Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Volume VIII: Advanced Concepts

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1. INTRODUCTION

The goal of the Nonproliferation Alternative Systems Assessment Program has been to provide recommendations for the development and deployment of more proliferation-resistant civilian nuclear-power systems without jeopardizing the development of nuclear energy. In this context, proliferation resistance is the capability of a nuclear-power system to inhibit, impede, or prevent the abuse of associated fuel-cycle materials or facilities, i.e., their diversion from civilian to military uses. Developing more proliferation-resistant systems requires identifying the materials or facilities most vulnerable to abuse and devising technical and institutional measures that, developed over time, might be employed to reduce these vulnerabilities. For commercial or near-commercial nuclear-power systems that were readied in the past without explicit consideration of proliferation resistance, measures that can be backfitted must be identified. Technical measures were considered in Volume II; institutional measures and alternatives were considered in Volume VII. In principle, new concepts for nuclear-power systems could be designed so that materials and facilities would be inherently more proliferation-resistant. Such advanced, i.e., less-developed systems, are the subject of this volume.

Accordingly, from a number of advanced concepts that were proposed for evaluation, six representative concepts were selected: the fast mixed-spectrum reactor; the denatured molten-salt reactor; the mixed-flow gaseous-core reactor; the linear-accelerator fuel-regenerator reactor; the ternary metal-fueled electronuclear fuel-producer reactor; and the tokamak fusion-fission hybrid reactor. While brief descriptions of these six reactor concepts are provided here, more complete descriptions of the reactors and their fuel cycles may be found in Volume IX.

The denatured molten-salt and gaseous-core reactors represent circulating fuel concepts which do not require fuel withdrawal until the end of reactor life. With these systems, any significant diversion of fissile material during the operating lifetime of the reactor would be reflected in a severe degradation of reactor performance. The accelerator-driven concepts (the fuel regenerator and the fuel producer) and the tokamak hybrid system were proposed as fissile material producers which could provide reactor fuel when deployed under stringent safeguards. The accelerator-driven fuel regenerator, moreover, does not require reprocessing. The fast mixed-spectrum reactor was proposed as an extension of fast-breeder technology, but, in contrast to fast breeders which require reprocessing, it would permit operation on a once-through cycle.

These concepts share the following characteristics:

- Major technological difficulties and uncertainties;
- Fuel utilization advantages, in comparison with the light-water reactor; and
- Possible nonproliferation advantages, in comparison with the conventional plutonium cycle.

While these concepts share certain characteristics, they are also vastly different systems, with different attributes and varying performance characteristics. Further, they are now at varying stages of development and, in some cases, technical feasibility has not been demonstrated. For example, on the one hand, the fast mixed-spectrum reactor is viewed as an extension of fast-breeder reactor technology and molten-salt reactor operation has been demonstrated in a proof-of-principle experiment. On the other hand, the practicality of tokamak hybrid systems depends ultimately on a demonstration of the scientific feasibility of sustained fusion reactions and, although this demonstration is anticipated in the next 5 years, it has not yet occurred.

To permit the NASAP assessment to proceed, a conceptual design representative of each generic system of interest was chosen for evaluation and consistent assessment factors were developed. While each design chosen may not now represent the preferred approach for the technology, it is considered to be a reasonable surrogate for its class. It is important to remember, however, that additional concepts may ultimately be proposed which surmount the difficulties described in the assessments found in this volume.

The concepts chosen for this assessment were the following:

- Fast Mixed-Spectrum Reactor. The mixed-spectrum reactor is a fast-reactor concept that differs from other fast-reactor designs mainly in the use of a once-through fuel cycle and in the extremely high burnup required of the metallic fuel elements. The fast mixed-spectrum reactor was of interest because it offers some of the benefits of breeder technology without requiring spent-fuel reprocessing. The reactor would initially be fueled with low-enriched

uranium fuel; at equilibrium, make-up would be either natural or depleted uranium. The fast mixed-spectrum reactor would contain two distinct regions separated by a moderator shell. (See Figure 2, page 31.) The inner region would contain a fast neutron flux, similar to that found in other fast reactors, for high production of fissile plutonium fuel. The moderator shell would reduce the energy of the neutron flux so that the fissile material could be burned more efficiently in the outer region. Spent fuel discharged periodically would contain 7 to 8 percent plutonium.

- Denatured Molten-Salt Reactor. The molten-salt reactor is distinguished by its use of a molten mixture of inorganic fluoride salts as a fuel carrier. The molten fuel salt, which would circulate between the reactor core and the primary heat exchangers, would serve as the primary medium to transfer heat to an intermediate coolant, which in turn would produce steam in the steam generators. (See Figure 3, page 44.) The physical characteristics of the molten-salt mixture would allow the system to operate at near-atmospheric pressure and at high temperatures (about 700° C), permitting efficient production of electricity. The denatured molten-salt reactor would use a uranium-thorium fuel with U-233 and U-235 enrichments that are not weapons-usable, and the plutonium that would build up in the circulating salt would be protected by physical barriers against diversion.
- Mixed-Flow Gaseous-Core Reactor. The gaseous-core reactor would be characterized by the use of a fissioning gas mixture ($\text{UF}_6\text{-F}_2\text{-CF}_4$) as its fuel source. The gaseous fuel, which² would circulate continuously between the reactor core and the primary heat exchangers (as in the molten-salt reactor), would transfer heat to an intermediate coolant, which in turn would produce steam in the steam generators. (See Figure 4, page 57.) Neutrons leaking from the reactor core would be absorbed in a thorium-containing molten-salt blanket to produce fissile U-233. This reactor is of interest because it could be designed to have about one-tenth the fissile-fuel inventory of the present light-water reactors, and would not require the addition of fissile material beyond the first core loading. While it

would require continuous removal of fission products, diversion of fuel sufficient for nuclear-weapons purposes would cause a shutdown in the reactor operation.

- Linear-Accelerator Fuel-Regenerator Reactor. The fuel-regenerator reactor would produce fuel for other reactors rather than producing electricity. It would use a high-energy proton beam from a linear accelerator impinging on a liquid lead-bismuth target to provide an intense neutron source. (See Figure 5, page 69.) The reactor would be designed to produce fuel by increasing the fissile plutonium content of light-water¹ reactor fuel elements arranged to form a subcritical fission blanket. Thermal power production in the target and blanket would be needed to produce electricity, but generation of electricity would be incidental to the production of fissile material. The proposed reactor would still require electrical power from outside sources.

The fuel cycle would use light-water reactor fuel assemblies made with uranium enriched to about 2 percent U-235. After fabrication, these assemblies would be irradiated for approximately 1 year in arrays of individual pressure tubes surrounding the neutron source and then used as light-water reactor reload fuel. After depletion during a normal 3- or 4-year power production cycle, the fuel would be returned to the fuel regenerator for regeneration. After use in two light-water reactor burnup cycles, the fuel would be discarded. The major advantage of the fuel-regenerator reactor would be the ability to substantially extend uranium resources while using the current light-water reactor technology, with three light-water reactors being supported by one fuel regenerator. The fuel-regenerator reactor fuel cycle would not require reprocessing, and the fissile material would never be in a weapons-usable form.

¹Subcritical - unable to maintain or increase fission power without the use of an external source of neutrons.

- Ternary Metal-Fueled Electro-nuclear Fuel-Producer Reactor. The fuel-producer reactor would use a linear accelerator to produce a beam of high-energy protons. The beam would strike a liquid-sodium target to produce neutrons that subsequently would react with a subcritical blanket of fissile and fertile materials. (See Figure 7, page 82.) The liquid sodium would also be circulated through both the target and the blanket as a coolant and would transfer the heat to an intermediate sodium coolant loop, which in turn would be used to generate steam for power production. The fuel would be composed of a mixture of plutonium, thorium, and uranium. The plutonium would be the major source of fission energy, while the thorium would be a source of U-233, which would be extracted and used as denatured fuel for light-water reactors. (See Figure 6, page 80.) One fuel-producer reactor would provide the fuel for about five similarly-sized light-water reactors.

The concept would require a reprocessing cycle to recover the U-233 that is produced. It would produce more electricity than required for the accelerator.

- Tokamak Fusion-Fission Hybrid Reactor. The hybrid reactor concept would use a tokamak deuterium-tritium fusion reactor as a neutron source, which would be surrounded by a blanket containing thorium or uranium fertile material. Utilization of the 14.1 MeV neutrons emitted in fusion reactions could result in the production of large quantities of fissile material. The fusion-reactor plasma would be confined in a toroidal magnetic field maintained by D-shaped superconducting magnets. (See Figure 8, page 94.) The neutrons emitted from the plasma would be slowed down in the blanket and captured by the fertile nuclei to produce fissionable material. The blanket could produce sufficient fissile fuel to operate several fission reactors and simultaneously produce thermal energy, which could be converted to electrical power. Helium is proposed for use as the primary coolant to transfer heat from the blanket to the steam generators, where high-temperature, high-pressure steam would be produced to drive a conventional turbine generator. The hybrid reactor would produce its own tritium from lithium-bearing fuel. Its fuel cycle would require

reprocessing and fuel fabrication and would involve the handling of substantial quantities of weapons-usable materials.

How This Assessment Differs From Assessments Described in Preceding Volumes

The scope and structure of this evaluation of advanced technologies reflect an emphasis that differs from the evaluation of technologies described in the preceding assessments (Volumes II-VII). In the studies reported in those volumes, a number of developed or nearly-developed nuclear technologies were compared with respect to specific evaluation factors: proliferation resistance, resource utilization, commercial potential, economics and system analysis, and the safety and environmental questions affecting licensing. This study involved an examination of these areas, but, in addition, it involved a design evaluation and an examination of the research, development, and demonstration needed for the less-developed concepts. For the more highly-developed technologies, the assessments centered on exogenous matters such as market projections, uranium availability, utilities' preference, and options to assure a viable nuclear power industry; here the emphasis is on assessing the technological status of the less-developed systems and the degree of development which would be needed to ready the concepts for possible commercial deployment. This assessment of commercial potential is critical, since, ultimately, only deployed systems can contribute to a reduction of proliferation risk.

An evaluation of the commercial potential of a system in the early stages of its development is difficult. The same commercialization guidelines and assessment criteria were consistently applied to all advanced concepts, and it was assumed that they would follow the same generic research, development, and demonstration path to establish commercial acceptance as the developed concepts (see Volume IV, Chapter 3). However, for the advanced concepts there are additional requirements for basic research to establish feasibility, and, where needed, for small experimental plants to demonstrate proof of principle. Accordingly, it is estimated that it could take 40 years before some of the advanced concepts could start to penetrate the commercial market.

It should be noted, however, that there are special circumstances that can significantly alter the development schedule of a particular advanced technology. Certain developmental steps may be added or eliminated based on

changes in the rate at which technological developments occur or on changes in economic or nonproliferation goals. Development schedules can also be altered when ongoing research and development programs produce results that impact the development of an advanced concept. For example, the Department of Energy's ongoing fusion technology program should have significant impact on hybrid reactor development needs; progress in tokamak experiments conducted in the last 2 years has served to greatly enhance the prospects for the success of this concept. In addition, the development of the fast mixed-spectrum reactor will benefit directly from the current fast-breeder reactor technology development program.

Limitations to This Assessment

As noted above, this assessment faced certain difficulties and limitations. While the conceptual designs proposed for the assessment were considered to be reasonable surrogates for each class of reactor, shortcomings of a particular design cannot necessarily be viewed as common to all variations of the concept. In addition, the depth of documentation supporting the assessed concepts varied considerably. It is also difficult to apply criteria in the areas of resource utilization, economics, and commercial potential to concepts for which, in some cases, technical feasibility remains unproven. Further, these evaluations are more uncertain than those in previous volumes and are subject to change based upon new information obtained from the research and development required to bring the concepts to commercial readiness. Finally, because the evaluations were specifically structured to be consistent with the development and commercial deployment guidelines established in NASAP for the more developed technologies, the conclusions regarding these concepts should not be extrapolated beyond the boundary conditions of the NASAP study.

As all the concepts examined here have development times of 40 years or more, the context of proliferation concerns and the energy supply and demand factors which form the basis for current program decisions will have changed greatly before any of these technologies could be commercially deployed. Based on the evolutionary nature of nuclear power development to date, current technology will likely be slow to give way to new technologies and will do so only when clear-cut commercial advantages exist.

The following chapter summarizes the findings of these assessments, by assessment area, and provides overall conclusions. Chapters 3 through 8 provide details on the assessment findings for each individual concept.

1.0	2.5
0.5	1.5
0.2	0.8
0.1	0.4
0.05	0.2

2. SUMMARY OF ASSESSMENTS

Following are summaries of the assessment results for each of the advanced concepts under consideration. The similarities and differences between the concepts are highlighted to facilitate a direct comparative analysis of the concepts with regard to the assessment areas.

2.1 DESIGN ASSESSMENT

All six of these advanced concepts have technical difficulties that would have to be overcome through research and development before the concepts could become commercially attractive. The design assessment was performed by identifying needs in six specific areas: conceptual plant design; reactor-physics considerations; fuel-cycle alternatives; mechanical and thermal-hydraulic considerations; selection, development, and availability of materials; and engineering and operability.

2.1.1 Conceptual Plant Design

Each of the advanced concepts has significant plant-design difficulties, combining novel primary energy and fuel-producing cycles with steam generation and electric power production in relatively conventional turbine power plants. Since the technology of the fast mixed-spectrum reactor is based on that of either the liquid-metal fast-breeder reactor or the gas-cooled fast reactor, its plant design system has a correspondingly sound basis. However, the unusually long period for which the fuel assembly would remain in the reactor (17 years, compared to 3 to 4 years for currently-operating reactors) would result in exposure to neutron fluences far beyond current experience. A substantial fuel and core materials development program would be required to prove concept practicability.

Substantial knowledge of molten-salt technology has already been accumulated, and, although the engineering technology for a commercial reactor has not been demonstrated, most aspects of the denatured molten-salt reactor plant appear to be known. The problems of scaling up an 8-MW (thermal output) test reactor

to a commercial 1,000-MW (electrical capacity) power reactor would be substantial. Development of a commercial molten-salt reactor plant would require the optimization of construction materials, the development of a commercial source for fuel-salt constituents, and the resolution of materials compatibility problems associated with containing molten salts at high temperatures. Thus, the primary areas of development are expected to be associated with a demonstration of materials suitable for long-term use in the reactor environment and with scaling up plant equipment such as coolant pumps and steam generators.

Instrumentation, controls, and valve assemblies in the molten-salt reactor would also require significant additional development, and the highly radioactive fuel salt would require that all items normally in contact with the salt be enclosed within a containment structure and be amenable to remote inspection and maintenance. Development of the required remote-maintenance equipment and techniques would probably be difficult. Also, the integrity of the primary circuit and reactor containment would be very important and would require the development of unique design criteria, which would be reflected in codes and standards approved by the Nuclear Regulatory Commission. In particular, prevention of escape of tritium produced from lithium and in ternary fission would be difficult. Research would be required to define the backup safety systems required for a circulating-fuel reactor system. Although no reprocessing of the fuel would be required to remove fission products, hydrofluorination would be required to remove oxide contaminants.

The gaseous-core reactor, with its radioactive circulating fuel, would have generic problems similar to those of the molten-salt reactor. In addition, the corrosion problems of handling uranium fluoride gas and free fluorine are so severe that the feasibility of the gaseous-core concept is questionable. Control of reactivity in this concept, with its compressible fuel gas mixture, will be more difficult than in liquid-fueled molten-salt systems. Moreover, the problems of the gaseous-core reactor are less clearly understood, because very little experimental work has been done on this concept. In particular, construction materials would have to prove capable of withstanding the corrosive fuel gas at elevated temperatures and pressures. Fuel-gas stability problems and local deposition of fuel constituents and fission products would also present increased material compatibility and design difficulties. Due to the poor strength of the beryllium reactor cavity walls, the reactor vessel and entire molten-salt blanket system would be subjected to severe high pressure design criteria. Remote maintenance and inspection would be more difficult than with a molten-salt reactor due to the difficulty of locating fuel gas leaks. The high pressure and corrosive nature of the fuel gas would lead to significant design problems in the areas of reactor containment, related safety features, and postulated accidents.

Significant plant design difficulties would have to be overcome for the two accelerator-driven reactor concepts--the fuel-regenerator and the fuel-producer. The development of a full-sized commercially available system with a high availability rate and the ability to interface the nuclear system with a large accelerator could prove difficult. The accelerator performance requirements for both concepts are beyond the current state of technology and, therefore, would require substantial accelerator development. No accelerator has ever been operated continuously at outputs required for commercial systems. Until operating experience is obtained, a large degree of uncertainty will remain.

While the fuel-regenerator concept is based on an extrapolation of current accelerator and light-water reactor technology, its development would require the resolution of several materials questions. A formidable problem would be the development of fuel which could withstand more than twice the irradiation normally experienced in light-water reactor applications. Vacuum systems, circulating systems for the lead-bismuth target, the reactor pressure vessel, calandria pressure tubes, and fuel handling and material compatibility problems would also require significant engineering development. The proposed steam cycle is unconventional and would require an expansion valve that is not commercially available.

The present physics model for the fuel-producer is preliminary and does not include sufficient detail to permit verification of the concept's feasibility. The use of sodium as a coolant has been studied for many years and is being further developed as part of the liquid-metal fast-breeder reactor program. However, extensive work would be needed to demonstrate the use of liquid sodium as an accelerator target. The use of the ternary-metal fuel (thorium, uranium, plutonium) proposed for the fuel-producer would present difficulties; particular concerns are the vanadium-titanium fuel cladding and the pyrometallurgical reprocessing. There has been some work in both areas, but additional work would be needed to develop and prove the technology.

The fuel-producer requires a 90-degree deflection of the proton beam from the accelerator to permit entrance to the target-blanket region. Proton-deflecting systems of the required energy and current do not yet exist, and considerable development would be required to attain suitable systems. The accelerator beam window would be part of the primary coolant pressure boundary and would be subjected to severe radiation damage. The need for frequent replacement of the window would be a difficult design problem in the fuel producer and could lead to difficult design criteria in areas such as materials compatibility and leaktightness.

The tokamak fusion-fission hybrid reactor concept is the result of a series of preliminary studies performed for NASAP. The concept is one of several proposed applications of fusion technology; further development will depend heavily on the success of the fusion reactor program as now defined.

Successful development of the tokamak requires the development of a fusion driver with favorable ignition characteristics, burn time duration, and duty factor. A self-sustaining fusion reactor has never been operated and the development of a fusion reactor with the required plasma characteristics is not anticipated until near the turn of the century. The long-term operation of the hybrid reactor would depend on the lifetime of the first (innermost) wall and of other potentially sensitive components (e.g., fuel cladding, cooling tubes, insulators), all of which would be exposed to intense radiation from the plasma. The development of adequate first-wall material and superconducting magnets has been identified as difficult.

Several associated fission-related problems must also be resolved. Cooling schemes and fuel configurations must be determined. Remote handling for extracting and adding blanket fuel assemblies must be developed. Design of a complex reactor and blanket geometry that could be remotely maintained would be extremely difficult. Fuel and cladding material must be developed and demonstrated. The compatibility of the fertile, cooling, and moderating materials used in the blanket must also be established. Conditions of high-energy neutron flux, high temperature, and thermal-mechanical cycling would impose severe operating limits on the hybrid-reactor system. Both the cooling systems for the first wall and the blanket require development. Other areas requiring comprehensive technological advances include magnetics, cryogenics, plasma diagnostics, and fuel handling. Detailed conceptual design and optimization studies have yet to be performed on this and alternative hybrid systems and could possibly lead to substantial revisions in any future assessment of design and expected performance.

2.1.2 Reactor Physics Considerations

Analytical reactor-physics models were required to perform calculations for each of the six concepts. The models for all concepts would require additional development before final designs could be prepared, although they appear to be best defined for the molten-salt and gaseous-core reactors. (The molten-salt reactor model has been tested by actual operating experience.)

The reactor-physics model for the fast mixed-spectrum reactor is complex, and further refinement of analytical techniques would be required to demonstrate the feasibility of using natural uranium fuel.

The reactor-physics model for the hybrid reactor as assessed cannot be extrapolated from the known performance of other technologies. The feasibility of the proposed hybrid-reactor blanket has only been investigated using one-dimensional methods of calculating rates of neutron interaction, and the nuclear data for some of the materials used in these analyses have not been fully evaluated. Therefore, results must be treated as tentative.

The fuel-regenerator and fuel-producer reactor models are viewed by their developers as quite approximate at this stage; more refined models would likely lead to significant changes in reactor design.

2.1.3 Fuel-Cycle Alternatives

A wide variety of fuel-cycle alternatives has been suggested for each of the six reactor concepts. These suggested alternatives range from rather subtle changes for minor improvement in performance to major changes that would affect the basic design of the plant and fuel cycle. None of the assessed fuel-cycle concepts has been optimized, and several different objectives were used in fuel-cycle design. Since the fuel-cycle designs vary widely in purpose and resource requirements, comparisons among the different concepts are difficult, and the significance of the differences is unclear. Also, in determining economic and resource parameters for the fuel-producing concepts, the systems analyzed must include both the fuel-using and the fuel-producing components.

The mixed-spectrum and gaseous-core reactors were designed to be self-sustaining, with only natural uranium or thorium additions required for continuous operation. The molten-salt reactor was designed to operate with intermittent additions of 20-percent enriched uranium and thorium. The fuel-regenerator, electronuclear fuel-producer, and hybrid reactors were designed to produce fuel for other reactors: the fuel-regenerator would use low-enriched uranium feed; the electronuclear fuel-producer would use plutonium, thorium, and natural or depleted uranium feed; and the hybrid reactor would use natural or depleted uranium feed.

The differing fuel-cycle designs result in significantly different fuel-cycle requirements. The two self-sustaining reactor designs, the mixed-spectrum and gaseous-core, would require some enriched uranium for startup. However, neither would require enrichment services after startup, and only the mixed-spectrum reactor would require shipment of spent fuel prior to decommissioning of the plant. The gaseous-core reactor would require on-site reprocessing to transfer bred U-233 from the blanket to the fuel gas. The spent fuel of the mixed-spectrum reactor would contain substantial amounts of plutonium which would have to be disposed of. The molten-salt reactor would not require off-site reprocessing or shipment of spent fuel until the end of reactor life.

The three fuel-producing reactor concepts would each support from three to five additional reactors. The electronuclear fuel-producer and the hybrid reactor would require at least two types of reprocessing and fuel-fabrication facilities, while all three would require shipment of spent and fresh fuel.

The fuel-regenerator would produce substantial amounts of plutonium-bearing spent fuel which would have to be disposed of, following completion of the final reactor irradiation cycle.

2.1.4 Mechanical and Thermal-Hydraulic Considerations

Thermal-hydraulic analysis and mechanical designs are highly interdependent. All of the mechanical designs for the proposed cores depart from current commercial practice. The overall thermal-hydraulic system designs which appear to be most feasible are those for the fast mixed-spectrum and the molten-salt reactors, for which considerable analysis has already been performed. The proposed fast mixed-spectrum reactor mechanical design would be similar to either the liquid-metal fast-breeder reactor or the gas-cooled fast reactor, but its larger core and moderator region would increase design difficulty. The proposed mechanical design of the molten-salt reactor is based on the results of successful experimentation, and thus appears feasible.

The thermal-hydraulic design for the fuel-regenerator is still in the conceptual stages. The cooling for the target or blanket assemblies has little precedent, and the unconventional arrangement of this reactor presents many mechanical and thermal-hydraulic design difficulties. Vertical pressure tubes

are proposed to contain the fuel assemblies. Designing these pressure tubes and the vacuum-containing reactor vessel would be difficult, due to the arrangement of the reactor components and material compatibility difficulties.

The mechanical design of the fuel-producer reactor¹ fuel is proposed to follow the design of the Experimental Breeder Reactor II¹ which has been in operation since 1967. The cooling of the target and reactor combination will require substantial additional development.

The mechanical design for the gaseous-core reactor would require high-pressure designs for both the core and blanket regions, and the feasibility of the concept would depend on its ability to cool the reactor-cavity walls and to provide appropriate gas density to permit fissioning. Material compatibility problems would greatly complicate the design. Although the gaseous-core reactor would have to be designed to avoid fuel instability and possible deposition of fuel and fission products which might cause hot spots in the primary circuit, the overall core-heat transport appears feasible based on the current level of analysis and data.

Analysis of the mechanical design problems associated with the hybrid reactor concept has identified systems which require further development. The structure, cooling, first wall, and methods of attachment will all pose very difficult design problems. Analysis of the fuel arrangements for the hybrid reactor also indicates that the concept would not be limited by thermal-hydraulic considerations, assuming that the gas circulation systems and blanket cooling could be maintained.

2.1.5 Selection, Development, and Availability of Materials

Development of each of the advanced concepts would require a significant development of materials. The feasibility of the mixed-spectrum reactor would

¹The Experimental Breeder Reactor II (EBR-II) is an engineering test facility for breeder reactor components, located at the Idaho National Engineering Laboratory (INEL), at Arco, Idaho.

depend on the development of uranium metal fuel, cladding, and ducts that could withstand irradiation to very high neutron fluences. Further, the fuel would experience very high burnup and would operate at currently undemonstrated metal fuel temperatures. Investigations for the molten-salt reactor have shown that the selection of adequate materials should be possible, although major materials-development problems exist. Preliminary investigations for the fuel-producer reactor have shown that its materials would generally be satisfactory, with additional investigations required for the fuel-cladding material.

The materials problems in the fuel-regenerator are twofold--selection of an iron-based alloy (for containing the target) that is compatible with the liquid lead-bismuth and the design requirements of the zircaloy pressure tubes. The hybrid reactor would require the development of compatible materials that could withstand its high temperatures and intense radiation environment long enough to be useful.

The materials problems of the gaseous-core reactor appear to be so difficult that the construction and operation of this reactor are not likely.

The graphite moderator for the molten-salt reactor and the beryllium moderator for the gaseous-core reactor currently cannot be manufactured in the quantities and sizes required for commercial application. Thus, supply industries would have to be developed in parallel with the reactor development. Beryllium fabrication is considered especially difficult and might affect the commercial feasibility of the gaseous-core reactor.

Significant quantities of lithium would be required for the molten-salt, gaseous-core, and hybrid reactors. Satisfying these requirements would involve the development of a supply industry. The other materials and resources for the six concepts would probably be commercially available.

2.1.6 Engineering and Operability

All six advanced concepts would be more difficult to operate than a conventional light-water reactor. Operation of the mixed-spectrum reactor would be similar to that of a liquid-metal fast-breeder reactor or gas-cooled fast reactor and would probably not present unforeseen problems, since many sodium-cooled and gas-cooled reactors have been operated successfully. The molten-salt reactor is the only other concept that has some operating experience (obtained during an engineering experiment). Utilities would probably be concerned about the operation of a circulating-fuel reactor, such as the molten-salt or the gaseous-core reactors. Principal operating concerns would be remote maintenance requirements, disposal of the fuel after plant decommissioning, and the toxicity and radioactivity of the fluid fuel.

In addition to the difficulties anticipated with operation and maintenance of the accelerator to achieve the required high availability, the operating concerns associated with the fuel-regenerator would include control of the two-phase water coolant mixture, coordination of control between the accelerator and the target-blanket assembly, and the frequency of fuel reshuffling. Coordination of the accelerator and reactor will be quite difficult for both accelerator-driven concepts. In addition, the very large power requirements of these accelerators will cause enormous difficulties in coordinating startup and shutdown with the electrical grid.

Among the major problems associated with the hybrid reactor would be the coordination of the pulsed operation of the reactor with the operation of the steam generating plant, assurance of subcriticality at all times, and requirements for remote maintenance.

2.2 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

All six concepts would require major research, development, and demonstration programs before lead commercial plants could be built. The technology for the fast mixed-spectrum reactor is derived from either the liquid-metal fast-breeder reactor or the gas-cooled fast reactor technology. A major effort would be required to develop core and fuel materials. The denatured molten-salt concept has benefited from the fact that a small engineering prototype

reactor, the Molten-Salt Engineering Reactor, was successfully operated, thereby demonstrating the feasibility of the molten-salt concept.

The other four reactor concepts would require substantial research and development to demonstrate their underlying principles, and would also require engineering prototype reactors to demonstrate their technical feasibility. All six systems would require demonstration plants to prove that all aspects of the concept could be integrated with power plant operation and utility requirements. The construction of a lead commercial plant would be required for any possible power plant option.

The costs of the required research, development, and demonstration for the different concepts would vary considerably. For the mixed-spectrum reactor, these costs would somewhat exceed those for the conventional fast breeder, despite the direct benefit to be derived from current fast-breeder programs. The research, development, and demonstration costs of the other advanced cycles are more uncertain. Each stage of their development programs would likely uncover unforeseen technical problems.

The molten-salt reactor would probably require about the same amount of development as the fast-breeder, but with somewhat greater uncertainty. The fuel-regenerator reactor, which is based on light-water reactor technology supplemented by the use of an accelerator proton source, could possibly be developed at a lower cost than the fast breeder. The fuel-producer would combine some liquid-metal fast-breeder reactor technology with the use of an accelerator, and thus would be more costly than the breeder program, although it would benefit from expenditures in the current breeder program. If the technical feasibility of the gaseous-core reactor could be demonstrated at all, it would be more costly to develop than the fast-breeder reactor. The hybrid reactor could be the most costly of all to commercialize, but it would benefit directly from the current fusion program.

Any of these development programs would be carried out in stages--research and development, proof-of-principle experiment, demonstration plant, and lead commercial plant, with the earlier stages being less costly than the later stages, when larger plants would be required. The estimated schedules for these programs are given in Figure 1. Assuming that the suggested research, development, and demonstration programs encountered no major delays, all of the concepts would require 40 years or more before any commercial impact could

FAST MIXED-SPECTRUM REACTOR⁽²⁾

DENATURED MOLTEN-SALT REACTOR⁽²⁾

MIXED-FLOW GASEOUS-CORE^(2,3)
REACTOR

LINEAR-ACCELERATOR FUEL⁽²⁾
REGENERATOR REACTOR

TERNARY-METAL ELECTRONUCLEAR⁽²⁾
FUEL-PRODUCER REACTOR

TOKAMAK FUSION-FISSION⁽²⁾
HYBRID REACTOR

- 1 Decision to build proof of principle experiment
- 2 Proof of principle experiment begins operation
- 3 Demonstration Plant operation begins
- 4 Lead Plant operation begins

(1) Years shown are from start of program (1980) to initial operation of the resulting plant.

(2) Supporting research, development, and regulatory studies are assumed to be required from the start of the program to within five years of lead plant operation.

(3) This schedule assumes that basic feasibility questions will have been favorably resolved.

Figure 1. Estimated Research, Development, and Demonstration Schedules for the Advanced Concepts

be realized. (See Volume IV, Chapter 3, for NASAP commercialization assumptions.) Differences in total commercialization times among the concepts are due to expected variations in the time required to complete the basic research needed to demonstrate the feasibility of the concepts.

2.3 PROLIFERATION RESISTANCE CHARACTERISTICS

All of the advanced reactor concepts would take 40 years or more to deploy, and it would be several decades beyond that before they could contribute in a major way to worldwide energy production. None would eliminate the need for interim commitments to near-term technologies. Consequently, even though some of the advanced concepts considered may offer possible nonproliferation benefits, they have only limited potential for influencing the overall level of proliferation risk for many decades.

The fast mixed-spectrum reactor and its fuel cycle offer essentially the same proliferation resistance characteristics and advantages over closed fuel cycles (that require reprocessing and refabrication facilities) as the light-water reactor once-through system. The vulnerabilities are somewhat greater, but it calls for basically the same types of technical and institutional nonproliferation measures, rather than the new institutional approaches that are under consideration for closed fuel cycles.

Both the molten-salt and gaseous-core reactors are perceived to have similar proliferation resistance features, in particular the limited access to fissile material and the difficulty of removing it from the fuel cycle. In each case, no spent fuel is discharged until the end of reactor life. The need for external reprocessing and refabrication facilities and the associated transportation and storage of chemically separable weapons-usable materials, including spent fuel, would be eliminated. The molten-salt concept retains the vulnerabilities associated with enriched makeup fuel but appears to offer somewhat greater resistance to diversion and misuse of reactor materials. By reducing accessibility to sensitive materials and eliminating sensitive facilities, both of these systems appear to offer nonproliferation advantages relative to closed fuel-cycle systems like the fast breeder.

The fuel-regenerator is a plutonium producer and should be deployed only under international auspices in support of dispersed reactors. The fuel-regenerator would also have to be carefully safeguarded to prevent its being used as a covert source of weapons-usable material.

The electronuclear fuel-producer and the fusion-fission hybrid reactor would both produce large quantities of fissile material for support of dispersed reactors. Their fuel cycles would also involve extensive reprocessing and fuel fabrication operations. The fuel production facilities and associated fuel cycle facilities of these reactors should only be deployed under appropriate international auspices. Under the appropriate deployment constraints, the proliferation resistance of these systems would be comparable to that of conventional closed fuel cycles with analogous deployment constraints.

An advantage of the three fuel-producing concepts would be their ability to support a larger number of dispersed reactors than the liquid-metal fast-breeder reactor, thereby reducing the number of fuel-producers required to support a given level of nuclear generating capacity. They could also facilitate a transition to the use of denatured uranium-thorium fuels in dispersed reactors. Such fuels do not contain chemically-separable weapons-usable materials and now appear more proliferation-resistant than fuels that do.

2.4 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

All six concepts could have serious licensing problems. These problems would have to be addressed through complete research, development, and demonstration programs. The molten-salt and gaseous-core designs would share the intrinsic disadvantage of fluid fuel and would have fewer barriers to the release of radioactivity than the light-water reactor. Inadvertent criticality and proton-beam misfocusing would be potential accident-causing conditions in both the fuel-regenerator and the fuel-producer. The hybrid reactor would have the basic safety and licensing problems of a fusion device, as well as those related to the use of fertile, fissile, and fusile material in the blanket. Licensing of the mixed-spectrum reactor would be contingent upon the development of high-performance fuel, cladding, and duct materials, and proving that uranium metal fuels could be used safely in a large fast reactor.

Compared to currently operating reactors, none of the six concepts appears to have significant potential for reducing the overall environmental impact of nuclear power systems, although fewer mining and milling operations would be required in all concepts. Improved thermal efficiency and, therefore, less heat rejection would be expected from the mixed-spectrum, molten-salt, gaseous-core, and hybrid reactors. The fuel-regenerator fuel cycle would be significantly less efficient due to the large amount of energy required as input to the accelerator.

The five fission-only concepts would create approximately the same quantities of fission products per unit of thermal energy. The quantities of fission products per unit of thermal energy resulting from the hybrid reactor would be reduced, compared to other concepts, because a large fraction of the energy would be produced by the fusion reactions. However, it would have additional forms of radioactive waste due to irradiation of the first wall and structural materials and to the production of tritium. The fuel-regenerator and fuel-producer might have highly radioactive wastes from spallation products in the target. (Low-level waste would be produced during the operations of all six concepts, but the relative quantities of these wastes would depend greatly on the detailed designs of the plants.)

2.5 RESOURCE UTILIZATION

All six concepts would significantly extend the usefulness of the existing uranium resource base. Table 1 summarizes their levels of uranium resource utilization and compares them with the resource utilization level of the light-water reactor operating in the once-through mode. The gaseous-core reactor could substantially reduce dependence on mined uranium because all fertile and fissile material loaded into the reactor would be burned. The other concepts would be less resource efficient, but alternate fuel-management schemes, such as reprocessing or reconstituting fuel, could substantially increase the fuel efficiency for these concepts.

2.6 ECONOMICS

All of the advanced concepts are still in the conceptual design stage; therefore, their estimated costs are still highly uncertain. However, the relative

Table 1. Uranium Resource Utilization Summary

Concept	Fuel	Fuel Repro- cessing	Uranium Utilization Improvement Factor*
Fast Mixed-Spectrum Reactor	Uranium enriched up to 11% U-235 for startup and natural uranium for refueling	No	3
Denatured Molten-Salt Reactor	Uranium enriched to 20% U-235 and thorium	No	3
Mixed-Flow Gaseous- Core Reactor	Uranium enriched to 10% U-235, for startup; thorium after startup	On-site	20-80
Linear-Accelerator Fuel- Regenerator Reactor	Uranium enriched to less than 2% U-235	No	3
Ternary Metal-Fueled Electronuclear Fuel- Producer Reactor	Plutonium, thorium, natural uranium	Yes	2
Tokamak Fusion-Fission Hybrid Reactor**	Natural uranium, lithium, and deuterium	Yes	4**
Light-Water Reactor	Uranium enriched to 3-5% U-235, once-through cycle	No	1

* Ratio of the uranium utilization of the advanced reactor to the standard once-through light-water-reactor fuel cycle as measured by U_3O_8 utilized per GW of electrical power produced.

**Uranium utilization improvement factor would be considerably higher if depleted uranium were used.

levels of capital costs, operating and maintenance costs, fuel cycle costs, and total generating costs can be compared, using the light-water reactor as the base case. Total generation costs were calculated using the 30-year levelized cost methodology. Levelized costs take into account the varying times at which costs will be incurred over the operating lifetimes of different reactors as well as the time value of money. This approach permits power costs for systems with different expenditure patterns and different system characteristics to be compared. (For the purposes of comparison, estimates for the fuel-producers were based on a system of reactors, including the reactors which use the product fuel.) The results of these comparisons are presented in Table 2.

The capital and operating and maintenance costs for all the advanced concepts exceed those of the light-water reactor. (Plant capital costs for the fuel-producing reactors could not be directly compared with light-water reactor plants of equivalent electrical output, however, since the fuel-producers also produce fuel, which has value.) In light of these projections for higher capital and operating costs, lower fuel-cycle costs would be the only means of making the advanced concepts economically competitive. As a result of their improved levels of uranium resource utilization, all of the advanced concepts would be less affected by uranium costs than the standard light-water reactor.

In balance, total generating costs of the denatured molten-salt, tokamak fusion-fission hybrid, and mixed-flow gaseous-core reactors all may be competitive with light-water reactors at U_3O_8 prices of greater than \$160/lb. Total generating costs for the remaining concepts (the accelerator-driven fuel-producers and the fast mixed-spectrum reactor) appear to be higher than those for the light-water reactor. Due to the speculative nature of the concepts evaluated, economics should not be used at this time as an important discriminator.

2.7 COMMERCIAL CONSIDERATIONS

Suitability for commercial application is assessed by first assuming that commercial plants could be constructed, if desired. (See Volume IV.) Commercial plants are built only after research, development, and demonstration programs have been completed, during which time outstanding issues are resolved and demonstration and lead plants successfully operated.

Table 2. Comparison of Projected Power Costs

	Light-Water Reactor	Fast Mixed- Spectrum Reactor	Denatured Molten-Salt Reactor	Mixed-Flow Gaseous-Core Reactor	Linear- Accelerator Fuel- Regenerator Reactor ₅	Ternary Metal- Fueled Electro- nuclear Fuel- Producer ₅ Reactor ₅	Tokamak Fusion- Fission Hybrid ₅ Reactor ₅
Capital Cost	Base	Above Base	Above Base	Above Base	(4)	(4)	(4)
Operating and Maintenance Cost	Base	Above Base	Above Base	Above Base	Above Base	Above Base	Above Base
Fuel Cycle Cost ₁	Base	Near Base	Below Base	Below Base	Below Base	Near Base	Below Base
Total Generating Cost	Base	Above Base	(2)	(3)	Above Base	Above Base	(2)

1. Reference U_3O_8 price for all systems was \$160/lb U_3O_8 .
2. May be able to compete with light-water reactors at U_3O_8 prices $\geq$ \$160/lb.
3. If technical feasibility problems were favorably resolved, may be able to compete with light-water reactors, if U_3O_8 prices were $\geq$ \$160/lb.
4. Capital costs of these facilities cannot be directly compared, because a system of reactors is required to use the fuel.
5. Cost comparisons for these reactors are based on estimates for a system of reactors, including the reactors which use the product fuel.

A commercial suitability assessment must deal with perceptions that utilities might have regarding new concepts. A utility will examine a new concept to judge whether the plant is licensable, operable, and capable of offering competitive economics. Any unfamiliar type of power plant would have to show a significant economic advantage before it could displace a proven plant. Because of the conceptual nature of designs assessed by NASAP, an assessment of future commercial potential is quite difficult. It is clear that all of the six reactors would have difficult paths to follow, with considerable uncertainties to be overcome before technical feasibility and, later, commercial acceptability could be demonstrated. It would take at least 25 years to develop and demonstrate the operability of any of the advanced concepts, with additional time required for the construction of a lead commercial plant and penetration of the commercial market. Thus, based on the information currently available, none of the six concepts appears to offer a viable, competitive means of improving proliferation resistance within the NASAP horizon of 2025.

2.8 OVERALL CONCLUSIONS

For all advanced systems examined in the NASAP framework, at least 40 years would be required before operation of a lead commercial plant could begin. Significant additional time (about 20 years) would be needed to substantially penetrate commercial markets. During this period, a large number of near-term systems may have been deployed. Therefore, even though some of the advanced reactor concepts considered may offer potential nonproliferation benefits, none can influence the overall level of proliferation risk before 2025.

The molten-salt and gaseous-core reactors, because they provide limited access to fissile material and operate with low excess reactivity, could potentially enhance proliferation resistance over the liquid-metal fast-breeder fuel cycle. The fast mixed-spectrum reactor would share certain basic proliferation vulnerabilities with the light-water reactor operating in a once-through mode. The technical and institutional measures needed to safeguard the systems would be similar. When compared with the liquid-metal fast breeder reactor, the fast mixed-spectrum reactor would offer certain non-proliferation advantages, because no directly weapons-usable material would appear anywhere in the fuel cycle. The fuel cycles for these three reactors do not require external reprocessing, refabrication, or transportation of weapons-usable material; they would, therefore, offer nonproliferation benefits compared to closed fuel cycles like fast-breeder systems.

The fuel-producer concepts--the fuel-regenerator, the fuel-producer, and the hybrid reactor--would all require appropriate controls to protect against misuse of the reactor. However, they may have an advantage over more conventional plutonium recycle concepts because they can produce larger amounts of fissile material. Thus, fewer facilities would be required to support a fixed external generating capacity.

All of the six advanced concepts would have difficult paths to follow to demonstrate technical feasibility and commercial acceptability. All would require large expenditures of research and development funds and would take considerable time to develop. It is estimated that 25 years is the minimum amount of development time required before a decision to construct a lead commercial plant for the molten-salt or mixed-spectrum reactor could be made. About 40 years is the minimum time required for the hybrid or the gaseous-core reactor. The accelerator-driven concepts--the fuel producer and fuel regenerator--would require intermediate development times. However, a technology evaluation may show that not all systems merit further development. For example, the gaseous-core reactor may not be technically feasible because of materials compatibility and corrosion problems. Others, like the accelerator-driven fuel-regenerator, may not be commercially attractive because of projected high total generating costs and operability problems.

Some concepts, like the mixed-spectrum reactor and the hybrid concept, could benefit from ongoing development programs. The technology of the mixed-spectrum reactor is derived from the fast-breeder reactor program and improvements in the fast-breeder system could benefit the mixed-spectrum. While the fission-fusion hybrid concept evaluated in NASAP is a poor representative of fission-fusion hybrid systems, the ongoing fusion technology development program should identify alternate concepts within the class of tokamak-driven hybrid reactors, as well as better fusion driver concepts. Therefore, as fusion technology develops, much-improved hybrid concepts could become available.

While none of the six concepts appears to be a credible commercial alternative to the liquid-metal fast-breeder within the NASAP horizon of 2025, there are a number of reasons for continued interest in the fast mixed-spectrum reactor: It is a once-through cycle fast reactor with proliferation risk characteristics similar to those of the light-water reactor; only about one-third as much uranium is required as for the once-through light-water reactor; the system will benefit directly from fast-breeder development programs; and, finally, the research and development required to develop the high-burnup metal fuel

could benefit the on-going liquid-metal fast-breeder reactor program. Accordingly, a limited research and development effort on the high-burnup fuel seems justified, at present.

3. FAST MIXED-SPECTRUM REACTOR

3.1 OVERVIEW

The fast mixed-spectrum reactor is a fast breeder reactor design concept. Despite its similarities to conventional fast breeders in terms of fundamental plant technology, the fast mixed-spectrum reactor's design represents a substantial departure in terms of certain important operating characteristics. The reactor would be started up with fuel at an average uranium enrichment of about 7 percent U-235, with a maximum of 11 percent U-235, and would operate on a once-through-and-store fuel cycle. Unlike the conventional fast-breeder reactor, where make-up fuel consists of plutonium mixed in natural uranium, the fast mixed-spectrum reactor is designed to be self-sustaining on an equilibrium fuel feed of natural or depleted uranium alone. Following the initial loading, no enrichment is needed and no reprocessing is required. The current design is based on the use of a metal fuel to ensure the required high breeding gain and good neutron economy.

Fuel would remain in the reactor a very long time (about 17 years according to current design studies) and a substantial burnup of heavy metal would occur during this period. The discharged fuel would contain substantial amounts of plutonium (approximately 7 percent), which would have to be safeguarded.

Development of the fast mixed-spectrum reactor would rely on technological advances that are presently not assured, e.g., high burnup metallic fuel and the development of cladding and duct materials which could withstand a high neutron fluence. The design and its limitations, possibilities, and uncertainties are presently being explored in an initial feasibility study. (See Volume IX, Section 1.12.1.) For the most part, extensions of current fast-breeder research and development programs, rather than new programs, will be needed to establish feasibility and to prepare for demonstration of the reactor. However, a substantial new fuel development program will be required to demonstrate the feasibility of the metal fuel performance. Although there are still significant design and operating concerns, analysis thus far supports the validity and feasibility of the concept, if the fuel performance targets can be met.

The reactor's high level of uranium utilization is attractive. A level of initial fuel enrichment too low for direct use as a weapon, coupled with the lack of reprocessing, should combine to make the fast mixed-spectrum reactor attractive from a non-proliferation point of view.

3.2 DESIGN ASSESSMENT

3.2.1 Conceptual Plant Design

The fast mixed-spectrum reactor concept is very similar to either a liquid-metal fast breeder or a gas-cooled fast reactor except for some major differences that would be required to accommodate the fuel design and fuel cycle. Thus, the plant design features for the fast mixed-spectrum reactor would be essentially the same as those of the other fast-breeder reactors. The non-nuclear parts of the plant would be very similar to fast-breeder system designs, and the balance of plant arrangement could be similar to a gas-cooled fast reactor housed in a prestressed concrete pressure vessel or a loop- or pot-type liquid-metal-cooled fast breeder. The basic reactor concept is displayed in Figure 2. The schematic core layout should be considered as representative of a specific design layout rather than generic.

The radiation damage to fuel cladding and structure caused by fast neutrons would be as much as four to eight times larger than that occurring in a conventional fast breeder. Also, the very high fuel burnup (145 MWd/kg average and 180 MWd/kg peak) would require fuel performance beyond the state of the art.

The reactor design could be based on existing fast-breeder reactor technology, with special design modifications to accommodate the graphite or beryllium moderator, the larger core, and the special equipment that would be required for fuel rearrangement (shuffling). If a gas-cooled mixed-spectrum reactor concept were adopted, the primary heat system would need to be designed to operate at 2,000 psi (compared to 1,300 psi for a gas-cooled fast reactor and 740 psi for a high-temperature gas-cooled reactor); thus, additional design problems could be anticipated.

FAST MIXED-SPECTRUM REACTOR CONCEPT

FAST FUEL

MOD. FUEL

MODERATOR

F - FUEL-BEARING CONTROL RODS

S - SHUTDOWN RODS

1 - MODERATED FUEL ZONE

2 - HARD SPECTRUM FUEL ZONE

3 - TRANSITION FUEL ZONE

Figure 2. CROSS-SECTIONAL VIEW OF THE FAST MIXED-SPECTRUM REACTOR

Reactor containment concepts for fast breeders are essentially established. A special fuel gas venting system may be required. Fuel venting is a process in which fission product gases are vented either directly to the coolant or to a special fission product venting system. The existence of fission products in the coolant would require an extensive fission gas collection system. Other radioactive waste systems would be more conventional and within the state of the art.

The design and performance criteria for heat removal and emergency shutdown may be more severe due to increased fission-product inventories, larger core size, and fuel venting. For the gas-cooled concept, other auxiliary systems, steam generators, and power conversion equipment would have to be compatible with the 2,000 psi primary system pressure, and the integrity of the various system interfaces would have to be assured.

3.2.2 Reactor Physics Considerations

At this stage, estimates of criticality and capability to breed as a function of the fuel configuration are based on the results of preliminary physics calculations that contain important uncertainties. The adequacy of the calculations must be checked against more rigorous and more detailed neutron transport calculations and critical experiments to assure feasibility of this design. The fuel cladding and ducts in the reactor would have to contain sufficient structural material to satisfy criteria for long-term strength, which may not be represented by the amount of structure now included in the physics models. Also, the fission product inventory of the equilibrium core would be very high, so the fission product cross-section model would require more detailed analysis than is currently provided. A very complex series of calculations would be required to predict performance of the reactor during its lifetime.

If the more complex analysis shows insufficient reactivity, it could possibly be increased by using one of several methods. One method may be to use low-enriched uranium as the equilibrium feed. Optimization of moderator configurations and fuel shuffling strategies could also be used.

3.2.3 Fuel-Cycle Alternatives

The fuel cycle for the mixed-spectrum reactor would be relatively simple because of its once-through aspect. However, practical operation of the reactor could be complicated by requirements for fuel rearrangement (although several possible shuffling techniques appear possible). Since much of the fuel in the reactor at the end of reactor life would not have achieved the maximum possible burnup, a pairing of two reactors has been suggested so that fuel discharged from the first reactor could be used as part of the initial core of the second reactor. This would improve the average burnup of the two reactors significantly. No reprocessing would be required; however, this fuel cycle would require the storage of spent fuels containing 7 to 8 percent plutonium, while light-water-reactor spent fuel contains about 1 percent plutonium.

3.2.4 Mechanical and Thermal-Hydraulic Considerations

Dense packing of fuel in the reactor core would be required to achieve a high conversion or breeding ratio¹ and would affect mechanical design and cooling system requirements. The thermal-hydraulic aspects of the reactor design have not been fully explored. The pumping power of the gas-cooled reactor would tend to be high, and studies would be required to identify possible means to reduce it.

The complex fuel-management scheme and the wide variation in fissile content of the fuel elements might require more extensive orificing to control coolant flows than is normally used in a fast breeder. Otherwise, the overall thermal-hydraulic problems would be no more difficult than those of fast breeders.

¹ Conversion ratio is the ratio of fissile material produced to that consumed. If the ratio is greater than unity, the system is said to "breed."

3.2.5 Selection, Development, and Availability of Materials

Primary system materials for the components and piping to handle either sodium or helium have been developed and should provide satisfactory service.

The feasibility of this reactor's fuel cycle would depend on the development of fuel materials, cladding, and ducts that would be irradiated for periods five to eight times longer than experienced or expected in fast breeders and withstand a neutron fluence as much as four to eight times the current target for the liquid-metal or gas-cooled fast-breeder reactors. The high neutron fluence and long irradiation time might cause unacceptable duct deformation.

The fuel-pin centerline temperature would be approximately 850°C, which would be higher than previously experienced during irradiation of the proposed metal fuel. This temperature would bring the metal-alloy fuel into a metallic phase that differs from the one in which EBR-II² experimental fuel is operating.

The technical feasibility of the fast mixed-spectrum reactor would depend on the development of fuel, cladding, and ducts that could withstand irradiation to very high neutron fluences and very high burnups (approximately 140 MWd/kg average and approximately 180 MWd/kg peak). Major technological advances would be required.

²EBR-II--Experimental Breeder Reactor-II is an engineering test facility for breeder reactor components, located at the Idaho National Engineering Laboratory (INEL), at Arco, Idaho.

3.2.6 Engineering and Operability

Actual operating experience indicates that either gas-cooled or sodium-cooled fast mixed-spectrum reactors could be operated effectively to produce power for a utility grid. Therefore, the outlook for operation acceptable to a utility is favorable. The major differences between it and other fast breeders, from an operational viewpoint, would be that semiannual refueling might be required and that fission product gases would probably have to be vented from the fuel, captured, and permanently stored.

3.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

While the development of the fast mixed-spectrum reactor would benefit directly from current fast-breeder technology programs, the concept is in a very early stage of development, and there are significant design and operation concerns which require resolution. Major additional work would be required in the areas of reactor physics, thermal-hydraulics, materials, reactor design, and safety, and a significant amount of time would be needed to gain the necessary technological assurances. The metallic fuel design problem in particular may severely limit the performance of the reactor. The fuel system significantly exceeds present knowledge. The very high neutron fluence requirements and high burnup of the fuel is considered to be beyond practical extrapolation of present technology. The current fast breeder programs are concentrating on oxide and carbide fuels. Thus, a new, high-risk program would be required to develop metal fuel.

Because the technology is more advanced than that of conventional breeders, the development of fast mixed-spectrum technology would be more difficult and more expensive than either the liquid-metal or gas-cooled fast breeder programs. In addition, the research, development, and demonstration for this concept would be expected to take at least 40 years; thus, the concept's benefits and impacts could not be felt until after 2025.

3.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The most important nonproliferation feature of the conceptual fast mixed-spectrum reactor is its capability to operate in a once-through mode with natural or depleted uranium makeup fuel. Enriched uranium would be used only for startup. The spent fuel would contain large amounts of plutonium, which need not be recycled to sustain reactor operation.

The most sensitive element of the fast mixed-spectrum reactor fuel cycle would be the uranium enrichment facilities needed to produce startup fuel (enriched up to 11-percent U-235 compared to 3 to 5 percent for the light-water reactor) and control rod material (uranium enriched up to 20-percent U-235). Facilities designed to produce enrichments of 11 to 20 percent would be more easily modified for high-enriched uranium production than facilities limited to 3 to 5 percent enrichment. However, in either case it is important to limit the deployment of enrichment facilities.

Fresh enriched uranium startup fuel for the fast mixed-spectrum reactor would require about five times less separative work to be diverted for weapons purposes than fresh light-water reactor fuel and would be more desirable to a potential proliferator. However, this enriched fuel would be available only at the beginning of the reactor life cycle.

A 1,000-MW fast mixed-spectrum reactor would generate about 600 kg of total plutonium annually, compared to about 260 kg in a light-water reactor of the same capacity. The fast mixed-spectrum reactor discharges fewer fuel assemblies each year (12, versus about 80 for the light-water reactor), which would make a single fast mixed-spectrum reactor fuel assembly a more attractive target for diversion, but would reduce spent-fuel storage requirements.

The fact that only fertile material would be added after startup would offer the nation using a fast mixed-spectrum reactor increased energy security but would reduce the leverage that supplier nations could exert with regard to nonproliferation agreements. It should also reduce incentives for nations to develop indigenous enrichment capabilities or to reprocess spent fuel. However, if the demand and price for uranium were rising rapidly, the fast mixed-spectrum reactor's unusually high demand for uranium at startup and the

relative attractiveness of its spent fuel as a source of plutonium might create pressures for nations to acquire a plutonium startup capability for additional fast mixed-spectrum reactors by means of reprocessing.

While the fast mixed-spectrum reactor would offer both advantages and disadvantages, compared with the light-water reactor operating on a once-through fuel cycle, the basic vulnerabilities associated with fresh and spent fuel would be similar. Moreover, the technical and institutional measures needed to protect the fast mixed-spectrum reactor fuel cycle would be conceptually similar to those needed in the near term for the light-water reactor fuel cycle.

Compared to the liquid-metal fast-breeder reactor, the conceptual fast mixed-spectrum reactor would not have the vulnerabilities associated with reprocessing of spent fuel and with the preparation, shipment, and storage of fresh mixed plutonium-uranium oxide fuel, because it would be a once-through system. Even if the liquid-metal fast-breeder reactor is considered in a context where the deployment of reprocessing and plutonium fuel fabrication facilities were limited, the fast mixed-spectrum reactor would offer nonproliferation advantages, because no directly weapons-usable material would appear anywhere in the fuel cycle, whereas the liquid-metal fast-breeder reactor would entail commerce in materials that are either in weapons-usable form or in forms that are relatively easy to exploit for weapons purposes. In addition, the technical and institutional demands of a nonproliferation regime to accommodate the liquid-metal fast-breeder reactor fuel would be greater, in degree and kind, than for the fast mixed-spectrum reactor.

3.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

No in-depth safety and environmental reviews have been provided for the mixed-spectrum concept. Consequently, conclusions about safety and environmental aspects are necessarily speculative. The fast mixed-spectrum reactor, like other fast breeders, would be fundamentally licensable if the fuel and core materials could be developed and demonstrated. The same safety issues would need to be explored and similar design determinations would have to be made from an appropriate safety analysis.

With two important exceptions, the safety of gas-cooled or sodium-cooled versions of this technology would not be very different from that of their conventional fast breeder counterparts, which use uranium-oxide or mixed uranium-plutonium-oxide fuels. The first exception relates to the behavior of the fuel if a severe transient occurred. Upon melting, oxide and metal fuels might differ in their transient behavior. The metal fuel might readily expand, or even foam, due to the release of dissolved fission product gas and because of sodium vapor pressure in the sodium-cooled version. However, the opposite possibility of fuel densification must also be considered, and relevant experiments should be performed to determine actual behavior.

The second exception is that the low-fissile enrichments of the fuel would tend to reduce the chance of recriticality should meltdown occur. The tendency of metal fuel to form inseparable eutectics with steel would further reduce the effective fissile density. In addition, fuel from the higher power density regions could tend to be diluted by fuel from the other areas, further decreasing the fissile enrichment and, hence, the chances of recriticality.

As stated, the fast mixed-spectrum concept has not yet been developed to the point where specific environmental issues can be defined and addressed. However, it is not expected to present any environmental issues over and above those already associated with conventional fast breeders. A possible exception may be the question of what the environmental impact would be of the permanent disposal of spent fuel containing very large amounts of plutonium.

3.6 RESOURCE UTILIZATION

Estimates of uranium resource utilization indicate that the first 30 years of mixed-spectrum reactor operation might yield about three times the energy from uranium as the light-water reactor on a once-through fuel cycle. Using fuel sharing by a paired set of reactors would increase this factor to about four times the energy. This increased uranium utilization would result from the conversion of significant quantities of U-238 to plutonium and from burning the plutonium in situ. Of course, operation of succeeding reactor generations would greatly increase the overall uranium resource utilization, since fuel discharged at the end of one reactor's life might be used to start another.

3.7 ECONOMICS

No detailed estimates of fast mixed-spectrum reactor economics have been made due to a lack of plant and fuel design details. Capital, operating, and maintenance costs are expected to be very similar to liquid-metal fast breeder costs. Fuel-cycle costs have been estimated based on preliminary data and are higher than the costs of either a light-water reactor on a once-through cycle or a liquid-metal fast breeder. The fuel costs would be high because no credit is given for the plutonium, while most costs for uranium, enrichment, and fabrication occur when operation begins. The resulting total generating costs would be higher than light-water reactor costs unless uranium prices exceeded \$160/lb U_3O_8 .

3.8 COMMERCIAL CONSIDERATIONS

If the reactor's outstanding design issues were resolved so that working demonstration and lead plants could be constructed, utilities would probably find the fast mixed-spectrum reactor as acceptable to operate and maintain as fast-breeder reactors. Its direct relationship to the technology of the gas-cooled and liquid-metal fast-breeder reactors, as well as its relatively small dependence on uranium supply and enrichment services after the first core and in equilibrium operation, should be perceived as advantages. The fast mixed-spectrum reactor also has a somewhat higher assurance of licensing compared to the other advanced reactor concepts considered in this volume. In addition, the concept's high level of uranium utilization, coupled with the use of paired reactor fuel cycles to obtain greater fuel burnup, could also enhance the reactor's economics and thus its commercial attractiveness.

Factors which may serve to impede the commercialization potential of the mixed-spectrum reactor include its refueling requirements (although simpler, less frequent fuel-shuffling strategies may be developed); anticipated difficulties in handling, shipping, and storing the highly irradiated spent fuel; and apprehension about the behavior of metal fuel and critical reactor materials under extended irradiation conditions.

There are uncertainties involved in performing an economic analysis of a system in the conceptual design stage. However, the economics of the fast mixed-spectrum reactor do not appear to be competitive with light-water reactor economics until U_3O_8 prices exceed \$160/lb.

4. DENATURED MOLTEN-SALT REACTOR

4.1 OVERVIEW

Unlike any other of the advanced concepts assessed for this volume, the concept for the denatured molten-salt reactor has been developed through the reactor experiment stage. The Molten-Salt Reactor Experiment (MSRE) involved an approximately 8-MW (thermal output) reactor, which operated successfully from 1965 to 1969. This experiment was not a breeder, however, since the MSRE did not contain thorium in the fuel salt or have continuous fuel processing to remove fission products. Rather, the MSRE was considered to be a basic proof-of-principle demonstration of the fluid-fuel reactor concept. Thus, the basic feasibility of the technology for the denatured molten salt reactor has been demonstrated. The denatured fuel cycle is one of several fuel systems proposed for use in the molten-salt reactor.

Due to the information acquired during the MSRE, the denatured molten-salt reactor is further along on the development timeline than the other advanced reactors assessed. The experiment resulted in a delineation of problem areas that is more explicit and complete than is available for the other advanced concepts. This delineation does not, in and of itself, indicate a lack of feasibility for the denatured molten-salt reactor; rather, it is a reflection of the availability of highly detailed information. For most of the other advanced concepts, highly detailed information is unavailable, due to their very early stages of development.

Several critical technical problems would need to be resolved and key developmental steps taken before the denatured molten-salt reactor could be commercially deployed. These problems include:

- Identifying materials for containing molten reactor fuels at high temperatures for long periods.
- Control of the tritium which would be produced from the lithium component of the fuel carrier salt.
- The system's remote maintenance requirements (based on the high radioactivity of the reactor-coolant circuit).

- Scaling up the fuel and coolant pumps and heat exchangers.
- Developing the required instrumentation and controls.
- Developing methods for collecting and storing the accumulated radioactive gases.

The principal advantages of the denatured molten-salt reactor include its good neutronic performance and its high resource utilization (the concept requires only about one-third the uranium used by the once-through light-water reactor). Many sensitive, out-of-reactor operations (reprocessing, recycle fuel preparation, and spent-fuel storage or disposition and the associated transportation) would occur only once, at the end of each reactor's lifetime, and the only on-line chemical processing required would be a hydrofluorination facility for periodic removal of oxide contaminants. Sensitive front-end operations would be limited to the initial loading and startup of the reactor, except for intermittent enrichment services, which would be substantially reduced over the requirements of light-water reactors. Because of its low excess reactivity, any significant diversion of fluid fuel would be reflected in a degradation of reactor performance. The opportunities for misusing the fuel cycle would consequently be limited.

The system's principal disadvantages are associated with its new and, as yet, unfamiliar technology, the problems associated with licensing a fluid-fuel reactor, and the long timescale that would be required for deployment. The reactor would also require high capital costs (although very low fuel costs could, to some extent, compensate for them).

In balance, the denatured molten-salt reactor offers several proliferation resistance advantages, coupled with relatively favorable total generating costs and an efficient U_{308} utilization. The status of molten-salt technology is sufficiently advanced that a decision to build a small demonstration plant (one of several developmental steps that would need to be taken) could be made by 1990, provided that a successful technology program were undertaken in the interim. The lead commercial plant would, however, be at least two technological generations beyond this point, so that the concept would have little commercial impact within the NASAP planning horizon (2025).

4.2 DESIGN ASSESSMENT

4.2.1 Conceptual Plant Design

The denatured molten-salt reactor's unique plant-design features primarily derive from the necessity of containing a circulating molten mixture of very radioactive, high-temperature fuel salts. (See Figure 3.) The following design problems would have to be resolved before a plant could be licensed:

- Providing for reliable draining of fuel salts during postulated accident conditions.
- Ensuring residual heat removal in the fuel-salt drain tanks.
- Ensuring cooling of the liners of the equipment cells (primary containment walls and floors) in the event that spilled fuel salt fails to flow to the drain tank.
- Preventing the escape of stored fission-product gases.

The entire primary circuit and most appendages, including a hydrofluorination facility for oxide removal to maintain fuel-salt purity, would have to be amenable to remote inspection and maintenance. These special plant-design features must be emphasized because they would be important to the plant's licensability. However, it is anticipated that they could be engineered and built as required.

Practical building arrangements for the systems and components of the plant would be required. A building would need to be designed that could provide the structural integrity and support for the reactor vessel and primary heat-transport system, while simultaneously providing radiobiological and thermal shielding.

Figure 3. SIMPLIFIED FLOWSHEET FOR ONCE-THROUGH DENATURED MOLTEN-SALT REACTOR

The capability for fabricating the Hastelloy N¹ and graphite components of the reactor would have to be demonstrated. Also, nuclear detectors capable of operating and enduring in the adverse heat and radiation environment around the reactor would have to be developed. The seals, valves, electrical disconnects, wiring, and insulation in the reactor control system would have to meet stringent standards of performance. All parameters which affect reactor performance, such as reactor-core thermal-stress distributions, hydrodynamics, vibrations, dimensional changes, and control, would have to be fully analyzed.

The production of tritium in the primary circuit would increase the potential for release of radioactive material and subsequent exposure of personnel. The magnitude and effects of tritium diffusion from the primary to secondary heat-transport system would have to be analyzed, and a means for limiting tritium diffusion through the walls and piping of the secondary heat-transport system would have to be demonstrated. In addition, both flow measurement instrumentation and the control devices would have to be capable of withstanding the severe temperature environment and cyclic behavior of the primary heat-transport system.

The primary heat exchanger and the fuel-salt circulating pump performance have not been demonstrated and designs are incomplete. The molten-salt circulating pumps would have to be scaled up by factors of 10 to 20, requiring engineering and design studies and tests. Criteria for primary containment systems would have to be developed and the feasibility of the designs demonstrated before licensing. The means for transporting, shielding, immobilizing, processing, storing, and disposing of both high- and low-level radioactive wastes would also be required.

Primary system components that could withstand the effects of solidification of the molten-salt, or a means for preventing the salt from solidifying within components, would be required to avoid the potential for expensive plant shut-downs. Molten-salt spills and accidental leakage would have to be eliminated and extensive design and development work would be required to guard against these accidents.

¹The previous denatured molten-salt reactor programs identified Hastelloy N (a high-temperature, corrosion-resistant, nickel-based alloy) as the preferred material for primary or secondary system components that contact either fuel salt or coolant salt.

If a sodium-potassium eutectic, which has a low melting point, were used as the intermediate coolant, the potential for alkali-metal/water accidents would impose additional constraints on heat exchanger designs and require that special handling procedures and precautions be observed. Alternative coolants for residual heat removal in the fuel-salt drain tank would also need to be considered.

Steam generators would need to be designed which were capable of operating with molten-salt on one side and supercritical steam on the other. High heat-exchange inlet temperatures, in combination with the coolant-salt freezing temperature characteristics and thermal gradients in the steam generator tubing, would present problems that would have to be resolved. The design for the steam generator would have to allow for the effects of water intrusion into the coolant-salt and define the degree of water intrusion that could be tolerated. Alternate (subcritical) steam cycles should be considered and assessed for possible cost impact.

4.2.2 Reactor Physics Considerations

A concise description of the reactor physics model for the denatured molten-salt reactor has not been developed. However, the model implied from earlier molten-salt studies provides an adequate basis for extrapolation of reactor characteristics. In the time since a detailed analysis has been performed, significant changes in thorium cross-section information have been verified. Use of the latest thorium cross sections could potentially alter the required thorium loading, as well as some of the reactor-performance characteristics.

4.2.3 Fuel-Cycle Alternatives

The denatured molten-salt reactor would require 20 percent enriched uranium feed, but would not require fuel reprocessing. It would produce fissile-fuel wastes only on decommissioning. The feasibility of the concept depends on the accuracy of the physics analysis, but it appears feasible based on the current knowledge.

4.2.4 Mechanical and Thermal-Hydraulic Considerations

One of the major requirements imposed on the core design was a uniform temperature rise in the salt flowing through the core to protect the graphite moderator from severe thermal stress. Due to the number of assumptions required to evaluate the core temperature distribution, a degree of uncertainty exists in the analysis. However, based on the various evaluations, it is believed that maximum graphite temperatures could be kept low enough to extend core graphite life to nearly 30 years (the life of the reactor). Coolant velocities have been adjusted to maintain an acceptable rise in temperature across the core. The pressure drop would have to be adjusted by orificing to achieve the required flow distributions. The thermal parameters in both the reactor core and the primary and secondary heat-exchanger systems would need to be evaluated further, but the overall mechanical and thermalhydraulic system design appears feasible.

4.2.5 Selection, Development, and Availability of Materials

The background information and documentation supporting the selection of principal materials for the denatured molten-salt plant indicates that their use is both feasible and practical. However, there are still major questions associated with providing materials to contain molten reactor fuels at high temperatures over long periods of time. A major materials problem is how to optimize the minor alloying additions to Hastelloy N to improve resistance to embrittlement when exposed to the fuel-salt, fission products, and radiation environment. If core graphite performance proved less than desired, the graphite would have to be changed during the plant life, impacting the economics of operation. No facilities are presently available for enriching the lithium (to remove the isotope of lithium with the higher neutron absorption cross section) for the fuel salt. However, the technology for this separation has been demonstrated.

4.2.6 Engineering and Operability

Conclusions regarding the operation of a denatured molten-salt reactor are based partially on the results of an experiment with such a reactor (see

Section 4.1), but much design, engineering, and development work would have to be accomplished before an optimized set of operating procedures could be provided.

Normal operation of the denatured molten-salt reactor would be expected to differ from light-water-reactor operation because much more attention must be given to chemistry control. Reactor-induced transients and the potential for excursions would pose fewer problems in the denatured molten-salt reactor due to the limited excess reactivity. No effort would be required for refueling outages, since none would be required.

It is expected that maintenance problems would be much more severe because much remote maintenance would be required in the reactor building. Development of remote maintenance techniques could allow most maintenance at hot temperatures, and maintenance of nonprimary-loop equipment would probably require no cool-down.

Based on the current conceptual design, it is estimated that the denatured molten-salt reactor would require 9 days to reach operating conditions. Startup would probably occur less than once per year, and thus would not have a major impact on plant operation. When it did occur, however, the process would be lengthy and probably uneconomical. Furthermore, the substantial auxiliary power needed to heat the reactor might create a large demand for energy from an external power source.

The interactions of the reactor plant and the on-site electrical generating plant components during startup have not yet been defined. The effects of heat-up time should be investigated, as should alternate means for heating up the reactor (in order to reduce the plant outage period). Also, the procedures for handling the effects of transient conditions and the reduction and loss of electrical load have not been developed.

Suitable in-service inspection equipment and techniques are not currently available and would have to be developed to help ensure the physical integrity of the primary piping. Methods for shielding the various radioactive cells of the plant to limit radiation exposure must be developed. Tritium production and transport might also cause radiation exposure, unless adequate means of dealing with tritium were employed.

4.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

The molten-salt concept has been developed through the reactor experiment stage. The Molten Salt Reactor Experiment, an 8-MW (thermal output) reactor, operated successfully from 1965 to 1969; therefore the basic technology is now understood. However, much engineering development and demonstration would be required before construction and operation of a full-sized plant could begin. The research, development, and demonstration leading to the orderly development of a denatured molten-salt reactor plant design would include:

- Identifying the special materials required for construction, i.e., modified Hastelloy N and graphite, and developing a commercial source.
- Improving high-temperature technology for the denatured molten-salt environment.
- Enlarging component sizes and capacities from current designs and developing industrial capacity to supply the components on a commercial scale.
- Addressing significant safety issues, such as tritium handling and fuel-salt spill procedures, and testing of safety systems to ensure proper operating reliability and effectiveness for commercial licensing.
- Developing commercial sources for the unique fuel salt used in the denatured molten-salt reactor.
- Refining remote maintenance procedures and equipment.

These programs would require the construction of test facilities to demonstrate various aspects of the design and development process and to prove the soundness and acceptability of components and equipment. Additionally, the testing facilities could be used to develop and demonstrate maintenance requirements for the various components.

Facilities needed to commercialize the denatured molten-salt reactor would include an engineering prototype, a demonstration reactor, and a lead commercial plant. These facilities would be necessary to demonstrate plant operation, reactor and fuel-system licensability, component technology, and technical and economic feasibility.

4.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The most important nonproliferation advantage of the denatured molten-salt reactor concept would be that, in principle, sensitive, out-of-reactor, back-end fuel-cycle operations (reprocessing, recycle fuel preparation, spent-fuel storage or disposal, and associated transportation) would only occur at the end of each reactor's lifetime. Consequently, opportunities for acquiring weapons-usable material from the fuel cycle would be limited.

The most sensitive element of the fuel cycle would be the enrichment facilities necessary to produce uranium enriched to 20-percent U-235 for the initial reactor loading and for periodic fuel additions. These facilities would be inherently easier to modify for high-enriched uranium production and more difficult to safeguard than enrichment facilities especially designed to produce 3- to 5-percent enriched fuel for light-water reactors. Fresh fuel in transit or at the reactor could be subject to diversion and upgrading to high-enriched uranium in a clandestine enrichment facility. The denatured molten-salt reactor system may be slightly less vulnerable in this regard than most other denatured systems, since its feed requirements and mass flows would be substantially smaller. However, uranium enriched to 20-percent U-235 would require about five times less separative work than low-enriched uranium (3- to 5-percent U-235) to produce weapons-usable material.

Molten-salt reactors could offer resistance to diversion because the entire reactor system could be enclosed within the primary containment envelope, where the level of radiation would be high and all operations would have to be performed remotely. The opening of the containment for periodic maintenance could be subjected to international inspection and surveillance.

In addition to being difficult and detectable, a diversion of material would interfere with normal reactor operation. Substantial diversion--aimed at producing more than one or two weapons within a year--would require extraordinary measures to avoid a major disruption of reactor operation. Either enrichment or sophisticated materials and chemical processing technologies, or both, would be required to obtain weapons-usable material from the diverted fuel. The complexity and cost would probably be at least as great as for analogous facilities for other fuel cycles.

The denatured molten-salt reactor fuel cycle would offer greater resistance to proliferation than the liquid-metal fast-breeder reactor system because no directly weapons-usable material would appear anywhere in the fuel cycle. In contrast, the liquid-metal fast-breeder system would entail commerce in materials that are either in weapons-usable form or in forms relatively easy to convert to weapons use.

4.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

The assessment of the denatured molten-salt reactor concept has identified several potential licensing and safety problems: It would use a molten fuel with no cladding; thus, two of the barriers or inhibitors to radioactive fission-product release in light-water reactors, the crystal structure of the fuel and the fuel cladding, would not be available in denatured molten-salt reactors. The denatured molten-salt reactor design addresses this problem by postulating a second containment structure which would accommodate main coolant-system ruptures, but substantial licensing review of this containment philosophy and verification of the design would be required. Considerable code and standards development for components would be needed.

Although all leakage from postulated ruptures within the primary containment would be collected in the reactor drain tank, blockage of the drain line to the drain tank following a spill might cause overheating and failure of the primary containment in its presently conceived air-cooled configuration. Further identification and analysis of design-basis accidents would be required to evolve licensable containment and drain tank designs.

The storing of gaseous fission products would also contribute to potential licensing problems. Extraction processes and storage provisions would be examined critically by regulatory bodies.

The system's small excess reactivity would limit the rate of possible power excursions. In addition, the heat capacity of the large mass of the fuel and graphite moderator could accommodate extra heat from power excursions.

The environmental impact of the system would not differ significantly from that of operating light-water reactors. Operational and fuel-cycle differences between this concept and a light-water reactor of similar size would result in lower land use for the denatured molten-salt reactor because it would require substantially less uranium mining. Because of higher thermal efficiency, heat rejection would be lower, resulting in lower cooling water makeup requirements. Areas that would result in increased environmental impacts include the lithium-isotope separation facilities, the effect of possible tritium releases, fluoride handling problems, and plant decommissioning. However, it is unlikely that any of these differences would have a significant impact on the concept's acceptance.

4.6 RESOURCE UTILIZATION

This concept would require 20-percent-enriched uranium feed and, for the same amount of mined U_3O_8 , would yield three times as much power as a standard light-water reactor on a once-through fuel cycle.

4.7 ECONOMICS

The estimated capital cost for a power generating station is about 50 percent higher than the capital cost of a similarly sized light-water reactor. The non-fuel operation and maintenance cost of a 1,000-MW plant appears to be approximately 50 percent greater than that of a conventional light-water reactor. The total generating costs could become lower than those of the light-water reactor when the price of U_3O_8 approaches \$160/lb. The total estimated generating cost suggests that, within the timeframe of its possible development, the denatured molten-salt reactor might be economically competitive with light-water reactors.

4.8 COMMERCIAL CONSIDERATIONS

Before a utility will order any reactor, it must be convinced of the plant's safety, licensability, operability, and economic competitiveness. An impediment to commercialization of the denatured molten-salt reactor would be the

unfamiliar chemistry of the molten salt. Sufficient experience would have to be accumulated with the molten-salt systems to satisfy commercial operability criteria, which could be quite difficult.

The reactor's remote maintenance requirements would also cause uncertainty. The potential effect of the remote maintenance requirements on reactor downtime would need to be well defined. While estimates of overall capacity factor may be predicted with a fair degree of assurance, the requirement for remote maintenance and continuous operation would combine to make the timing and duration of outages uncertain. Most utilities are very sensitive to outages in some seasons of the year, and the possibility of long outages during sensitive seasons would make utilities reluctant to purchase a denatured molten-salt reactor.

While all safety and licensing issues associated with the fission-product gas-handling system would probably be resolved through research, development, and demonstration, the fission product gas-handling and clean-up systems would be complex and would require a level of responsibility and care not currently required of utilities operating light-water reactors. A reluctance to assume these responsibilities might occur. The potential problem of shipping and disposing of highly concentrated fission-product gases could also add to this resistance to purchase.

The total generating costs of the reactor, while still uncertain, show a slight advantage over the light-water reactor as uranium prices approach \$160/lb. This advantage would increase as uranium prices rise. Considerable economic incentives would be needed for utilities to accept the level of responsibility inherent in molten-salt reactor operation.

5. MIXED-FLOW GASEOUS-CORE REACTOR

5.1 OVERVIEW

The mixed-flow gaseous-core reactor is one of several gaseous-core reactor concepts, all of which are characterized by the use of a fissioning gas mixture to sustain the fission reaction. The circulating fuel gas also serves as the primary heat-transport system. The use of a molten-salt blanket would allow the system to be operated without the introduction of fresh fissile fuel after the initial reactor loading. The molten-salt blanket would require reprocessing to remove U-233 for transfer to the fuel gas, while the fuel gas would require reprocessing to remove fission products. If the core and blanket concepts can be successfully engineered, the development and implementation of the required processing plants will be one of the most challenging aspects of developing this concept and could be the critical step in commercializing the gaseous-core reactor.

Many of the technological difficulties associated with the mixed-flow gaseous-core reactor stem from the corrosive nature of the radioactive fuel gas and the high-temperature environment. Although simple critical experiments have been performed, the concept has not been demonstrated in a reactor and several key fuels and material problems would have to be resolved before licensing criteria could be developed and a reactor commercially deployed. The principal technological barrier would be to demonstrate that the proposed construction materials could withstand the fuel gas at elevated temperature and pressure.

Almost every area of plant design would require significant development and demonstration. Some of the design and fuel problems presented by the mixed-flow gaseous-core reactor include:

- Containing a potential breach of the fuel-gas primary-coolant loop and the molten-salt blanket system.
- Developing special tritium-handling features to control the release of tritium generated as a result of neutron reactions with the lithium in the blanket salt.

- Developing a primary heat-transport system that can be remotely operated, maintained, and inspected.
- Quantifying the as yet uncertain behavior of the fuel gas and its chemistry at elevated temperatures.

The status of mixed-flow gaseous-core technology would, therefore, require extensive research, development, and demonstration, with a decision to build a proof-of-principle plant not occurring before 1990 to 1995. Should its many technological and design problems be resolved, however, the mixed-flow gaseous-core reactor would offer the advantages of very low fuel inventory and very good uranium resource utilization. (It requires only about one-tenth the uranium used by the once-through light-water reactor and produces up to 84 times more energy from the same amount of uranium ore.) The system's proliferation resistance is also relatively high, as its low excess reactivity would serve as a sensitive indicator of reactor misoperation or diversion. A diversion of significant amounts of fissile material would probably shut down the reactor. However, a country with mixed-flow gaseous-core reactors would be less vulnerable to sanctions against its nuclear power industry, since no external source of fissile fuel would be needed for equilibrium operation.

In balance, the system's high facility costs (estimated to be 40 to 100 percent higher than for a similarly sized light-water reactor), coupled with the extensive list of technical problems which remain to be resolved, suggest a low probability for commercialization within the NASAP planning horizon of 2025.

5.2 DESIGN ASSESSMENT

5.2.1 Conceptual Plant Design

The reactor-containment building, fuel processing, and hot-cell areas of the mixed-flow gaseous-core reactor depart significantly from light-water reactor design. The reactor vessel, intermediate fuel piping, heat exchangers, and fuel-gas circulators would probably be located within a single primary containment structure to allow for more efficient containment of the fuel gas. (See Figure 4.) Most of the shielding would have to be placed outside the

Figure 4. MIXED-FLOW GASEOUS-CORE REACTOR CONCEPTUAL CONFIGURATION

suggested containment structure to allow for remote handling and maintenance. Also, it appears that the intermediate heat-exchanger would be too large to allow consideration of a monolithic reactor vessel similar to that of the high-temperature gas-cooled reactor. Thus, another type of reactor vessel would probably have to be developed.

Designing the reactor would be extremely difficult because of the corrosive nature of the fuel gas and the high-temperature environment. Material compatibility problems associated with the construction of the beryllium moderator system would be another source of design difficulty. A thin metallic coating of nickel to protect the beryllium moderator from the fuel gas coolant has been suggested, but does not appear to be feasible.

The primary heat-transport system would have to be designed for the severe corrosion and operating conditions imposed by the radioactive fuel gas. It would require the design of gas-tight seals throughout the system and the development of remote maintenance techniques to service the equipment. Also, the design of the system would have to deal with potential deposition of fuel constituents and fission products on the interior surfaces of pipes and equipment.

The containment would have to be designed to permit recovery and storage of the fuel gas after leaks or accidents. These systems have not been designed previously, and they are expected to be difficult to develop. Cleaning and decontaminating the structural and equipment surfaces after leakage of fuel gas might be impractical. The radioactive waste control, engineered safety, and fuel gas cleaning systems, among others, would also pose severe design problems, due to the characteristics and environment associated with the fuel gas.

The design and demonstration of on-line systems to remove fission products from the fuel gas and to reprocess and recover the U-233 generated in the molten-salt blanket would be very difficult.

5.2.2 Reactor Physics Considerations

Predicted reactor performance is uncertain, since the reactor-physics model has not been adequately verified. Selection and verification of cross sections and development of an adequate reactor-physics model appear feasible with current technology.

5.2.3 Fuel-Cycle Alternatives

The fuel cycle would require onsite reprocessing for both the gaseous fuel and molten-salt blanket and the resulting fission products would need to be disposed of. The required reprocessing techniques are currently beyond the state of the art and process chemistry development would have to be included as a part of a research and development program. Neither technique seems assured at this point, and failure to develop either reprocessing scheme would make the concept infeasible. On decommissioning, the fuel in the plant could either be disposed of or used to start up another gaseous-core reactor.

5.2.4 Mechanical and Thermal-Hydraulic Considerations

Transients in the gaseous-core reactor would probably be self-limiting because the expanding fuel-gas would automatically dissipate both general and local hot spots. However, localized gas-flow transients might cause unstable local conditions. It would be essential that the system avoid thermally-induced chemical instability of the fuel. Current data indicate that the core heat transport would probably be adequate. However, the constraints of reactor criticality and fuel-gas residence time have not currently been considered, and these could change the flow analysis and operating conditions significantly.

Flow geometry would have to provide adequate wall cooling and acceptable thermal stress in the cavity walls. The mixing characteristics for the fuel-gas flow are currently unknown, and these would greatly influence the final mechanical design. Heat transfer in the beryllium moderator cannot be determined at this time because the heat-transfer coefficients between the fuel-gas

mixture and moderator, and between the moderator and the molten-salt blanket, are unknown. However, the thermal stresses in the moderator shell would likely be a major design limitation.

The current design does not use the heat generated in the blanket for power production. However, further analysis of power generation from the blanket may require recirculation of the molten salt through heat exchangers for energy recovery.

5.2.5 Selection, Development, and Availability of Materials

Material compatibility with the corrosive fuel-gas would be a serious and probably limiting problem. The greatest difficulty would be the corrosive effect of the excess free fluorine, necessary to keep the plutonium in gaseous form, on the beryllium moderator and structural materials comprising the remainder of the primary loop and the fuel-gas cleanup system. The proposed method of protecting the beryllium moderator with a thin plated layer of nickel does not appear feasible. In addition, materials with suitably low corrosion rates do not appear to exist for the remainder of the primary circuit.

Little is known about the stability of plutonium fluorides that are produced in the circulating gaseous fuel. Deposition of a solid- or liquid-phase plutonium in the core would lead to power instabilities and probably the burnout of structural elements. Research on plutonium chemistry in a gaseous-core reactor environment would therefore be required.

The feasibility of fabricating the large beryllium moderator element is also questionable. The beryllium would be dissolved by the molten-salt blanket, and the proposed nickel plating would not appear to offer adequate protection. If fabrication and attachment difficulties could be overcome, graphite with special properties might be used to protect the moderator from the molten salt.

The molten-salt system would have to operate at the same pressure as the fuel circuit (about 700 psi) to prevent large stresses in the moderator element. This would create major problems in the design and operation of the reactor pressure vessel.

Conclusive data show that presently proposed materials are not sufficiently corrosion resistant, while physics considerations limit selection of materials with more favorable corrosion properties.

5.2.6 Engineering and Operability

The operations of the mixed-flow gaseous-core reactor are completely theoretical, and much work in design, engineering, and development would have to be accomplished to establish optimized procedures. All phases of operation would be greatly complicated by the toxic and radioactive nature of the fuel gas. Remote techniques would be required for all maintenance activities in the primary containment. This remote maintenance would require special designs and procedures and would greatly increase the complexity, cost, and schedule for maintenance operations.

Normal operations would probably be more complex than for light-water reactors because much more attention would have to be given to chemistry and pressure control. In addition, fuel-gas processing, blanket processing, and reactor operation would be carried on simultaneously.

Fuel materials and fission products would have to be handled on a daily basis. Personnel handling fuel-gas components outside the primary containment would probably need protective outer clothing and breathing apparatus. Fission-product handling and storage would also increase the level of complexity of the plant operation.

Reactor startup would be accomplished by preheating the primary system and injecting the fuel gas with increasing partial pressure until criticality is achieved. Startup power requirements would probably be large, due to heating requirements for the reactor and the molten-salt blanket. Normal shutdown of

the reactor could probably be accomplished by reducing the reactor primary pressure by venting the fuel gas into a dump tank. Since significant fuel gas would remain in the primary system, toxic gas leakage and radiation are likely to be problems and most engineered safety systems would have to be operational even during shutdown.

Overall, the gaseous-core reactor would probably be substantially more difficult to operate and maintain than light-water reactors.

5.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

A substantial amount of research, development, and demonstration would be required before construction and operation of a full-sized plant could be undertaken. Activity leading to the orderly development of a mixed-flow gaseous-core reactor plant would include:

- Basic physics research to demonstrate the feasibility of the concept.
- Demonstration that the proposed construction materials could withstand the fuel-gas at the elevated temperatures and pressures.
- Development of remote maintenance procedures and equipment.
- Development of large components.
- Addressing significant safety issues and providing for commercial licensing.

These programs would require the construction of various test facilities to demonstrate various aspects of the design and development process and to prove the soundness and acceptability of components and equipment. The construction and engineering program for the facilities would encompass the major construction projects leading to the engineering prototype, the demonstration plant, and the lead commercial plant. These facilities would be necessary to demonstrate plant operations, reactor/fuel systems licensability, component technology, and technical and economic feasibility.

5.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The mixed-flow gaseous-core reactor operating on denatured uranium fuel would offer several nonproliferation features unique among the nuclear power systems considered. The small fuel requirement for operation, coupled with barely self-sustaining internal fuel production, would keep the total fissile material inventory in the power system small (about 200-300 kg) and nearly constant for the life of the reactor. Fissile fuel would be required only for the initial fuel charge. Since only fertile material would be added after startup, no annual enrichment services would be needed. Periodic spent fuel discharges would be eliminated and the entire fuel inventory would be disposed of at the end of reactor life or used to start up another gaseous-core reactor. Because of the small fuel inventory and low excess reactivity of the reactor, diversion of significant quantities of fissile material would cause the reactor to shut down. This feature would provide a potentially sensitive indicator of reactor misuse or material diversion.

The small quantities of fuel in the system, the lack of annual shipments of sensitive materials, and the smaller number of supporting fuel cycle facilities would significantly limit the opportunities for subnational or covert national diversion as well as the amount of material available in the event of an overt national seizure of the reactor.

The most sensitive elements of the system would be the startup inventory of U-235 and the on-site blanket reprocessing facility. This facility would include a few places where limited quantities of materials could be extracted which could be chemically converted to weapons-usable materials. High levels of radioactivity would necessitate remote access, however, and thereby facilitate surveillance activities. Because in-plant fuel gas and blanket reprocessing is required, the safeguards system would have to be rather sophisticated, perhaps comparable to that required for a conventional reprocessing facility. On the other hand, the safeguards effort could be focused primarily on a single facility--the reactor installation itself.

The threat that some nation would use this system as a means of acquiring nuclear expertise and potential nuclear weapons capability should be less with this system than with more conventional systems. Development of sensitive technologies such as isotopic enrichment, PUREX reprocessing, or plutonium metal handling would not be required. However, since no external source of

fissile fuel would be needed for equilibrium operation, the system may reduce any leverage that might be exerted with regard to compliance with nonproliferation agreements.

The conceptual mixed-flow gaseous-core reactor system would be more proliferation-resistant than the liquid-metal fast-breeder system because the quantity of fissile materials would be limited and, except at startup and final fuel disposal at the end of reactor life, available only from within the reactor installation itself.

5.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

Several design features present potential licensing difficulties. The gaseous fuel would have no cladding and would be toxic, corrosive, and radioactive. Two of the barriers or inhibitors to release of radioactive fission products that exist in light-water reactors, the crystal structure of the fuel and the fuel cladding, would not be available. The gaseous-core reactor design addresses this problem by postulating a double containment building. However, regulatory authorities might require other barriers. All containment barriers would have to demonstrate their ability to contain the corrosive fuel gas as well as the molten-salt blanket.

Fission products produced by the fuel-gas and blanket processing would contribute to potential licensing difficulties. The safety of the extraction and storage procedures would have to be demonstrated, i.e., with a proven low possibility for release.

The design-basis accidents would be related to ruptures and leakage from the fuel-gas, molten-salt, and fission-product storage systems. Leaks from the fuel-gas system would be particularly difficult to prevent and contain. Thus, acceptable demonstration of containment systems would probably be difficult.

Control of reactivity by varying the fuel gas pressure is unique to this concept and will require substantial verification to support licensing. Protection against power excursions may be inherent in the physical and nuclear characteristics of the fuel gas. However, stability of the fuel gas to control transient behavior has yet to be demonstrated.

The possible presence of fuel gas would greatly increase the number and extent of precautions required to protect plant personnel. In-plant control of fuel-gas leaks would be a major part of the design to reduce radiation exposure.

The overall environmental impact of this concept could be significantly different from that of currently operating light-water reactors. Operational and fuel-cycle differences between this concept and a similarly sized light-water reactor would result in several different environmental impacts. On the one hand, the more favorable heat rate (8,900 Btu/kWh) would reduce the heat rejection to the environment and require less cooling water, and the concept's simple and efficient fuel cycle would require much less land for mining and uranium enrichment. On the other hand, possible environmental problems would include both operational and accidental releases and hazards in the use of fluorine; the hazards of the integral fuel processing included in the gaseous-core reactor fueling; and the possibility of tritium release.

5.6 RESOURCE UTILIZATION

The fuel resource utilization for this concept is purported to be very good because it would produce about 20 to 80 times more energy from the same amount of uranium ore than a standard light-water reactor once-through fuel cycle. Utilization would be very high because all the fissile and fertile material charged into the reactor would be burned by the reactor, while none would be lost or removed.

5.7 ECONOMICS

Assuming that the technical problems could be resolved, total facility costs are estimated to be 40 to 100 percent higher than for a similarly-sized light-water reactor. Due to remote maintenance and operation of this concept, the nonfuel operating and maintenance costs are estimated to be double those of light-water reactors. The estimated generating costs might approach those of the once-through light-water reactor with permanent fuel storage at U_3O_8 prices of \$160/lb.

5.8 COMMERCIAL CONSIDERATIONS

Utilities are expected to have serious concerns over the construction, operation, and maintenance of a mixed-flow gaseous-core reactor. One of the reactor's biggest shortcomings would be the unfamiliar and hazardous chemistry of the fuel gas. Before utilities would order the gaseous reactor, sufficient experience would need to be accumulated with both the fuel-gas and the molten-salt blanket systems to compensate for the technology's newness. Gaining sufficient experience to satisfy commercial criteria would be quite difficult.

The remote maintenance requirements would also cause uncertainty because the operations and their potential effect on downtime would not be well defined. Although overall capacity factor can be estimated, the requirements for remote maintenance and continuous operation would combine to yield uncertainty in the timing and duration of outages. The possibility of long outages during sensitive seasons would make utilities reluctant to purchase a mixed-flow gaseous-core reactor.

While all safety and licensing issues associated with the fission-product handling system would probably be resolved through research, development, and demonstration, the extra complexity and responsibility likely to be associated with this system could result in some reluctance to purchase it. The fuel-gas and fission-product handling systems would require a level of responsibility and care not currently required by utilities operating light-water reactors. The potential shipping and disposal problems posed by the highly concentrated fission products might also add to the buying resistance.

The reactor's total generating cost advantage would probably not be great enough to stimulate buying. By the time this reactor could be demonstrated, improvements and increased familiarity with light-water reactors and other more near-term technologies which may have been deployed would increase resistance to buying. The system's total generating cost estimates are also far more uncertain than for the light-water reactor. However, at some elevated uranium price, the mixed-flow gaseous-core reactor could have an economic advantage that might induce utilities to purchase it.

6. LINEAR-ACCELERATOR FUEL-REGENERATOR REACTOR

6.1 OVERVIEW

The accelerator-driven reactor concepts are characterized by the use of high-energy particle accelerators to drive fission reactor assemblies. While the basic principles of using an accelerator to produce neutrons and using neutrons to breed fissile material are both well-known, several major extrapolations beyond the current state of the art would be required to develop a commercial-sized reactor.

The linear-accelerator fuel-regenerator reactor is one of several proposed combinations of accelerators, targets, and fission blanket assemblies. (See Chapter 7 and Volume IX, Section 1.8.) The reactor would use a high-energy proton beam from a linear accelerator impinging on a liquid lead-bismuth target to produce an intense neutron source. The concept is designed to produce fuel by enriching the fissile content of light-water reactor fuel elements in the fission blanket. One linear-accelerator fuel-regenerator would be expected to enrich fuel for three light-water reactors.

While the concept is based on an extrapolation of accelerator and water reactor technology, its development would require the resolution of several key materials questions. A formidable problem would be the development of a fuel which could withstand more than twice the average exposure normally experienced in light-water reactor applications. A linear accelerator would also need to be developed which was not only two or three times the size of presently-designed units, but capable of operating almost continuously. Many problems relative to scaling up the accelerator size and properly interfacing it to the target are anticipated. A more detailed discussion of the research and development problems associated with the accelerator interface, the target blanket assembly, the target liquid-metal cycle, and the steam-power conversion cycle is presented in Volume IX, Section 1.8.3.2.

The principal advantage of the linear-accelerator fuel-regenerator would be its ability to produce reactor fuel directly from fertile material. This would significantly extend uranium resources. In addition, no reprocessing or refabrication of radioactive fuel would be required. Certain proliferation

vulnerabilities would exist, however, due to the high plutonium and low fission-product content of the fuel regenerator's initial enrichment cycle and to the high plutonium content of its spent fuel.

The major disadvantages of the linear-accelerator fuel-regenerator would include its high capital cost; its complex plant design, construction, and operation; its high power requirements; and the nonuniform nature of the fuel it would produce in addition, despite its reliance on light-water reactor-type fuels and systems, the licensability of the linear-accelerator fuel-regenerator would remain uncertain until criteria were developed for the use, in light-water reactors, of the irradiated fuel it would produce.

6.2 DESIGN ASSESSMENT

6.2.1 Conceptual Plant Design

The combination of a linear-accelerator and a reactor represents a very special arrangement problem for which there is no design precedent. (See Figure 5.) The arrangement of the transition section between the accelerator and containment building would be especially important, because failure of this section could have very serious results. Designing buildings to provide the structural integrity and support for the target and blanket assembly, its vessel, and the primary liquid-metal cooling system, while maintaining proper alignment with the linear accelerator, would be a special problem. In addition, these structures would be required to provide biological and thermal shielding. Component placement studies to determine space allocations, piping, and electrical needs would be required.

Particle accelerators now exist that provide the high-energy, 1,500 million electron volts (MeV) protons required and accelerators have achieved proton beam currents of 300 milliamperes (mA) at relatively low particle energies; but, to date, an accelerator to provide the combination of high particle energy and high continuous beam current has not been designed. Thus, a very significant scale-up of existing accelerator technology would be required.

Figure 5. LINEAR-ACCELERATOR FUEL-REGENERATOR TARGET ASSEMBLY

The linear-accelerator would also have to operate at a reasonably high duty factor. Since most current accelerator applications are experimental and require only intermittent operation for relatively short durations, attaining a high duty factor might be difficult. Coordinating the control of the linear-accelerator with the safety circuits and engineered safety features of the driven reactor would be very important. The special valves that isolate primary containment from the proton-beam tube under accident conditions would also be very important, because they would enable the accelerator to be seismically decoupled from the reactor and containment. Radio-frequency power supplies would have to be developed to meet the high power and availability requirements and would represent a very high (approximately 900 MW) electrical load on the facility turbine-generator or the utility grid. This high load would cause special problems in startup and shutdown, especially sudden shutdown. Ion sources for proton injection capable of meeting the high current requirements do not exist and would also require special development.

The design of the lead-bismuth jet spray for the target is unique. Exposure of structural materials to lead-bismuth in the fuel-regenerator environment might result in adverse chemical reactions. Pressure tubes nearest to the target area might be subjected to metallurgical degradation by lead-bismuth splashing; thus, a splash shield between blanket and target might be required. Uniformity of the neutron source over the length of the target is important to the concept and might be difficult to achieve. By contrast, very steep neutron flux and thermal power gradients in the blankets and individual fuel assemblies might be expected which would adversely affect fuel design. Use of zircaloy as a structural material for the pressure tubes would be critical, especially since tube failure and possible failure propagation would be safety concerns. The possibility of either dryout or flooding would be an additional safety concern in the two-phase water-stream coolant. (Helium or heavy-water coolants may prove to be satisfactory alternatives to two-phase water.)

The fuel regenerator concept would require that the fuel pellets and fuel-cladding materials sustain extended irradiation in the power reactor and the irradiation cycle. Keeping the blanket subcritical under all conditions would be a potential safety problem that might require a separate reactor shutdown system. The neutron reflector and shield would require special design work, due to unusual geometry and the presence of high energy particles. The proposed levels of fuel burnup would be substantially beyond the current light-water reactor fuel experience, and failure to achieve these fuel-performance goals would seriously degrade performance.

The high density of lead-bismuth would require special pumps, heat exchangers, and piping support systems. Currently, there is insufficient information available on induced radioactivity in the lead-bismuth from high-energy neutrons and protons and on additional radioactivity associated with the spallation process to allow adequate design of the system.

A nonstandard containment design (perhaps double containment) would be required, due to the need for linear-accelerator alignment and the need to maintain containment integrity at the accelerator-target interface. Complete containment of the lead-bismuth target system might also be desirable, depending on the levels of induced radioactivity.

The turbine-generator, condenser, regenerative feedwater heat exchangers, pumps, turbine bypass, startup boiler, and piping will be less difficult to develop. The major design problems for the steam cycle would be to produce and control the two-phase coolant feed and, to a lesser degree, the moisture separation requirements for turbine throttle steam.

The engineered safety features would present additional design problems, due to large amounts of decay heat, the potential for accidental criticality, and the possibility of proton-beam misfocusing.

6.2.2 Reactor Physics Considerations

Experimental investigations have been carried out to calculate neutron yield from the spallation process. Calculations have also been made to determine the fissile-fuel production and thermal-power density in a simple target-blanket model. Although these results do provide a tentative physics basis for the fuel-regenerator, extensive additional investigations would be necessary to demonstrate the feasibility of the concept.

6.2.3 Fuel-Cycle Alternatives

The fuel-regenerator fuel cycle would require low-enriched uranium fuel, but no reprocessing, and spent fuel could be permanently stored at the end of its useful life. This proposed fuel cycle would be feasible only if light-water reactor fuel performance could be substantially increased over present levels.

6.2.4 Mechanical and Thermal-Hydraulic Considerations

The cooling system for either the target or blanket assemblies has little design precedent. The design of the lead-bismuth target jet spray, collection system, and the flow-rate control system would have to meet the requirements set by the various physics and mechanical considerations. For the blanket, the problems would center on providing and controlling the two-phase cooling. (However, two-phase cooling may ultimately not be required, because either helium or heavy water might prove more feasible.) The entire target liquid-metal system external to the target-blanket (consisting of pumps, piping, and heat exchangers) would be an unconventional arrangement and would present many design difficulties, because the lead-bismuth has high density and is chemically active.

6.2.5 Selection, Development, and Availability of Materials

The fuel-regenerator would probably use an iron-base alloy (where exposure to lead-bismuth is involved), zircaloy-clad uranium-oxide fuel assemblies, zircaloy pressure tubes, a lead-bismuth target, a graphite reflector, and water-steam coolant. These materials are available in the needed quantities. One critical feasibility question is whether an iron-base alloy exists which has adequate corrosion-resistance in contact with lead-bismuth. The alternative of using a corrosion-resistant refractory metal would add a high degree of complexity, and feasibility has not been proven. Zircaloy would have to be qualified (under the American Society of Mechanical Engineers pressure vessel codes) as a structural material for the pressure tubes and demonstrated to last the full plant lifetime. If this demonstration proved impossible, a method for periodic replacement would have to be devised.

6.2.6 Engineering and Operability

Normal operations of the fuel-regenerator are expected to be more difficult than those of a light-water reactor. One reason for this would be control of the two-phase coolant mixture; another would be coordination of control between the accelerator and the target-blanket assembly, because of the increasing reactivity of the blanket during the irradiation cycle. Control would be especially critical during transients. The need for frequent refueling and fuel shuffling would also complicate operations. In-service inspection and maintenance requirements could be expected to be considerably more difficult than for a light-water reactor due to the pressure-tube-calandria type of construction.

Electrical power supplies for the linear-accelerator would involve very difficult startup and shutdown operations. During startup, bringing the current of the accelerator beam up to its full operating value would require that an electrical power supply be increased from zero to approximately 900 MW. The necessity of dumping this load during a sudden facility shutdown would be another very serious problem, as would be the necessity of maintaining some form of shutdown cooling.

Maintenance of primary system components would require special consideration, due to the high radioactivity levels associated with extended fuel burnup and activity in the lead-bismuth alloy. High radiation levels, coupled with the possible need for frequent refueling and fuel shuffling, make protection against radiation exposure more difficult than with light-water reactors.

In addition to the annual refueling of the fuel-generator's fuel assemblies, which would be comparable to the annual refueling of a light-water reactor, interim shutdowns might be required for fuel shuffling; or, alternatively, a complicated online method of remote fuel shuffling might be required.

6.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

A substantial amount of research, development, and demonstration would be required before construction and operation of a full-sized fuel-regenerator

plant could be undertaken. A substantial portion of this required work would be directed toward a number of major unresolved problems: the ability to scale up the linear-accelerator and demonstrate adequate reliability and availability, the fuel performance for extended burnup, and materials compatibility with the lead-bismuth alloy. Failure to resolve any one of these would jeopardize the fuel-regenerator program.

Activity leading to the orderly development of a plant design would have to include:

- Basic physics research for both the fuel-regenerator and light-water reactor.
- Experimental physics investigations of core lattice parameters, neutron source yield, and reactivity effects.
- Target-blanket thermal-hydraulic investigations.
- An accelerator-scaling and testing program.
- A materials investigation and qualification program.
- A fuel-performance investigation and qualification program.
- Development of special systems, such as a lead-bismuth circulating system and engineered safety features.
- A component development and testing program.
- A training program dealing with plant operations, maintenance, and testing.

Special experimental and test facilities would have to be designed and built to carry out the programs described above. The facilities construction and engineering program would include an engineering prototype, a demonstration plant, and a lead commercial plant. These facilities would be necessary to ensure technical and economic feasibility by demonstrating plant operations; reactor, accelerator, and fuel-systems licensability; and systems and component technology.

6.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The linear-accelerator fuel-regenerator would be a fissile material production facility supporting about three dispersed reactors. Although it could be substituted for reprocessing and plutonium recycle as a resource extender, and possibly for enrichment facilities as a producer of fresh fuel, it would entail significant proliferation vulnerabilities of its own. The fuel-regenerator could readily be misused for overt production of weapons material or the regenerated fuel could provide a target for diversion of chemically separable weapons material. Consequently, from a nonproliferation viewpoint, deployment of the system should be limited to deployment under appropriate international auspices.

If deployment of fuel-regenerator systems were limited in this way, it would have comparable vulnerabilities to closed fuel-cycle systems like the fast-breeder, in which reprocessing and refabrication facilities were deployed under similar arrangements. Fresh fuel produced in the system would contain plutonium contaminated with some fission products. However, it would not provide the isotopic barrier associated with low-enriched or denatured uranium fuel. The regeneration process would increase the plutonium content of spent fuel. Thus, both fresh and regenerated fuel would become potentially attractive targets for national and subnational diversion.

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The high support ratio of the fuel regenerator concept would permit fewer fuel producing reactors for a given generating capacity and thereby help to restrain the spread of sensitive facilities and technologies when compared to standard fast-breeder fuel cycles.

6.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

An assessment of the licensing and safety requirements for this concept has identified several potential problem areas. Although the design-basis accidents have not yet been defined, several potential accident conditions have been identified. These include: blanket meltdown; coolant-pipe ruptures; failure of calandria pressure-tubes, linear-accelerator containment-isolation valve failures, lead-bismuth jet nozzle flow disruption; loss of lead-bismuth flow; failure of the shutdown heat-removal system; and overpower transients

caused by accelerator proton-beam misfocusing. Requirements of the accident-mitigation systems would depend upon future analysis of the potential accident conditions.

Use of regenerated fuels in present light-water reactors, as well as in the fuel-regenerator itself, would be a significant potential licensing and safety issue due to the extended radiation exposure, the high fuel burnup, and the plutonium content.

The environmental impact associated with the facility would be approximately the same as for current reactors. Direct land use would be about the same as that of a 1,000-MW light-water reactor; heat rejection would be about the same as that of a 600-MW light-water reactor. The land use for uranium mining and milling and for spent-fuel disposal would be substantially reduced due to the greater uranium utilization and fuel burnup of the fuel-regenerator. Nevertheless, if the entire system, including fuel-regenerator and supported light-water reactors, were examined, the environmental impact might exceed that of light-water reactors alone. Land would be required for four rather than three reactors because the fuel-regenerator would be a net energy user. The overall thermal efficiency would be 25 percent, compared with 33 percent for light-water reactors alone, which implies greater heat rejection. Plant effluents of all types would be increased by the fuel-regenerator's contributions, without a corresponding increase in energy production.

6.6 RESOURCE UTILIZATION

The fuel cycle for a fuel-regenerator with three supported light-water reactors would extract approximately three times as much energy from mined uranium as does the standard light-water reactor once-through fuel cycle. This increase in resource utilization would result from converting substantial quantities of U-238 into fissile material, which would be burned to produce energy.

6.7 ECONOMICS

Plant capital cost comparisons cannot be made directly with a light-water reactor plant of equivalent electrical output, since the fuel-regenerator would be a net consumer of electrical power. Approximately half the estimated 900 MW required to operate the plant would be supplied by the turbine-generator, and the other half by outside power sources. The plant, including the accelerator, would cost approximately 60 to 120 percent more than a 1,000-MW light-water reactor.

Operating and maintenance costs are estimated to be approximately 25 percent higher than those for a 1,000-MW light-water reactor. Comparing the operation of a fuel-regenerator in conjunction with three standard 1,000-MW light-water reactors with light-water reactors only, the total generating costs for the joint operation would be at least 20 percent higher than those for light-water reactor operation only. This assumes uranium prices of \$160/lb of U_3O_8 .

6.8 COMMERCIAL CONSIDERATIONS

The fuel-regenerator does not appear to be commercially attractive. The unfamiliar technology and complex plant operation would lead to a resistance to purchase. The potential difficulty of licensing light-water reactors to use the regenerated fuel would only intensify this resistance. If licensing conditions were similar to the present situation, utilities would probably not consider the fuel-regenerator's fuel for operating light-water reactors, unless it were substantially cheaper than normal uranium fuels. Additional areas that could increase utility resistance are:

- Electrical power requirements of the fuel-regenerator, the difficulty in supplying this power during startup, and the effects that sudden shedding of this load could have on the electrical grid.
- Apprehension about using the fuel to greatly extended burnup values.
- Frequent fuel shuffling requirements between annual refuelings.
- The stringent and complex remote maintenance and inservice requirements.

For a totally unfamiliar plant type such as the fuel-regenerator to receive consideration over proven power-plant types, it would have to show a significant economic advantage. The total generating costs of operating a fuel-regenerator in conjunction with three 1,000-MW light-water reactors show distinct disadvantages when compared with the costs of three light-water reactors. This disadvantage decreases as the uranium price increases, but it is still substantial at uranium prices of \$160/lb of U_3O_8 . As uranium prices increase above this level, a point would be reached at which the costs of a fuel-regenerator plus three light-water reactors would begin to show an advantage over the costs of light-water reactors alone.

Another major deterrent to the commercial feasibility of this concept would be possible future developments in light-water reactor technology. For example, to make the fuel-regenerator technically feasible, a large amount of light-water reactor fuel development would be required. However, this same development effort could directly improve light-water reactor fuel performance, thus making the fuel-regenerator even less competitive.

7. TERNARY METAL-FUELED ELECTRONUCLEAR FUEL-PRODUCER REACTOR

7.1 OVERVIEW

The ternary metal-fueled electronuclear fuel-producer reactor was one of two accelerator-driven reactor concepts assessed as part of the NASAP study. (See Chapter 6 and Volume IX, Section 1.8.) The fuel-producer would use a high-energy proton beam from a linear-accelerator impinging on a liquid sodium target to produce a high-intensity neutron source. The sodium would serve as both a target and a coolant to transport heat produced in the target and blanket to an intermediate sodium coolant loop.

The fuel for the electronuclear fuel-producer would be composed of plutonium, thorium, and uranium. The proposed fuel cycle would use reprocessing and fabrication of the ternary-metal fuel to extract the bred U-233 and to produce fresh plutonium fuel for the fuel-producer. The bred U-233 would be fabricated into denatured light-water reactor fuel and would be sufficient to fuel approximately five light-water reactor plants. Light-water reactor spent fuel would be reprocessed to recover the U-233 and plutonium, and the plutonium would be used as part of the plutonium requirement for the fuel-producer. (See Figure 6.) Refueling would occur about every 90 days.

As with the linear-accelerator fuel-regenerator, the basic principles for the electronuclear fuel-producer (using an accelerator to produce neutrons and using neutrons to breed fissile material) are well-known. However, the design contains many unproven features and extensive work would be needed to prove basic feasibility. The use of sodium as a coolant is currently being examined as part of the liquid-metal fast-breeder reactor program and the technology for the fuel cycle has been demonstrated on a small scale. Substantial research and development would be required to extrapolate the accelerator to the necessary size; to design an adequate target window (a 90° deflection angle for the accelerator beam has been proposed and the deflection device would require considerable development); and to provide safe and reliable fuel and plant designs. Additional research and development requirements associated with the accelerator interface, the target blanket assembly, the fuel assembly, heat transport systems, and the steam-power conversion cycle are delineated in Volume IX, Section 1.8.3.3.

Figure 6. Fissile Material Flows - Ternary Metal-Fueled Electronuclear Fuel Producer and Supported Light Water Reactors (LWR)

While the development of the electronuclear fuel-producer would benefit to a significant extent from liquid-metal fast-breeder technology, the fuel-producer's development would be more complex, time-consuming, and costly. The concept's major advantage would be its ability to produce reactor fuel from fertile material, thus significantly extending uranium resources. This would be offset by such disadvantages as the requirement for full-scale reprocessing and refabrication of fissile material; high capital, operating, and total power costs; complex plant operations; sodium handling problems; and the need for frequent fuel shuffling. The proliferation risks presented by access to both full-scale reprocessing facilities and weapons-usable fissile material would have to be controlled through institutional measures.

The operation of an electronuclear fuel-regenerator might require special provisions to ensure an effective, integrated operation, since the facility would be both a net power producer (1,400 MW) and a producer, reprocessor, and fabricator of fissile fuels. These special requirements, coupled with a complex plant operation, high capital costs, and low proliferation resistance, would serve to deter commercialization beyond the NASAP planning horizon of 2025.

7.2 DESIGN ASSESSMENT

7.2.1 Conceptual Plant Design

Like the fuel-regenerator, the fuel-producer is a combination of linear-accelerator and reactor and would represent a very special arrangement problem, one for which there is no design precedent. (See Figure 7.) The design problems of the linear-accelerator fuel-regenerator arrangement and the necessary accelerator design work would also apply to the fuel-producer.

Very steep neutron flux and thermal power gradients in the blankets and individual fuel assemblies would be expected. These would cause serious fuel and structural design problems. Keeping the blanket subcritical under all conditions would be a potential safety problem and could require a separate reactor-shutdown system. The neutron reflector and shield would also require special designs.

Figure 7. TERNARY METAL-FUELED ELECTRONUCLEAR FUEL-PRODUCER

Technology developed for the liquid-metal fast-breeder program would be applicable to the primary and secondary heat-transport systems, using sodium or sodium-potassium as the coolant fluid. No significant technological barriers are foreseen in this area. Optimization studies concerning the use of sodium versus sodium-potassium are suggested, since expensive methods for system heating would be required if sodium alone were used.

A nonstandard containment design would result from interfacing the linear-accelerator with the target. The electronuclear fuel-producer requires a right angle deflection of the proton beam for top entry into the reactor. In addition, a permanent window must be used to isolate the vacuum of the accelerator section from the sodium target. Double containment might be necessary due to spallation products in the primary coolant and the accelerator-target interface problems.

While the types and quantities of radioactive wastes peculiar to this concept have not been determined, handling the wastes appears feasible based on research on liquid-metal fast-breeders.

Special design problems and requirements for engineered safety features might be expected due to the large amounts of decay heat, potential for accidental criticality, and the possibility of proton-beam misfocusing. Special shielding requirements would result from the high induced activity in the sodium-coolant and stray radiation from the linear-accelerator.

A conventional high-pressure turbine-generator operating on superheated steam with regenerative feedwater heating is assumed. Superheat steam generators for use with sodium would require additional development, but other steam-cycle equipment and the turbine-generator would probably be of the same type currently used in large fossil-fueled plants. Future availability of a turbine-generator rated at 1,400 MW is considered technically feasible using present technology.

7.2.2 Reactor Physics Considerations

The present physics model for the fuel-producer is preliminary and does not include sufficient detail to permit verification of the concept's feasibility.

A much more refined model, with provisions for parametric investigations, would be necessary to prove the basic feasibility, optimize the performance, and establish the safety of the design.

Extensive research would be required for the various cross sections involved, especially for the yield of neutrons from the accelerator proton beam by spallation. Anticipated problems include steep neutron flux and power gradients, an increase in the subcritical multiplication during the fuel-irradiation cycle, and energy deposition by protons in sensitive reactor components.

7.2.3 Fuel-Cycle Alternatives

The fuel-producer system, consisting of the fuel-producer reactor with five supported light-water reactors, would require no enriched uranium feed, but it would require plutonium from outside sources, such as light-water reactor spent fuel. This concept would require reprocessing and fuel fabrication for the fuel-producer and for the reactors from which it receives part of the plutonium feed material and to which it returns fissile uranium. (See Figure 6, page 80.) These processing activities would produce fission-product wastes for which disposal services would have to be provided. Therefore, the feasibility of the fuel-producer concept would depend on the development and deployment of the required fuel-cycle services.

7.2.4 Mechanical and Thermal-Hydraulic Considerations

Although the use of an existing fuel-assembly mechanical design taken directly from the Experimental Breeder Reactor-II¹ has been recommended, the mechanical design for the fuel-producer has not been addressed. Basic thermal-hydraulic parameters have been defined to only a limited extent. Critical items of concern that must be investigated during research, development, and demonstration

¹The Experimental Breeder Reactor-II (EBR-II) is an engineering test facility for breeder reactor components located at Idaho National Engineering Laboratory (INEL), at Arco, Idaho.

include the need for removing the heat generated in the thorium metal section at the end of the target, the intrinsically steep radial and axial power gradients, the increased thermal power production at the end of each refueling cycle due to the increase in blanket reactivity, and the need for emergency cooling. The mechanical design would also have to provide some means of controlling coolant-flow distributions.

7.2.5 Selection, Development, and Availability of Materials

A definition of plant material requirements is currently limited to those materials required for the electronuclear fuel-producer reactor alone; material for the balance of the facility would probably be commercially available. The only potential problem with material concerns the cladding alloy, which might also be used as the core structural material. A vanadium 20-percent titanium alloy has been suggested as the fuel cladding based on its low neutron energy spectrum degradation. Some additional investigation into the embrittlement of the alloy might be required to establish its expected lifetime and demonstrate compatibility with the sodium coolant. The selection of fuel materials, coolant-target material, and reactor-containment material all appear feasible, but these would have to be verified by additional investigations.

7.2.6 Engineering and Operability

Startup, shutdown, and normal requirements and procedures for operations would require extensive study. No actual precedent for operation of accelerator-driven reactors exists. Basic considerations in this area would include coordinating start-up of the accelerator, reactor, and turbine-generator; supplying the high electrical power requirement of the accelerator, which would be approximately 900 MW at full power; melting the sodium before plant startup; and safe shutdown of the facility under normal and emergency conditions.

Some guidance in sodium-related plant operations could be obtained from the development program of the liquid-metal fast-breeder reactor, since both reactors would have primary and secondary heat-transport systems using sodium as a heat-transfer material, similar steam and power conversion systems, and

presumably some similarity in engineered safeguards systems. Despite some differences, neutron and gamma-ray fluxes, radiation levels, fission products, and induced radioactivity would be similar. Spallation products would be a source of significant additional radioactivity in the fuel-producer. Complicated equipment, requiring remote operation and maintenance because of high radiation levels, might be anticipated for the in-service inspection of the fuel-producer and its primary heat-transport systems. The maintenance of primary system components would probably also be hampered by similar problems.

Special attention would need to be given to the fission products and radioactive thorium produced during onsite fuel reprocessing. Occupational radiation exposure limits would require special consideration, due to the high levels of induced radioactivity and the spallation products in the sodium coolant.

7.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

A substantial amount of research, development, and demonstration would be required before construction and operation of a full-size fuel-producer plant could be undertaken. The ability to scale up the linear accelerator, demonstrate adequate reliability and availability, and develop the liquid metal target technology would be major concerns. Failure to resolve these basic items would jeopardize the fuel-producer program. The activity leading to the orderly development of a plant design would have to include basic physics research; an experimental physics program to investigate core lattice parameters, neutron source yield, and reactivity effects; target-blanket thermal-hydraulic investigations; an accelerator scaling-up and testing program; and a materials investigation and qualification program. A fuel-performance investigation and qualification program; development of special systems; a component development and testing program; and a plant operations, maintenance, testing, and training program would also be required.

Special experimental and test facilities would have to be designed and built to carry out this program. The program of construction and engineering of facilities would probably include an engineering prototype, a demonstration plant, and a lead commercial plant. Technical and economic feasibility would depend on a demonstration of plant operations; licensability of reactor, accelerator, and fuel systems; and systems and component technology.

7.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The electronuclear fuel-reproducer would essentially serve as a fuel factory supporting approximately five dispersed reactors. The total system requires reprocessing facilities (for the blanket fuel of the fuel-producer as well as for the spent fuel of the supported reactors) and fuel fabrication facilities. Since the product of the fuel-producer would be weapons-usable material, and since the reprocessing and refabrication facilities would be difficult to safeguard effectively, these elements of the total system should only be deployed under appropriate international auspices.

When deployed under appropriate international auspices, the proliferation resistance characteristics of the fuel-producer energy system would depend on the nature of the dispersed reactors. The denatured uranium-thorium fueled reactors would exhibit greater proliferation resistance, as compared with plutonium recycle and fast-breeder cycles, primarily because of the isotopic and radiation barrier embodied in the fresh fuel and the lower plutonium content in the spent fuel.

A potential advantage of the conceptual electronuclear fuel-producer compared with liquid-metal fast-breeder reactor systems is the fact that it could support a larger number of dispersed reactors; hence, fewer fuel production centers would be needed to serve a given level of nuclear generating capacity. This could help to restrain the spread of sensitive facilities and technologies.

7.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

A major safety consideration in the fuel-producer is the potential for accidental criticality in the subcritical blanket regions as well as in the reprocessing and fabrication facilities. Although the design-basis accidents have not yet been identified, several potential accident conditions have been tentatively identified, including blanket meltdown, coolant pipe ruptures, blockage or loss of coolant flow, shutdown heat-removal system failure, and reactor overpower transients resulting from the misfocusing of an accelerator proton beam. Extensive study would be required to identify and analyze the design-basis accident, to design accident-mitigation systems, and to ensure

compliance with safety design criteria. Significant precedent in licensing and safety issues could be expected from the liquid-metal fast-breeder program. The licensing and safety aspects of the plant's special reprocessing, fabrication, and radioactive waste disposal facilities would also have to be considered.

Land use, water use, heat rejection, fuel-cycle impacts, and decommissioning would have environmental impacts significantly greater than those of the currently operating light-water reactor because additional fuel service facilities would be required. The thermal efficiency of the fuel-producer system of reactors is expected to be below the efficiency of light-water reactors alone. Although it is expected that plant effluents could be held within the limits presently imposed on light-water reactor plants, the radiation sources to be considered in the fuel-producer will make meeting these requirements more difficult. The fuel producer would use much less uranium than the light-water reactor, and the environmental impact from the mining and milling operations would be greatly reduced.

7.6 RESOURCE UTILIZATION

The fuel-producer requires significantly less total uranium than a standard light-water reactor fuel cycle with permanent storage of spent fuel. When combined with light-water reactors using denatured U-233 fuel, the fuel-producer reactor could produce about twice as much power from the same amount of uranium as the standard light-water reactor once-through fuel cycle, because significant quantities of thorium would be converted to U-233, which could be used to produce energy.

7.7 ECONOMICS

As with other fuel-producing reactors, a direct capital cost comparison with a light-water reactor of equivalent electrical output cannot be made. This is because, in addition to electricity, fuel material would be produced and there would thus be no consistent basis for comparison. The capital cost of the electronuclear fuel-producer is estimated to be 140 to 240 percent greater than that of a 1,000-MW light-water reactor. The operating and maintenance costs would also be expected to be about double those for a low-enriched

uranium light-water reactor. Even with uranium prices greater than \$160/lb, the 30-year levelized total generating cost for a system consisting of the fuel-producer and five denatured-fueled light-water reactors would be higher than the cost for the light-water reactor fuel cycle with permanent storage of spent fuel.

7.8 COMMERCIAL CONSIDERATIONS

Utilities would be expected to have many serious concerns about construction, operation, and maintenance of a fuel-producer facility that would be reflected in a reluctance to make commitments for such a plant. Some of the utilities' more serious concerns would include: interfacing the electrical power requirements of the linear-accelerator with the electrical grid, the reduced net thermal efficiency, complex remote maintenance and in-service requirements, and the requirements for fuel reprocessing and fabrication.

For a totally unfamiliar plant type such as the fuel-producer to receive consideration over proven and demonstrated power-plant types, a very significant economic advantage would have to be shown. The total generating costs of the fuel-producer operating in conjunction with five 1,000-MW light-water reactors show distinct disadvantages when compared with light-water reactors alone. At U_3O_8 prices of somewhat higher than \$160/lb, this disadvantage would disappear.

8. TOKAMAK FUSION-FISSION HYBRID REACTOR

8.1 OVERVIEW

The fusion-fission hybrid reactor uses an intense neutron source from a fusion device to drive a subcritical blanket of fertile and fissile fuel assemblies. The reactor can be designed solely to produce fuel, solely to produce power, or to produce a combination of fuel and power. A number of designs have been proposed, utilizing a variety of fuel cycles.

The particular concept for the fusion-fission hybrid reactor which was selected for the NASAP assessment (see Volume IX, Section 1.11) uses a tokamak deuterium-tritium fusion reactor as a neutron source. The reactor would operate in conjunction with five light-water reactors, fueled with the excess plutonium produced by the hybrid. The concept would require fuel fabrication and reprocessing for the hybrid reactor blanket and the light-water reactor fuel. The viability of the concept depends on a demonstration of sustained fusion reactions.

The concept assessed is considered very tentative and, even in the class of tokamak-driven fusion-fission hybrids, it is uncertain whether it represents an optimum design for either fissile fuel or power production. Detailed conceptual design and optimization studies could possibly lead to substantial revisions in a future assessment of the design and expected performance of the tokamak hybrid reactor. In addition, many of the questions raised about the reactor's design, construction, and operation are the subject of ongoing fusion technology development programs; the results of these programs, as well as the liquid-metal fast-breeder and gas-cooled reactor programs, should have a significant impact on hybrid development needs.

The assessment of the tokamak fusion-fission hybrid reactor design indicates a variety of design, operability, materials, safety, and licensing problems which would need to be addressed and resolved before the reactor could be commercially deployed. The reactor design would face the difficulties encountered in pure fusion devices and would be further complicated by the requirements for a blanket containing fertile, fissile, and fusile material. (The development of a fusion driver with favorable ignition characteristics, burn

time duration, and duty factor would be essential.) A successful research, development, and demonstration program would have to include basic plasma physics research, thermal-hydraulics studies, the development of remote fuel handling facilities, and materials development. Test facilities would need to be built to demonstrate the feasibility of the design and to prove the operability and acceptability of components and equipment.

The proliferation resistance characteristics of the hybrid reactor are similar to those of the other fuel-producers assessed by NASAP. Operation at locations where stringent safeguards could be applied would be needed to ensure that the reactor was operated in the nuclear fuel production mode. The proliferation risks with the hybrid would be similar to or less than those associated with conventional liquid-metal fast-breeder reactor systems, since fewer hybrids would be needed to support the same electrical generating capacity.

The primary advantage of the hybrid reactor would be its ability to produce significant amounts of electrical power as well as substantial quantities of fissile fuel, which would be used to fuel other reactors. If it can be demonstrated that this can be done at a competitive cost, the concept would represent an alternate path in the development of pure fusion technology. The disadvantages of the concept, as represented by the design assessed by NASAP, include the extensive research which would be required to develop the fusion driver; the uncertainties surrounding the fusion-fission technology mix; and the reactor's high capital, operating, and maintenance costs.

8.2 DESIGN ASSESSMENT

8.2.1 Conceptual Plant Design

While several design concepts for the hybrid system have been suggested, all are in the very earliest stage of development. The plant design as discussed in this assessment is based on preliminary feasibility studies performed for NASAP. Despite the inadequacies of the feasibility studies, ongoing analysis of the hybrid reactor concept has identified major uncertainties and potential problems which would have to be resolved before a viable tokamak hybrid facility could be built and operated.

The plant design (see Figure 8) could be based on the experience gained from pure fusion facilities and modified to allow for the additional complication of handling the fissile fuel produced in the blanket. Turbine size, thermal storage systems, steam generators, and tritium and fissile fuel extraction systems would be defined as the reactor parameters become more certain from experience gained in tokamak experiments.

The reactor design would have to accommodate the requirements of both the pure fusion device and the blanket containing fertile, fissile, and fusile materials. Engineered safety features would be required to prevent inadvertent criticality. The technical problems of replacing the first (innermost) wall, fueling the blanket, and performing remote maintenance would have to be resolved. The pulsed operation of the reactor would impose special problems on the design of the primary heat system. The problems associated with tritium and fission-product inventories would also have to be resolved. The handling of liquid lithium, if it is used as the tritium-producing material, would also present special problems. Special safety systems might need to be designed to prevent loss of coolant pressure, fuel meltdowns, release of tritium, damage from a plasma dump, and damage from non-nuclear hazardous materials.

8.2.2 Reactor Physics Considerations

Accurate plasma-physics, neutronic, and magnetic calculations would be necessary for defining the optimum plasma, magnetic field, and blanket parameters for the reactor. The plasma physics model appears consistent with current optimistic models. The reactor physics model for analysis of the blanket will require extensive research and development for verification. The neutronic model used to analyze the proposed blanket region is considered inadequate for the highly anisotropic high-energy neutron flux associated with the blanket design.

8.2.3 Fuel-Cycle Alternatives

The assessed concept would use a hybrid reactor operating in conjunction with five light-water reactors fueled with the excess plutonium produced by the hybrid. This concept would require fuel fabrication and reprocessing for the hybrid reactor blanket and the light-water reactor fuel and waste disposal for

Figure 8. TOKAMAK FUSION-FISSION HYBRID REACTOR CROSS SECTION

the reprocessing wastes. Natural uranium, deuterium, and lithium feed would be required for fuel. Thus, the feasibility of this fuel-cycle concept would depend on the parallel development and deployment of the associated fuel-cycle services.

8.2.4 Mechanical and Thermal-Hydraulic Considerations

The mechanical design of the blanket modules and the first wall represents a major design problem. The first wall would have to be designed to maintain the internal vacuum while exposed to high-intensity radiation and high temperatures. The blanket modules would also be exposed to high-intensity radiation and high temperatures and would have to be removable so that the product fuel could be extracted from the reactor. The assessed design has not adequately considered all the requirements and, thus, may be expected to change significantly if it is further developed.

Thermal-hydraulic analysis and the mechanical design are strongly interdependent. Closely coupled methods of thermal-hydraulic and structural analysis would have to be developed for the hybrid reactor in order to adequately analyze its complex geometries and pulsed operation. Preliminary analysis of the response of proposed fuel forms to startup transients or pulsed power operation has been performed using methods developed for the safety programs of the light-water and liquid-metal fast-breeder reactors. Ultimately, experimental verification would be needed.

8.2.5 Selection, Development, and Availability of Materials

The material comprising the first wall would be exposed to elevated temperatures and intense irradiation. The austenitic stainless steels are currently preferred, but the system would have to be designed so that the first wall could be periodically replaced. Materials such as niobium would offer many advantages, but they present fabrication and operational limitations that might negate their usefulness. Thus, there are materials problems associated with the hybrid reactor that are serious enough to influence operating capabilities and economics.

8.2.6 Engineering and Operability

Startup, shutdown, and normal operating requirements and procedures have yet to be established. No precedent for operating fusion-fission hybrids exists, and experience with fusion devices is limited. Many problems with basic reactor operations and power-generating equipment would be anticipated, including coordination of the pulsed operation of the reactor with the power-generating cycle; satisfying the large amount of electrical power required for plant startup, shutdown, and heat removal; and coordination of all the auxiliary systems. Reactor maintenance requirements would be very stringent, and extensive development of systems, equipment, and procedures which could be remotely controlled would be required. Provisions would have to be made for routine replacement of the first wall around the fusion driver.

8.3 RESEARCH, DEVELOPMENT, AND DEMONSTRATION REQUIREMENTS

Substantial research, development, and demonstration would be required before construction and operation of a full-sized plant could begin. The current fusion energy program will address the most important fusion-related research, development, and demonstration needs of the tokamak hybrid reactor. Operation of the fusion driver will depend upon feasibility demonstrations, operation of engineering test facilities, and ultimately, the operation of an engineering prototype reactor planned for the fusion energy program. (For additional information on the Department of Energy's fusion energy program, see publication DOE/ER-0018.)

However, in addition to the fusion program, the activities leading to the orderly development of this concept would include:

- • Basic physics research to demonstrate the feasibility of the concept.
- Basic research on thermal hydraulics.
- Developing remote fuel-handling facilities.
- Developing the required components.

- Addressing safety issues and commercial licensing criteria.
- Performing studies on fuel and cladding.

These programs would require the construction of test facilities to demonstrate various design and development aspects and to prove the soundness and acceptability of components and equipment. The tokamak hybrid reactor construction and engineering program would encompass an engineering prototype, a demonstration plant, and a lead commercial plant.

8.4 PROLIFERATION RESISTANCE CHARACTERISTICS

The tokamak hybrid reactor would be a net producer of fissile material. It would operate in a system with five dispersed light-water reactors. Since the total system would include reprocessing and fabrication facilities for both the hybrid blanket fuel and the spent fuel from the dispersed reactors, the system would require effective safeguards and the hybrid installation itself would be vulnerable to misuse aimed at the production of weapons-usable material. Consequently, the hybrid reactor and its supporting fuel cycle facilities should only be deployed under appropriate international auspices.

When so deployed, the proliferation resistance of hybrid-based nuclear energy systems would be essentially determined by the nature of the dispersed reactors. The assessed hybrid concept was proposed to support five light-water reactors using the conventional closed fuel cycle and plutonium fuel. Other alternative fuel cycles may be possible to achieve better system proliferation resistance. The proliferation resistance of these dispersed plutonium-fueled reactors should be quite similar to other recycle systems which use dispersed plutonium-fueled reactors; such as plutonium recycle in light-water reactors and the fast-breeder fuel cycle.

The high support ratio of the hybrid concept would permit fewer fuel producing reactors for a given generating capacity and thereby potentially help to restrain the spread of sensitive facilities and technologies when compared to standard fast-breeder fuel cycles.

8.5 SAFETY, ENVIRONMENTAL, AND LICENSING CONSIDERATIONS

Although specific design-basis accidents have not yet been defined for the hybrid reactor, a number of potential accidents have been identified. These include tritium release, a plasma energy dump, inadvertent criticality, fission-product release, electromagnetic-system excursions, vacuum and cryogenic system breakdowns, fuel-pin failures, loss of coolant accidents caused by hazardous materials such as hydrogen and lithium, and missile-generated accidents.

Certain accident conditions, particularly the potential for hydrogen explosion and those related to electromagnetic safety, have been addressed only in a preliminary way. Much more research, development, and demonstration would be required before the full impact of all potential accident conditions on personnel and equipment could be defined and adequate engineered safety systems developed to mitigate their possible effects.

Biological shielding requirements would differ greatly from that of a light-water reactor because of differences in radiation sources and geometries. The combined effects of large amounts of tritium and neutron-activated components and the presence of fission products and actinides in the blanket would require the development of adequate shielding and containment systems as well as remote handling and automation capability.

The tokamak hybrid reactor is expected to operate at high temperatures and high thermal efficiency. Therefore, heat rejection and water use should be favorable compared to other reactor systems. The tokamak hybrid reactor will require reprocessing and fabrication facilities for both the hybrid reactor fuel and the light-water reactor fuel. The environmental impact of these facilities would be the same as for similar facilities for other fuel cycles. The environmental impact of uranium mining and milling should be greatly reduced from those of the light-water reactor with low enriched uranium fuel, and enrichment services would not be required for the hybrid. Use of uranium enrichment tails or reprocessed uranium from other fuel cycles could further reduce the mining and milling impacts.

The licensing issues for the tokamak hybrid reactor will be those which are generic to pure fusion reactor plants as well as those related to the use of fertile and fissile material in the blanket. Fuel produced by the hybrid reactor will have to be licensed for use in dispersed light-water reactors. Criteria for operating the hybrid with large inventories of tritium and lithium and criteria for the magnetic and cryogenic systems must also be established.

8.6 RESOURCE UTILIZATION

The proposed fuel cycle could substantially increase the amount of energy extracted from uranium. When combined with light-water reactors fueled by plutonium, the tokamak hybrid reactor would be capable of producing about four times as much power from the same amount of uranium as the standard light-water reactor once-through fuel cycle due to the significant amounts of U-238 that would be converted to plutonium in the hybrid.

8.7 ECONOMICS

As with other fuel-producing reactors, capital cost comparisons cannot be made directly with a light-water reactor of equivalent electrical output because fuel materials, as well as electricity, are produced. The adjusted capital cost estimate for the hybrid reactor is approximately 200 to 400 percent more than the cost of a 1,000-MW light-water reactor. The operating and maintenance costs are estimated to be approximately 50 to 100 percent higher than those for the light-water reactor.

Estimated fuel costs for the hybrid reactor operating in conjunction with the five light-water reactors for which it supplies plutonium approximate the current fuel costs for a 1,000-MW light-water reactor with permanent spent-fuel storage. However, the higher capital cost of the hybrid reactor and five light-water reactors would require uranium prices above \$160/lb. before the system's total power-generation costs would be competitive with light-water reactor costs.

8.8 COMMERCIAL CONSIDERATIONS

The hybrid reactor design assessed by NASAP does not appear to be attractive commercially. There are many serious concerns about the construction, operation, and maintenance of a hybrid reactor system, and utilities might be reluctant to make commitments for such a plant. These concerns would include the high capital-investment requirements; use of a completely new power plant technology; the necessity for pulsed operation, which has no precedent; remote maintenance and in-service inspection requirements; and special fuel-reprocessing and fabrication requirements. Although significant precedent in safety and licensing can be expected from developmental work on both the liquid-metal fast-breeder and high-temperature gas-cooled reactors, development of the tokamak hybrid reactor would present some completely new safety and licensing considerations.

The total generating costs for a tokamak hybrid reactor operating in combination with five supported light-water reactors do not show any economic advantage over light-water reactors operating on a once-through fuel cycle until the U_3O_8 price increases significantly.

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