
LWBR-MEU3 (Th), Recycle-NR1	0	0	0	0	0	0	0	0	0	0	0	-
LMFBR-Pu(U)/W	0	0	0	0	0	0	0	0	0	0	0	-
LMFBR-Pu(U)/Th	0	0	0	0	0	0	0	0	0	0	0	-

*0.2% Enrichment Tails Composition

70% Capacity Factor

1% Fuel Fabrication Loss

1% Reprocessing Loss

Table A-2. Enrichment Requirements (10^3 Kg-SWU/GW)*

Reactor Type	Initial Core		Annual Equilibrium		Final Core		Annual Average		30-Year Lifetime			% Enrichment (Initial Core, if Different)
	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge	Discharge	Net	
PWR-LEU Current, OT	208	0	111	4	111	77	114	6	3,426	188	3,238	2.9(2.2)
PWR-LEU 15% Imp., OT	208	1	105	0	105	142	108	5	3,249	147	3,102	4.1(2.2)
PWR-LEU 30% Imp., OT	243	3	83	0	83	96	89	1	2,659	99	2,560	4.0(2.4)
PWR-LEU Current/LEU SGR	208	0	79	5	79	54	88	6	2,640	180	2,460	2.4(2.2)
PWR-LEU Current/LEU X, SGR	260	0	93	1	90	54	99	2	3,251	69	3,182	3.8(2.5)
PWR-Pu(Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
PWR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
HWR-LEU, OT	14	0	29	0	29	0	29	0	855	0	855	1.2(.8)
HTGR-MEU5 (Th), OT - Opt	227	24	111	2	111	96	115	6	3,460	165	3,295	19.8
HTGR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
HTGR-MEU3 (Th), Recycle	0	0	0	0	0	0	0	0	0	0	0	-
LWBR-MEU5 (Th) - WR1	744	61	232	61	232	373	249	72	7,461	2,149	5,312	93.0
LWBR-MEU3 (Th), Recycle HGC	0	0	0	0	0	0	0	0	0	0	0	-
LWBR-MEU3 (Th), Recycle - NR1	0	0	0	0	0	0	0	0	0	0	0	-
LMFBR-Pu(U)/W	0	0	0	0	0	0	0	0	0	0	0	-
LMFBR-Pu(U)/Th	0	0	0	0	0	0	0	0	0	0	0	-

*0.2% Enrichment Tails Composition
 70% Capacity Factor
 1% Fuel Fabrication Loss
 1% Reprocessing Loss

Table A-3. Fissile Material and Heavy Metal
Annual Charge (Discharge) Mass Flows

Reactor Type	U-233 (kg/GW)			U-235 (kg/GW)			Fissile Pu (kg/GW)			Heavy Metal (tons/GW)		
	Initial	Equilibrium	Final	Initial	Equilibrium	Final	Initial	Equilibrium	Final	Initial	Equilibrium	Final
PWR-LEU Current, OT	0(0)	0(0)	0(0)	1,751(177)	773(205)	733(1062)	0(114)	0(166)	0(423)	79.0(24.5)	25.6(24.3)	25.6(78.3)
PWR-LEU 15% Imp., OT	0(0)	0(0)	0(0)	1,751(108)	633(100)	633(1402)	0(47)	0(114)	0(497)	79.0(14.2)	15.3(14.2)	15.3(77.6)
PWR-LEU 30% Imp., OT	0(0)	0(0)	0(0)	1,919(109)	509(50)	509(1155)	0(30)	0(90)	0(497)	79.0(11.8)	12.7(11.6)	12.7(76.9)
PWR-LEU Current/LEU SGR	0(0)	0(0)	0(0)	1,751(171)	590(182)	590(861)	0(286)	840(453)	840(2048)	79.0(24.5)	25.3(24.0)	25.3(78.3)
PWR-LEU Current/LEU X, SGR	0(0)	0(0)	0(0)	2,000(103)	570(99)	552(861)	0(68)	146(188)	203(1188)	79.1(14.7)	15.1(14.2)	15.2(78.3)
PWR-Pu(Th), Recycle	0(143)	0(253)	0(572)	0(1)	0(3)	0(4)	2489(306)	1416(735)	1415(3313)	74.4(22.6)	23.1(21.8)	24.7(71.0)
PWR-MEU3 (Th), Recycle	1,905(113)	560(237)	560(1780)	38(4)	48(44)	58(320)	0(12)	0(49)	0(231)	74.4(13.5)	13.8(12.8)	13.8(70.1)
HWR-LEU, OT	0(0)	0(0)	0(0)	1,237(58)	501(40)	501(550)	0(57)	0(139)	0(528)	157.3(22.0)	41.8(40.1)	41.8(150.9)
HTGR-MEU5 (Th), OT-Opt.	0(62)	0(71)	0(250)	993(115)	488(24)	488(513)	0(7)	0(18)	0(74)	29.1(6.5)	5.5(4.7)	5.5(21.1)
HTGR-MEU3 (Th), Recycle	1,363(314)	549(303)	550(1224)	0(2)	3(16)	3(39)	0(24)	0(47)	0(141)	42.9(12.0)	13.0(12.1)	13.0(42.2)
HTGR-HEU3 (Th), Recycle	1,905(406)	520(448)	520(2136)	190(40)	78(71)	78(340)	0(0)	0(0)	0(0)	79.9(17.0)	17.8(16.7)	17.8(77.6)
LWBR-HEU5 (Th)-WR1	0(296)	0(296)	0(634)	2,939(249)	914(249)	914(1493)	0(0)	0(0)	0(0)	73.0(21.5)	22.7(21.5)	22.7(70.1)
LWBR-HEU3 (Th), Recycle HGC	2,690(491)	697(491)	697(1894)	36(30)	9(30)	9(114)	0(88)	0(88)	0(300)	152.5(37.9)	39.5(37.9)	39.5(146.3)
LWBR-HEU3 (Th), Recycle-NR1	2,734(0)	3013(2963)	0(3243)	1,995(0)	441(391)	0(417)	0(0)	0(0)	0(0)	133.1(0)	124.4(120.4)	0(129.1)
LMFBR-Pu(U)/W	0(0)	0(0)	0(0)	233(60)	71(51)	67(191)	4,742(1637)	1,658(1764)	1,652(5430)	113.6(32.1)	34.4(31.8)	33.0(109.8)
LMFBR-Pu(U)/Th	0(159)	0(458)	0(1116)	57(16)	19(12)	18(42)	5,079(1571)	1,716(1459)	1,754(4571)	110.3(31.2)	32.4(31.0)	33.5(106.6)

*0.2% Enrichment Tails Composition
70% Capacity Factor
1% Fuel Fabrication Loss
1% Reprocessing Loss

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PWR-LEU 15 Percent Improved, OT -- A once-through light-water reactor that uses low-enriched uranium (about 4 percent U-235) fuel. This reactor incorporates a high-burnup design of about 50 MWd/kg and fuel management changes which requires 15 percent less U_{308} than current light-water reactors. It is an expected improvement of current reactor technology.

PWR-LEU 30 Percent Improved, OT -- A once-through light-water reactor that uses U-235 fuel enriched to about 4 percent. This redesigned reactor incorporates a very high-burnup fuel design and fuel management changes which require 30 percent less U_{308} than current light-water reactors. It is a significant advancement of current reactor technology.

PWR-LEU Current/PWR-LEU, SGR -- A light-water reactor that uses U-235 fuel enriched to an average of 2.2 percent in its initial core loadings and 3.0 percent for makeup low-enriched uranium fuel in addition to self-generated-recycle plutonium fuel for later core loadings. Some U-235 makeup is required with the recycle plutonium. This reactor incorporates a design with current average burnup of about 30 Mwd/kg.

PWR-LEU Current/PWR-LEU X, 5GR -- A light-water reactor that uses U-235 fuel enriched to about 2.5 percent in its initial core loadings and then self-generated-recycle plutonium fuel and 4.3 percent enriched U-235 for makeup fuel for later core loadings. This reactor incorporates a high-burnup design.

PWR-Pu/(Th)Recycle -- A light-water reactor which uses plutonium fuel in fertile thorium to produce U-233 from the thorium to fuel other types of reactors.

HWR-LEU, OT -- A heavy-water reactor which uses U-235 fuel enriched to about 1.2 percent.

HTGR-MEU5(Th) OT-opt. -- A high-temperature gas-cooled reactor that uses 20 percent enriched U-235 fuel in thorium. This design is optimized for the once-through cycle.

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HTGR-MEU3(Th), Recycle -- A high-temperature gas-cooled reactor employing recycle and that uses denatured U-233 fuel mixed in thorium.

HTGR-HEU3(Th), Recycle -- A high-temperature gas-cooled reactor employing recycle that uses highly-enriched U-233 fuel mixed in thorium. This design has a smaller life-time U-233 requirement than the denatured U-233 high-temperature gas-cooled reactor (although it has a larger initial loading of U-233).

LWPR-HEU5(Th)-NR1 -- A light-water prebreeder reactor that uses 93 percent enriched U-235 fuel in thorium. This prebreeder design is based on a Department of Energy-Division of Naval Reactors design and would be retrofittable into current light-water reactors.

LWBR-HEU3(Th), Recycle-NR1 -- A light-water breeder reactor that uses highly-enriched U-233 fuel mixed in thorium. This reactor is a seed/blanket design based on a Department of Energy-Division of Naval Reactors design.

LWBR-MEU3(Th), Recycle HGC -- A light-water cooled breeder type of high-gain converter designed by Argonne National Laboratory and Oak Ridge National Laboratory that uses denatured U-233 fuel mixed in thorium.

LMFBR-Pu(U)/U -- A liquid-metal fast breeder reactor with a heterogenous, mixed oxide (plutonium and uranium) core and depleted uranium blankets.

LMFBR-Pu(U)/Th -- A liquid-metal fast breeder reactor with a heterogenous, mixed oxide (plutonium and uranium) core and thorium blankets.

D R A F T

A.2 URANIUM ENRICHMENT

A.2.1 Effect of Tails Assay on Uranium Feed and Separative Work Requirements

Enriched uranium fuel for power reactors is produced commercially from natural uranium that is fed to gaseous diffusion or gas centrifuge plants. In these processes, numerous "stages" of the separation process are connected to form a "cascade" in which the uranium in the product stream is enriched from the naturally occurring assay of 0.711 wt percent U-235 to a desired fuel assay such as 3.0 wt percent U-235, and depleted in a tails or waste stream to a lower assay such as 0.20 wt percent U-235. There is no theoretical lower limit above zero to the tails assay of the plant set by the technology of the gaseous diffusion or centrifugation processes. The tails assay may be reduced to conserve uranium feed, but the amount of separative work to obtain a unit of product with the desired enrichment must then be increased. The impact of the cascade operating tails assay on the relative amount of natural uranium feed required, based on the feed needed at 0.2 percent tails assay, is shown in Fig. A-7. The impact of tails assay on the relative amount of separative work is shown in Fig. A-8. These figures indicate that for 3.0 wt percent U-235 product, reducing tails assay from 0.20 to 0.10 percent U-235 will reduce feed requirements by 13.4 percent and will increase separative work by 39 percent. A reduction of tails assay from 0.20 to 0.05 percent will reduce feed requirements by about 18.6 percent and increase separative work by 82 percent.

A.2.2 Effect of Tails Assay on Product Cost

The principal factor in selecting the enrichment plant operating tails assay is economics. The economically optimum tails assay is a function of the ratio of the unit cost of feed to the unit cost of separative work. Optimum tails assays were determined for the anticipated range of feed and separative work costs in 1978 dollars during the time period extending through the year 2025. The selected values include \$40, \$100, and \$160/lb of U_3O_8 , and \$40, \$100, and \$150/kg unit of separative work. Although the current price of separative work is approximately \$100/SWU, a lower limit of \$40/SWU was included to represent the potential of advanced isotope separation technology.

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*AT TAILS ASSAY = 0.20% U-235; RATIO = 1.00

Figure A-7. Impact of Enrichment Tails Assay on Relative Natural Uranium Requirements
(Product Range From 1.2 to 93% U-235)

*AT TAILS ASSAY = 0.20% U-235; RATIO = 1.00

Figure A-8. Impact of Enrichment Tails Assay on Relative Separative Work Requirements
(Product Range From 1.2 to 93% U-235)

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The effect of tails assay on the unit cost of product is shown in Figure A-9 for the selected feed and separative work costs associated with the production of low enriched uranium. As indicated in the figure, at the current feed cost of about \$40/lb of U_3O_8 and a separative work cost of \$100/SWU, the unit cost of product increases about 8 percent when the tails assay is reduced to 10 percent from 0.20 percent U-235 and by 25 percent when the assay is reduced to 0.05 percent U-235. Since the cost of enriched uranium (feed, separative work, and conversion) is about 24 percent of the total power cost (at \$40/lb U_3O_8 and \$100/SWU) in once-through light-water reactors, a reduction of tails assay from 0.20 to 0.10 percent U-235 will increase the power cost by about 2 percent; a reduction to 0.05 percent U-235 will increase the power cost about 6 percent. If the cost of U_3O_8 were \$100/lb, the optimum tails assay at a SWU cost of \$100 would be about 0.13 percent, and a reduction in tails assay to 0.05 percent U-235 would increase power cost by about 2.5 percent.

Figure A-10 shows the effect on power costs of reducing the enrichment plant tails assay (and the associated savings in feed). As expected, a given percentage reduction in feed affects the power cost less at a lower unit feed cost. It should also be noted that the separative work requirement is increasing sharply in both cases. Thus, for a 10 percent savings in feed, at the present cost of feed and separative work, the incremental power cost would be small (about 1 percent) but the associated increase in separative work would be 20 percent.

A.2.3 Feasibility of Tails Assay Reduction

The present U.S. gaseous diffusion plant complex is designed for operation in the range of 0.20 to 0.30 percent U-235 tails assay, but it is reasonably flexible. Operating at lower than design tails assay has been studied and at 0.10 percent U-235 tails, the separative work loss is in the order of 5 percent without enrichment plant modification.

The development of Advanced Isotope Separation processes may lead to more economical stripping of tails and a much greater flexibility would be expected. However, this technology is in its infancy and not anticipated to reach maturity before the year 1990.

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Figure A-9. Sensitivity of 3.0% U-235 Product Cost to Tails Assay, U_3O_8 and Separative Work Cost

Figure A-10. Impact of Lower Enrichment Plant Tails Assay (and Reduced Feed Rate) on Power Cost for an LWR Power Plant

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In summary, it appears technically and economically feasible to reduce enrichment tails assay in the gaseous diffusion and centrifuge plants from 0.20 percent to 0.10 percent U-235 or less when uranium prices begin to increase, provided additional enrichment capacity is constructed in a timely manner. This tails reduction will save 13.4 percent of the feed requirements. Assuming successful development of advanced isotope separation technology and construction of plants beginning in the 1990's, a further reduction in tails to 0.05 percent U-235 should be technically and economically feasible by the year 2000, resulting in an additional savings in feed of about 5.2 percent.

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