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Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Volume I: Program Summary

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Assistant Secretary for Nuclear Energy
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DISCLAIMER

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Many organizations and individuals contributed to the NASAP study. While responsibility for program execution was assigned to the Division of Nuclear Alternative Systems Assessment within the Office of Nuclear Reactor Programs, Office of the Assistant Secretary for Nuclear Energy of the Department of Energy, other organizations within the Department of Energy contributed analyses and technical guidance to the project. These were the Offices of the Assistant Secretaries for Energy Technology, Resource Applications, Defense Programs, Environment, International Affairs, and the Office of Energy Research. The Department of State, the Arms Control and Disarmament Agency, and the Nuclear Regulatory Commission also contributed to shaping the analytic framework and reviewing the NASAP results. The over 50 interrelated studies prepared for NASAP were performed by 7 national laboratories, 13 independent research organizations, 10 companies from the nuclear industry, and 5 universities. The work of the International Nuclear Fuel Cycle Evaluation (INFCE) was also drawn upon.

Specific guidance to the program through periodic reviews was provided by a panel from industry, academia, and public interest groups convened by Professor Henry Rowen of Stanford University. Members of this panel included: Professor Rowen; Albert Carnesale of Harvard University; Thomas Cochran of Natural Resources Defense Council; Gordon Corey* of Commonwealth Edison; W. Kenneth Davis* of Bechtel Corporation; Lincoln Gordon of Resources for the Future; Frederick Hoffman of RAND Corporation; John Kearney* of Edison Electric Institute; Myron Kratzer of International Energy Associates, Ltd.; Joseph Nye of Harvard University (formerly of the Department of State); George Rathjens of Massachusetts Institute of Technology; Chauncey Starr* of Electric Power Research Institute; Jessica Tuchman-Mathews of The Washington Post (formerly of the National Security Council); and Albert Wohlstetter of University of Chicago. Table 1 is a list of contributing organizations.

However, while many individuals and organizations contributed to the preparation of this report, final responsibility for its content is solely that of the U.S. Department of Energy. The report should not be construed as representing a consensus of its contributors' opinions.

Following the preparation of the draft report, a public participation program was initiated. Members of the public were invited to meet with DOE officials and to submit their comments on the draft report. The Department of Energy has reviewed these comments, revised the report in a number of instances, and prepared an appendix to the Executive Summary that summarizes the comments and provides DOE's responses to them.

*These individuals also provided written comments on the draft report during the public comment period.

TABLE 1. ORGANIZATIONS PREPARING STUDIES FOR NASAP

PROLIFERATION RESISTANCE	RESOURCES AND FUEL-CYCLE FACILITIES	COMMERCIAL POTENTIAL	ECONOMICS AND SYSTEMS ANALYSIS	SAFETY AND ENVIRONMENTAL CONSIDERATIONS FOR LICENSING	INTERNATIONAL PERSPECTIVES	ADVANCED CONCEPTS	TECHNICAL DATA FOR REACTORS AND FUEL CYCLES
• Battelle Pacific Northwest Laboratory	• Hanford Engineering Development Laboratory	• Decision Focus, Inc.	• Burns and Roe, Inc.	• Argonne National Laboratory	• Atlantic Council of the United States	• Burns and Roe Industrial Services Corporation	• Argonne National Laboratory
• Brookhaven National Laboratory	• S. M. Stoller Corporation	• George Washington University	• Hanford Engineering Development Laboratory	• Babcock & Wilcox	• Booz-Allen and Hamilton, Inc.	• Oak Ridge National Laboratory	• Babcock & Wilcox
• Hudson Institute		• Arthur D. Little, Inc.		• Battelle Pacific Northwest Laboratory	• Brookings Institution		• Bettis Atomic Power Laboratory
• Lawrence Livermore Laboratory		• S. M. Stoller Corporation		• General Electric Co.	• Georgetown University		• Brookhaven National Laboratory
• Massachusetts Institute of Technology		• Westinghouse Electric Corporation		• NUS Corporation	• Harvard University		• Burns and Roe Industrial Services Corporation
• Pan Heuristics				• Oak Ridge National Laboratory	• Hudson Institute		• Combustion Engineering, Inc.
• Participants in Alternative Fuel Cycle Evaluation Program					• International Energy Associates Ltd.		• EXXON Nuclear Corp.
• RAND Corporation					• Institute for Energy Analysis-Oak Ridge Associated Universities		• General Atomic Corp.
• Science Applications, Inc.					• Nuclear Assurance Corporation		• General Electric Co.
• System Planning Corporation					• Pan Heuristics		• Hanford Engineering Development Laboratory
					• RAND Corporation		• Knolls Atomic Power Laboratory
							• Los Alamos Scientific Laboratory
							• Massachusetts Institute of Technology
							• Oak Ridge National Laboratory
							• Participants in Alternative Fuel Cycle Evaluation Program
							• Pennsylvania State University
							• Pickard, Lowe, Garrick and Associates
							• Southern Science Applications, Inc.
							• University of Washington
							• Westinghouse Electric Co.

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ACRONYMS

AGNS	Allied General Nuclear Services
EIA	Energy Information Administration
EURATOM	European Atomic Energy Community
IAEA	International Atomic Energy Agency
INFCE	International Nuclear Fuel Cycle Evaluation
LEAP	Long-Term Energy Analysis Program
NASAP	Nonproliferation Alternative Systems Assessment Program
NEA	Nuclear Energy Agency
NURE	National Uranium Resources Evaluation
OECD	Organization for Economic Cooperation and Development
PIES	Project Independence Evaluation Systems
WOCA	World outside centrally planned-economy areas

1. INTRODUCTION

This report summarizes the Nonproliferation Alternative Systems Assessment Program (NASAP): its background, its studies, and its results. This introductory chapter traces the growth of the issue of nuclear weapons proliferation and the organization and objectives of NASAP. Chapter 2 summarizes the program's assessments, findings, and recommendations. Each of Volumes II-VII reports on an individual assessment (Volume II: Proliferation Resistance; Volume III: Resources and Fuel Cycle Facilities; Volume IV: Commercial Potential; Volume V: Economics and Systems Analysis; Volume VI: Safety and Environmental Considerations for Licensing; Volume VII: International Perspectives). Volume VIII (Advanced Concepts) presents a combined assessment of several less fully developed concepts, and Volume IX (Reactor and Fuel Cycle Descriptions) provides detailed descriptions of the reactor and fuel-cycle systems studied by NASAP.

1.1 THE PROLIFERATION PROBLEM

The international community has developed a regime designed to provide substantial protection against the proliferation of nuclear-weapons (or nuclear-explosive) capabilities. Although currently deployed once-through nuclear power systems (so called because their spent fuel is stored rather than reprocessed for reuse) do not readily lend themselves to proliferation, they may facilitate the acquisition of the materials, facilities, and expertise necessary to develop nuclear weapons. In the future, more widespread or advanced nuclear power systems may more readily lend themselves to proliferation. As these systems evolve, their abuse, whether overt or covert, may provide a more attractive route to nuclear weapons capabilities than other routes, or it may enhance them significantly. The decision to obtain nuclear weapons, while affected by technological considerations, is basically a political one, whether made at a national or subnational level. It is important, therefore, to ensure that nuclear power systems, as they evolve, do not make this decision an easy one.

1.1.1 Is There a Problem?

The relevance of civilian nuclear power programs to proliferation centers on the access that they may provide to weapons-usable materials, facilities, or expertise, and on the significant influence that access may have both on the decisions of nations or subnational groups to seek nuclear weapons and on their ability to implement such decisions. Despite this common focus, there is a diversity of opinion about the likelihood of proliferation through the abuse of civilian nuclear power programs and about the relative importance of such programs to the proliferation problem. All nuclear weapons programs to date have developed from nuclear materials and facilities not subject to international safeguards. Even if other routes were more efficient or quicker, easier, and cheaper than abuse of the fuel cycle, it does not follow that no nation would abuse the fuel cycle. One premise of this assessment is that, even though there are several routes to a nuclear weapons capability, uncertainties about the perceptions of other nations, the differences in their situations, and the seriousness of proliferation by any route are so great that reducing the risk of proliferation by all routes, including civilian nuclear power programs, is essential to the overall management of the problem.

Another premise is that abuse of the fuel cycle cannot be regarded as a trivial part of the problem; in fact, abuse of the fuel cycle may be one of several attractive routes to a potential proliferator. Pakistan is a case in point. Zulfikar Ali Bhutto, the recently deposed leader of Pakistan, is reported to have stated that a safeguarded reprocessing plant was to be his means of acquiring a nuclear weapons capability (The Washington Post, December 8, 1978, p. A1). More recent events in Pakistan, including a reported effort to construct a clandestine enrichment plant, apparently reflect a national determination to acquire such a capability and thereby enhance the credibility of Bhutto's statement (The Washington Post, April 9, 1979, p. A1). Clearly, the idea of abusing a nuclear power system cannot be casually dismissed and has long been recognized as a possibility. The result is the current international regime of agreements, treaties, guidelines, and the international safeguards system.

1.1.2 What is the Problem?

The problem of proliferation is the danger posed by the movement toward or acquisition of a nuclear weapons capability by a nation or subnational group presently without it. This danger would be aggravated by the similarity of the nuclear materials and facilities involved in similar processes of developing either nuclear power or nuclear weapons capabilities. In turn, these similarities can make the real purpose of a nuclear development ambiguous throughout much of the process. The decision to acquire a nuclear weapons capability may be faced at any time in the course of this development and is influenced by three primary considerations. These are the supply of materials, facilities, and expertise; the demand for weapons; and the would-be proliferator's perceptions of the political and military risks entailed, that is, the risk of detection and response by one or more nations, or by the international community as a whole.

In facing the complex decision to move toward or to acquire nuclear weapons, a nation or a subnational group is likely to choose a course of action that ensures the greatest chance of success at the least risk of detection and response. Where there is a choice, it is between an independent military capability and an abuse of civilian facilities, which include nuclear-power, research and development, and critical facilities. As the development of a nuclear power program overlaps the development of a nuclear weapons program and is recognized as legitimate, so a decision to acquire a nuclear weapons capability can be implemented with reduced political and military risks. If all actions are legitimate, the risks are minimized because all actions are justifiable in terms of their nonmilitary purposes.

For this reason, proliferation resistance focuses upon the degree to which overlap between military and civilian nuclear power programs may be prevented or reduced. Where the two programs do not overlap, the distance between a civilian nuclear power program and the possession of nuclear weapons would be appropriately measured by the additional resources and time involved after a nation makes a commitment which violates agreements or conventions of international behavior. The nature of those resources and the time necessary to marshal them productively would help determine the likelihood of exposure to risk that a nation runs in moving toward or acquiring a nuclear weapons capability from a starting point in a civilian nuclear program.

This starting point is crucial, and the basis for controversy about the possibilities for proliferation through the abuse of a civilian nuclear power program. On the one hand, the resources required to develop an independent military program may be substantially less than those required to develop a civilian nuclear power fuel cycle. (For instance, it is within the capabilities of many nations to construct a heavy-water or graphite-moderated reactor fueled by natural uranium and to construct a reprocessing plant to produce a few weapons per year. The Office of Technology Assessment estimates the cost and time required to construct these facilities to be about $100 million and five years.) On the other hand, the resources required to develop an independent military program may be much more than those required to abuse an existing civilian program. Perhaps more important, developing an independent military program can involve a longer time for detection and response by one or more nations, or the international community as a whole, than moving to nuclear weapons from a civilian program. In fact, it may be easier for a decision to move toward weapons to be made as the result of a sequence of incremental moves which have, or appear to have, civilian objectives rather than all at once for specifically military purposes. Moreover, the potential for proliferation through the fuel cycles can be unclear to domestic as well as foreign observers and does not even have to be in mind when a nation chooses a nuclear power program. As a result, there can be drift, whether deliberate or inadvertent, toward easier routes to a nuclear weapons capability.

The period of time after which movement toward obtaining weapons is clearly distinguishable from legitimate civilian nuclear activity is critical. For then a nation runs a risk of detection and response; and only if the potential proliferator anticipates such a risk can it have a deterrent effect. This exposure time depends on the existence of a consensus about when an activity, even if legal, is politically unacceptable and violates international norms.

Accordingly, such a consensus needs to address the ambiguities which arise because all nuclear power fuel-cycle systems involve either "sensitive" (weapons-usable) material or a potentially "sensitive" facility (one that can produce, or can easily be modified to produce, weapons-usable material) that is in the system. Ambiguities may also arise about an out-of-system facility--one which is not part of the nuclear power fuel-cycle system under consideration. Such a facility may be used for another fuel cycle or other civilian purposes, like producing isotopes for medical or biological uses, or it may be used for nuclear weapons purposes, in which case it is called a "dedicated" facility. In short, the mere fact that a facility is out-of-system does not identify it as military or prove that its purpose is dangerous or proscribed, but it does make the purpose of the facility ambiguous until its actual purpose can be established. The potential for abuse of sensitive facilities when they are in-system or their inherent ambiguity when they are out-of-system defines the proliferation risk of nuclear-power fuel cycles.

Although no nuclear-power fuel cycle is completely free of proliferation risks, fuel cycles can differ significantly in their degree of resistance to abuse. Their relative degrees of proliferation resistance depend both on the technical features and activities of the fuel cycles and on the institutional arrangements and political situations under which they are used. At the present time, states can have material directly usable in nuclear weapons without having to make the decisions or to take steps to implement them which are unambiguously directed toward developing a nuclear weapons program, in contrast to a situation in which dedicated facilities have to be built.

The goals of the task at hand, to reduce the risks of proliferation through civilian nuclear power programs, are threefold. The first is to secure agreement, if possible, on the conditions and controls under which civilian nuclear activities are acceptable. The second is to ensure that no civilian starting points be easy, that the exposure time be long, and that the detection system be effective. The third is to ensure that when nations undertake to develop a nuclear power program, they recognize in advance that its abuse for nuclear weapons purposes is too risky politically or militarily because the adverse consequences would be too great to accept.

The purpose of the current international safeguards regime is to deter the abuse of civilian fuel-cycle materials or facilities through procedures which ensure timely detection, on the assumption that such detection could have unacceptably high risks. International safeguards are intended to warn of attempts to develop nuclear weapons from safeguarded materials or facilities. They are also intended to provide evidence that nuclear weapons have been prepared in violation of nonproliferation obligations without relying for such evidence on the detection of nuclear-weapons (or nuclear-explosive) tests.

To achieve this purpose, the regime must make the risk of detection great enough so that it would be easier for a potential proliferator to withdraw from international safeguards or establish an independent military program than to abuse a civilian nuclear program. At the same time, the regime must make the level of assurance provided for different components of different fuel cycles credible by considering the safeguards efforts required for such provision. The risk of detection and the credibility of safeguards efforts would provide very little assurance in a hypothetical situation in which all users of nuclear energy had direct access to nuclear weapons-usable materials or facilities, since it would be very difficult to verify all of their activities.

Despite the intent of the current international safeguards regime and its contribution to the proliferation resistance of civilian nuclear programs, the vulnerabilities of the fuel cycle remain a matter of continuing and significant concern. This volume assesses these vulnerabilities, both technical and institutional, so that the proliferation risks of the different fuel cycles and fuel-cycle systems may be reduced as civilian nuclear power systems are developed.

1.1.3 How Urgent is the Problem?

The problem is made urgent by trends in the development and deployment of different fuel cycles and nuclear power systems, and by political developments in some parts of the world. The current regime is characterized largely by once-through systems, in which the predominant reactor is the light-water reactor, and for which enrichment services are provided by a few states. Spent fuel is being held in interim storage, most of it at radiation levels that make reprocessing possible only with facilities which presently exist in few nations. In fact, there is only one large-scale plant currently in operation to reprocess spent fuel from light-water reactors, although smaller plants also exist. A variety of constraints, political and institutional, on international behavior have combined to keep the proliferation of nuclear weapons well within the limits some had projected. These constraints include alliance relationships, the current international regime controlling civilian nuclear activities, and an international climate in which the development of nuclear weapons is increasingly viewed as not being in the interests of any nation.

But there is a growing concern that there are at least two trends toward greater proliferation risks. First, more nations are acquiring access to sensitive materials and facilities. Several nations are planning or constructing enrichment facilities for greater assurance of fuel supply than they believe they can obtain from the few nations that now supply enrichment services. Some nations have stated that the need to dispose of the growing amount of spent fuel in interim storage is one consideration in their plans to build and operate reprocessing facilities. Some nations with uncertainties about the availability of uranium resources for the longer term and with a desire for national control over the fuel cycle are beginning to develop fast breeder reactors and their associated fuel-cycle components. Although there has been a consistent downward trend in all nuclear energy forecasts for the past several years, so that the spread of sensitive materials and facilities is less imminent, the underlying pressures responsible for this trend remain.

Second, some of these nations may perceive that they have incentives to acquire or to consider shortening the time for acquiring nuclear weapons capabilities. Not all of these nations have indicated a willingness to forego nuclear weapons or nuclear explosive devices by acceding to the Treaty on the Non-Proliferation of Nuclear Weapons (commonly referred to as the Non-Proliferation Treaty). Both the dynamics of evolving nuclear power systems and changing political realities require that the existing regime which controls civilian nuclear activities be reassessed to find ways to strengthen it against the dangers of nuclear proliferation.

The scope of this report has been limited to the weapons-usability of fuel-cycle material from those power, research, and test reactors, and from fuel-cycle facilities, that have potential for use in the United States and abroad. Limiting the scope of these studies to civilian nuclear systems meant that neither the dedicated weapons programs of foreign countries, nor the demand for weapons, nor the political dynamics that might cause a nation to abuse the nuclear fuel cycle were analyzed. Thus, not all of the proliferation pathways open to a nation have been covered in this study, and, correspondingly, not all of the available proliferation countermeasures have been analyzed.

The study's scope was influenced by three primary factors. First, although the proliferation risk posed by a civilian nuclear power program had been discussed extensively in a number of recent studies (Pan Heuristics' Moving Toward Life in a Nuclear Armed Crowd?, The Ford Foundation's Nuclear Power Issues and Choices, the Atlantic Council's Nuclear Power and Nuclear Weapons Proliferation, and the Office of Technology Assessment's Nuclear Proliferation and Safeguards), until NASAP, no thorough technical study of this risk had been made to measure the actual dimensions of the problem. Second, to the extent that civilian nuclear power programs do pose a proliferation risk, adjustments may be warranted in the nuclear systems currently in use or in those systems that will be developed and deployed domestically and abroad. Since individual parts of current research, development, and demonstration programs may be affected, the level of detail had to be commensurately fine. Finally, nuclear proliferation is far more than a weapons issue; it is one that is more properly discussed in the broader contexts of national energy goals and the role of nuclear power in meeting those goals, of resource limitations and security of supply, of economic and political aspirations, and of national objectives for independence from reliance on foreign energy suppliers. To deal with issues of such breadth has required the comprehensive assessment of reactor and fuel-cycle systems and programs from several perspectives.

1.2 HISTORICAL PERSPECTIVE: EVOLVING NONPROLIFERATION POLICY

The use of nuclear energy for the generation of electricity has been under development since the late 1940's. By the 1960's it had begun to make a substantial contribution to the electrical generating capacity of the United States and other major industrial nations. In 1967, 0.6 percent of electricity production in the United States was generated by nuclear power, and by 1977 that number had risen to 11.8 percent. Nuclear growth for the Organization for Economic Cooperation and Development (OECD) countries paralleled that of the United States; 8 percent of their electricity was supplied by nuclear power in 1976. In 1977 countries with the largest percentage of nuclear-generated electricity included: Belgium (22.4 percent), France (13.4 percent), the Federal Republic of Germany (11 percent), Sweden (21.7 percent), and Switzerland (16.8 percent).

With the continuing increases in both the cost of other energy sources and in the uncertainties regarding diminishing worldwide fuel supplies, many industrialized and developing nations are planning for increased use of nuclear power over the coming decades. Even with the lowering of estimates of future nuclear growth, the Department of Energy's Energy Information Administration (EIA) has forecast that nuclear power will provide between 25 and 30 percent of OECD's electricity in 1995.

European use of nuclear energy has been forecast to rise to 34 to 40 percent of total electricity production by 1995, led by an ambitious French light-water reactor program. More modest programs are anticipated for most non-OECD developing nations, and EIA has forecast that nuclear power will contribute on the order of 10 to 15 percent of their total electricity generated in 1995. It is against this background of growing use of nuclear power that the problem of proliferation must be examined.

1.2.1 Policy History

Concern about the relationship between civilian nuclear power programs and the proliferation of nuclear weapons is not new; the issue has been addressed in various forums since the mid-1940's. The U.S. has always played a leading role in promoting an international commitment to nonproliferation. Table 2 chronicles some of the major events in the history of nuclear weapons proliferation and the evolution of U.S. nuclear nonproliferation policy. From the close of World War II through the early 1970's, U.S. policy for the

TABLE 2. CHRONOLOGY OF EVENTS IN NONPROLIFERATION

1945	U.S. detonated first atomic bomb.
1946	Baruch Plan for international control of nuclear activities was submitted to the U.N. but not accepted by the USSR.
1949	USSR detonated its first nuclear device.
1952	United Kingdom detonated its first nuclear device.
1953	President Eisenhower presented "Atoms for Peace" initiative to the U.N. General Assembly.
1957	International Atomic Energy Agency (IAEA) was established under U.N. auspices.
1960	France detonated its first nuclear device.
1961	IAEA adopted the first international nuclear safeguards system primarily for material accountability and control.
1964	People's Republic of China detonated its first nuclear device.
1968	Treaty on the Non-Proliferation of Nuclear Weapons was negotiated and opened for signatures.
1970	Treaty on the Non-Proliferation of Nuclear Weapons entered into force.
1974	India detonated its first nuclear device.
1974	Major nuclear suppliers first met in London to develop guidelines for the export of nuclear material, equipment, and technology.
1975	Nuclear Suppliers Group was established.
1976	U.S. deferred commercial reprocessing.
1976	U.S. reiterated its policy of restricting the transfer of sensitive nuclear facilities (for reprocessing or enrichment).
1977	U.S. announced continuation of its embargo on the transfer of sensitive facilities.
1977	Expansion of U.S. uranium-enrichment capacity was proposed.
1977	International Nuclear Fuel Cycle Evaluation (INFCE) was inaugurated.
1978	Nuclear Suppliers Group established guidelines (published by the IAEA in INFCIRC/254) for transfer of nuclear materials, facilities, and technologies to be followed by 15 supplier nations.
1978	Nuclear Non-Proliferation Act of 1978 signed, codifying U.S. terms for nuclear cooperation.

containment of international nuclear proliferation evolved from a policy of tight control on nuclear information and technology to a policy of promoting nuclear development for peaceful purposes under agreements guaranteeing the civilian use of nuclear technology in exchange for nonproliferation undertakings. A major development in the evolution of this policy was the Non-Proliferation Treaty, which involves the acceptance by non-nuclear-weapons states of international safeguards on all their peaceful nuclear activities, and their agreement not to acquire or manufacture nuclear weapons or nuclear explosives, thereby continuing the process of establishing a legal framework and a general climate of opinion against the spread of nuclear weapons.

Following the Indian nuclear explosion in 1974, the nuclear proliferation problem--and concomitantly, U.S. nonproliferation policy--took a significant new turn. U.S. efforts have emphasized a policy directed at reducing the political incentives for a nation to seek nuclear weapons while promoting the development of peaceful nuclear activities under appropriate safeguards. U.S. policy continues to be based on these principles. However, in recent years it has become apparent that an increasing number of nations either already possess or plan to acquire certain nuclear fuel-cycle facilities that produce or can be used to produce weapons-usable uranium or plutonium.

The U.S. has reiterated its policy of restraint in the export of sensitive nuclear technology and materials; this policy culminated in the Nuclear Non-Proliferation Act of 1978. Additionally, the U.S. is working within the IAEA to encourage more effective safeguards, and through the Nuclear Suppliers Group to effect a set of guidelines governing conditions for export of sensitive technologies.

On April 7, 1977, President Carter issued a Nuclear Power Policy Statement which contained, among other things, several initiatives committing the United States to a strong nuclear nonproliferation position. The policy:

- Deferred indefinitely the commercial reprocessing and recycling of the plutonium produced in the U.S. civilian nuclear power program.

- Restructured the U.S. fast breeder reactor program to give greater priority to development of alternative breeder designs and deferred the date when breeder reactors would be put into commercial use.

- Redirected funding of U.S. nuclear research and development programs to accelerate research into alternative nuclear fuel cycles which do not involve direct access to material that can be used for nuclear weapons.

- Committed the U.S. to become a more reliable supplier of nuclear materials and equipment by expanding its enrichment capacity and proposing legislation which would clarify and stabilize the U.S. terms for nuclear cooperation.

- Proposed that the U.S. join other nations in the International Nuclear Fuel Cycle Evaluation (INFCE), a forum which at its organizing conference reached the consensus that "effective measures can and should be taken at the national level and through international agreements to minimize the danger of the proliferation of nuclear weapons without jeopardizing the development of nuclear energy."

These initiatives constitute the policy environment for NASAP. The following section reviews the goal and scope of the program.

1.3 THE NONPROLIFERATION ALTERNATIVE SYSTEMS ASSESSMENT PROGRAM

The Nonproliferation Alternative Systems Assessment Program, begun in late 1976, was restructured to respond to President Carter's April 1977 Nuclear Power Policy Statement. The goal of the NASAP study has been to provide recommendations for the development and possible deployment of more proliferation-resistant civilian nuclear power systems and institutions in light of nuclear energy needs. In this context, "proliferation resistance" is the capability of a nuclear power system to slow or stop the diversion of associated fuel-cycle materials or facilities from civilian to military uses. It may be achieved through a combination of the technical and institutional features of the system, to the detriment of would-be national or subnational proliferators. To develop more proliferation-resistant systems, it is necessary to identify the materials or facilities most vulnerable to abuse and to consider technical and institutional measures that, developed over time, might be employed to reduce these vulnerabilities.

The NASAP study focused on the potential proliferation implications of nuclear power systems. Accordingly:

- The study was limited to assessing civilian nuclear power systems and their associated fuel cycles and institutions. It did not assess other routes or the incentives and disincentives for specific nations to acquire weapons.

- The study was directed toward reducing proliferation risks. While improvements in such areas as resource utilization were investigated, improvements in the safety of today's systems were not. Rather, it was assumed that nuclear power systems would be designed to comply with today's regulatory framework. Nevertheless, differences among the various systems regarding safety and environmental implications were discussed.

- Several other important domestic nuclear power issues were outside the scope of the NASAP study. For example, how best to solve the waste management problem, what to do about the Allied General Nuclear Services reprocessing facility, and how much funding the breeder reactor should receive were not addressed directly by NASAP. These issues would, however, be affected by the adoption of NASAP recommendations.

- It is important to recognize that the NASAP studies are a contribution to, not a substitute for, discussions and analysis of broader national energy policy issues. They present but one of many perspectives on the problem of ensuring adequate energy in the coming decades. Other policy questions include the possibility of decreasing our reliance on imported oil through more vigorous conservation and the increased use of coal, and the desirability of increasing the supply of electricity as a substitute for imported oil. Energy policy decisions must, of course, be made in light of such broader perspectives.

The assessments of alternative reactors and fuel cycles were conducted by establishing the nuclear power system as the unit of analysis and partitioning the problem into major, more readily separable questions. Each assessment focused on answering one of these major questions. These questions, and NASAP's approach to answering them, follow.

Proliferation Resistance

> What is the proliferation resistance of each nuclear power system, and what technical and other measures can be used to make systems more proliferation resistant?

Proliferation resistance is the capability of a nuclear power system to inhibit, impede, or prevent the abuse of associated fuel-cycle materials or facilities from civilian to military uses. It may be achieved through a combination of the technical and institutonal features of the system, to the detriment of would-be national or subnational proliferators. The materials and facilities associated with candidate systems that are vulnerable to abuse were considered, and technical and institutional measures that, developed over time, might be employed to reduce these vulnerabilities, and thus increase proliferation resistance, were identified. The activities required to obtain weapons-usable material were analyzed so that the proliferation resistance of each system could be characterized in terms of assessment factors: the technical, manpower, and financial resources required; the time required to carry out activities; and the chances and consequences of detection of the activities (for comparison, a study of facilities dedicated to a weapons program was also made). The activities required and the associated possibilities for detection and deterrence depend both on the technical features of the fuel cycle under consideration and on the safeguards, protective measures, and other institutional measures that may apply. Estimates of the assessment factors rely upon many diverse variables which change over time, some of which can be quantified to some extent and many of which cannot. Accordingly, the assessments using these factors are presented as qualitative discussions which focus on the important considerations but which do not usefully lend themselves to methodological tabulations or qualitative rankings.

Resources and Fuel-Cycle Facilities

What resources and fuel-cycle facilities are required for alternative nuclear systems, and will uranium supplies be adequate to meet these requirements?

The resources and fuel-cycle facilities required to support probable levels of nuclear power demand were projected according to the reactors and fuel cycles that might be chosen and where they might be located. The outlook for producing the uranium and thorium fuels at the rates they may be needed was evaluated, along with measures that might be taken to overcome any imbalances in domestic and world uranium supply and demand. The requirements for major fuel-cycle facilities such as heavy-water production, uranium enrichment, spent-fuel storage, reprocessing, and fuel fabrication were also projected, and possible constraints on the deployment of alternative systems were identified.

Commercial Assessment

What is the potential for commercial implementation of the alternative nuclear systems that might be used in a more proliferation-resistant or resource-efficient nuclear regime?

The commercial potential of alternative nuclear reactors and fuel-cycle systems was analyzed in terms of the factors that may influence the demand for nuclear power, the willingness of private industry (utilities, reactor manufacturers, and other suppliers of products and services) to undertake the commercialization of new technologies, and the type and cost of research, development, and demonstration and other steps required to bring new technologies to the point of market readiness. Conclusions were derived from industry surveys, analyses of the current technical status of each system, and analyses of potential domestic and foreign electrical demand. Separate analyses were made of venture criteria for vendors, purchase criteria for utilities, and possible Federal and private sector roles in research, development, and demonstration and precompetitive deployment of new systems. In addition, public concerns and their implication for decisions on alternative nuclear power systems or classes of systems were analyzed.

Economic and Systems Analyses

Under what conditions would alternative nuclear systems become economically attractive in light of possible patterns of uranium supply and energy demand, and what are the economic implications of pursuing the more proliferation-resistant systems?

Economic analyses were made for alternative reactor and fuel-cycle systems in the United States. The total electric power-generating cost was estimated for alternative reactors to project when and under what conditions they might first become economically competitive. The effect of market introduction costs on the transition to new systems was considered, and the effects of cost uncertainties were evaluated. The costs of technical proliferation-resistance countermeasures were estimated to determine whether they would provide an economic impediment to their use.

Safety and Environmental Considerations for Licensing

What are the safety and environmental licensing considerations which could influence the choice of particular nuclear systems and nonproliferation options?

Safety and environmental licensing considerations were assessed for alternative reactors and fuel cycles in the U.S. to identify possible technical, cost, or timing constraints on their commercial deployment. Information was developed concerning technical status and unique safety considerations, plant effluents, land and water utilization, critical or nonrenewable materials, and socioeconomic factors. These factors were analyzed both for individually deployed facilities and for the cumulative effects of widespread deployment. Preliminary limited reviews of safety and environmental licensing considerations were made by the United States Nuclear Regulatory Commission to identify the major issues and problems which were considered in the assessment.

International Perspectives

What are the possibilities for international deployment of alternative nuclear systems, especially those with increased resistance to proliferation?

Studies were conducted to assist in the development of international nuclear deployment strategies for the U.S. These studies sought to determine what additional technological and institutional measures might improve the existing international nonproliferation regime to keep within acceptable bounds the risks from the further spread of nuclear power systems while at the same time meeting the needs of nations for nuclear energy. A range of technical and institutional options were identified and assessed along with the incentives available to effect these options. The assessments were conducted in terms of nonproliferation effectiveness and other considerations important to the acceptability or negotiability of the options to various parties. These other considerations were analyzed in terms of economic considerations, energy security, and other political factors. The consideration of actual acceptability is subject to an examination of the potential participation of specific countries in specific arrangements, and to the results of negotiation. Such examinations were beyond the NASAP scope.

Results from each of the assessments described above were the basis of the NASAP integrating analysis, which sought to answer the questions:

- To best promote our nonproliferation objectives, what research, development, and demonstration activities should be pursued by the U.S. Government?
- What institutional initiatives might be undertaken by the U.S. Government to augment the technical measures previously identified?

In the course of the NASAP studies, basic data required to characterize alternative nuclear systems were generated and collected. Both existing design studies and new conceptual designs were utilized for this purpose. Detailed descriptions of the reactors and fuel cycles are contained in Volume IX (Reactor and Fuel Cycle Descriptions) of this report. This volume and the volumes containing the assessment summaries were derived both from contractor reports and from Department of Energy information drawing on diverse technical inputs. A list of major NASAP-related reports is contained in the bibliography.

1.4 PROGRAM ASSUMPTIONS

The starting point for NASAP was the existing situation, that is: nuclear power reactors and fuel-cycle facilities now operating, under construction, and planned; research and test reactor programs and facilities as well as laboratory-scale and pilot fuel-cycle facilities, both operating and planned; and the institutional framework or international regime, consisting of treaties, agreements, and guidelines within which nuclear power programs are conducted, including the Non-Proliferation Treaty and the IAEA safeguards program.

From this base, two sets of assumptions were made, one set about reactor and fuel-cycle concepts to be studied, including those which are or have been under development and those which might offer future nonproliferation or other benefits; and a second group of assumptions about the forecast of future ranges of growth in nuclear electrical-generating capacity. These two sets of assumptions are discussed next.

1.4.1 Reactor and Fuel-Cycle Systems Studied

Numerous alternative reactor and fuel-cycle combinations are technically possible. In addition to those used today throughout the world, many others have been studied or have been under development during the last several decades. From this total, systems were selected for close study, making certain that the selected systems would be sufficiently representative to permit inferences to be drawn for systems that were not subjected to detailed analysis. Systems were grouped according to a number of criteria. First, the developmental status of the reactors provided a basis for classifying them into three groups: those proven commercially, those with major development programs under way, and those conceptual systems potentially offering resource-utilization improvements and improved proliferation resistance. The major nuclear reactors studied by NASAP are shown in Table 3. Many variations of these systems, as well as other, less developed systems, were also analyzed.

The second basis for categorizing nuclear power systems is their fuel cycles. A typical once-through nuclear fuel cycle is shown in Figure 1, and the activities in a typical closed fuel cycle (recycle) are shown in Figure 2. The supporting fuel-cycle activities shown in the figures--mining and milling, conversion, enrichment, transportation, fuel fabrication, reprocessing, and waste handling and treatment--were also studied.

In theory, any fuel cycle might be used in combination with any reactor type; but, in addition to possible proliferation-resistance benefits, physical constraints dictate which combinations provide the most desirable operating characteristics with respect to reactor physics, resource utilization, safety, and operating reliability. The more effective combinations and, hence, those most likely to be adopted were selected for detailed study. These served as proxies for similar fuel cycles not selected.

TABLE 3. NUCLEAR REACTOR SYSTEMS THAT RECEIVED THE MAJOR CONSIDERATION BY NASAP

Category I	Category II	Category III
Commercially Proven[1] or Modifications to Existing Systems	Under Major Development	Conceptual
Light-Water Reactor[2]	Light-Water Breeder Reactor[4]	Fast Mixed-Spectrum Reactor
Heavy-Water Reactor[3]	High-Temperature Gas-Cooled Reactor	Molten-Salt Reactor
	Liquid-Metal Fast Breeder Reactor	Gaseous-Core Reactor
		Accelerator-Driven Reactors
	Gas-Cooled Fast Reactor	Fusion-Driven Reactor

[1]The MAGNOX reactor and the advanced gas-cooled reactor types were omitted because it does not appear that additional plants of these types will be used outside the United Kingdom or France.

[2]Includes pressurized-water reactor and boiling-water reactor.

[3]Includes both the current Canadian natural uranium design and advanced designs developed for NASAP.

[4]This reactor is considered an evolutionary change from Category I reactors.

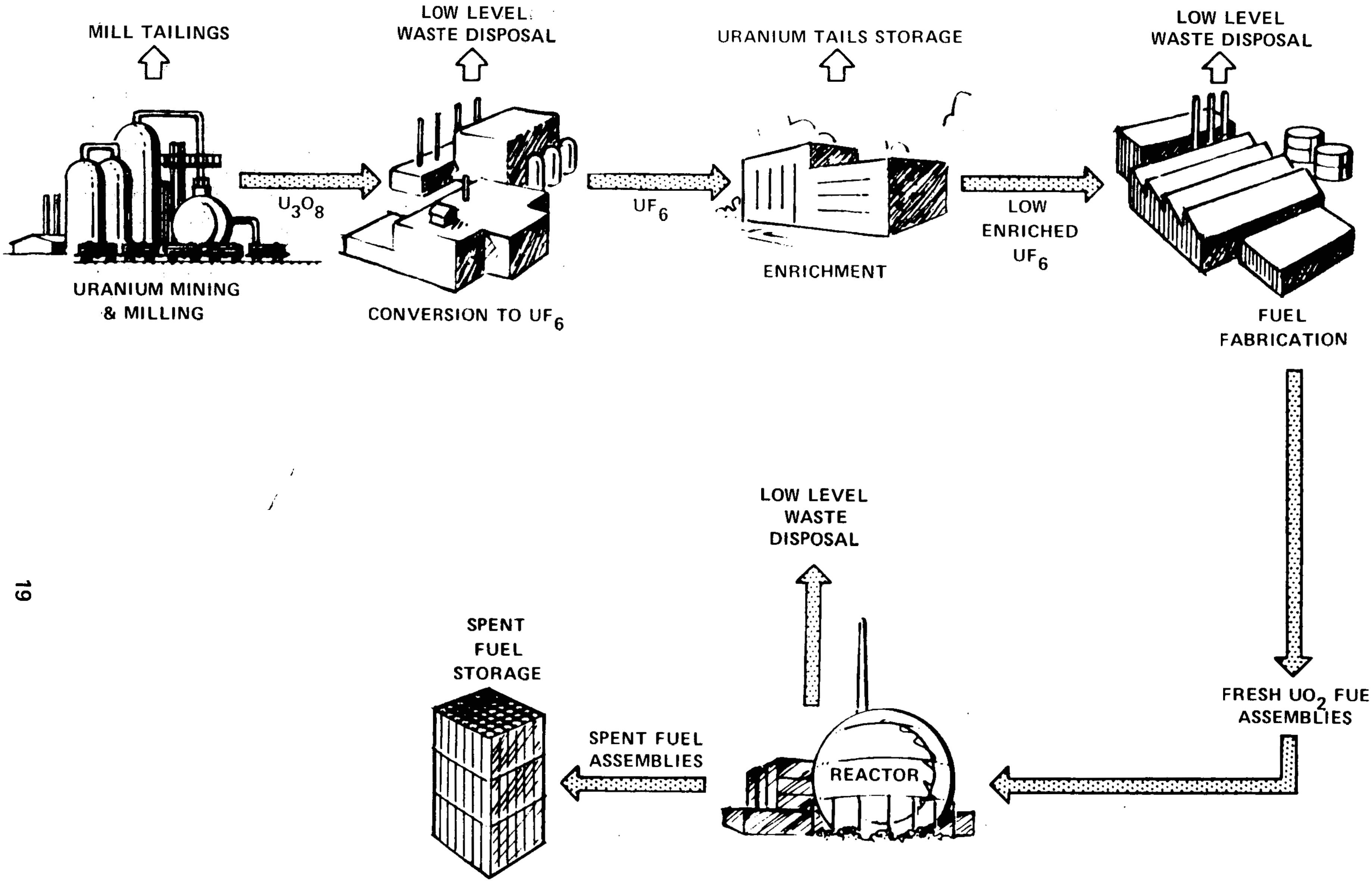

Figure 1. Illustrative Once-Through Fuel Cycle

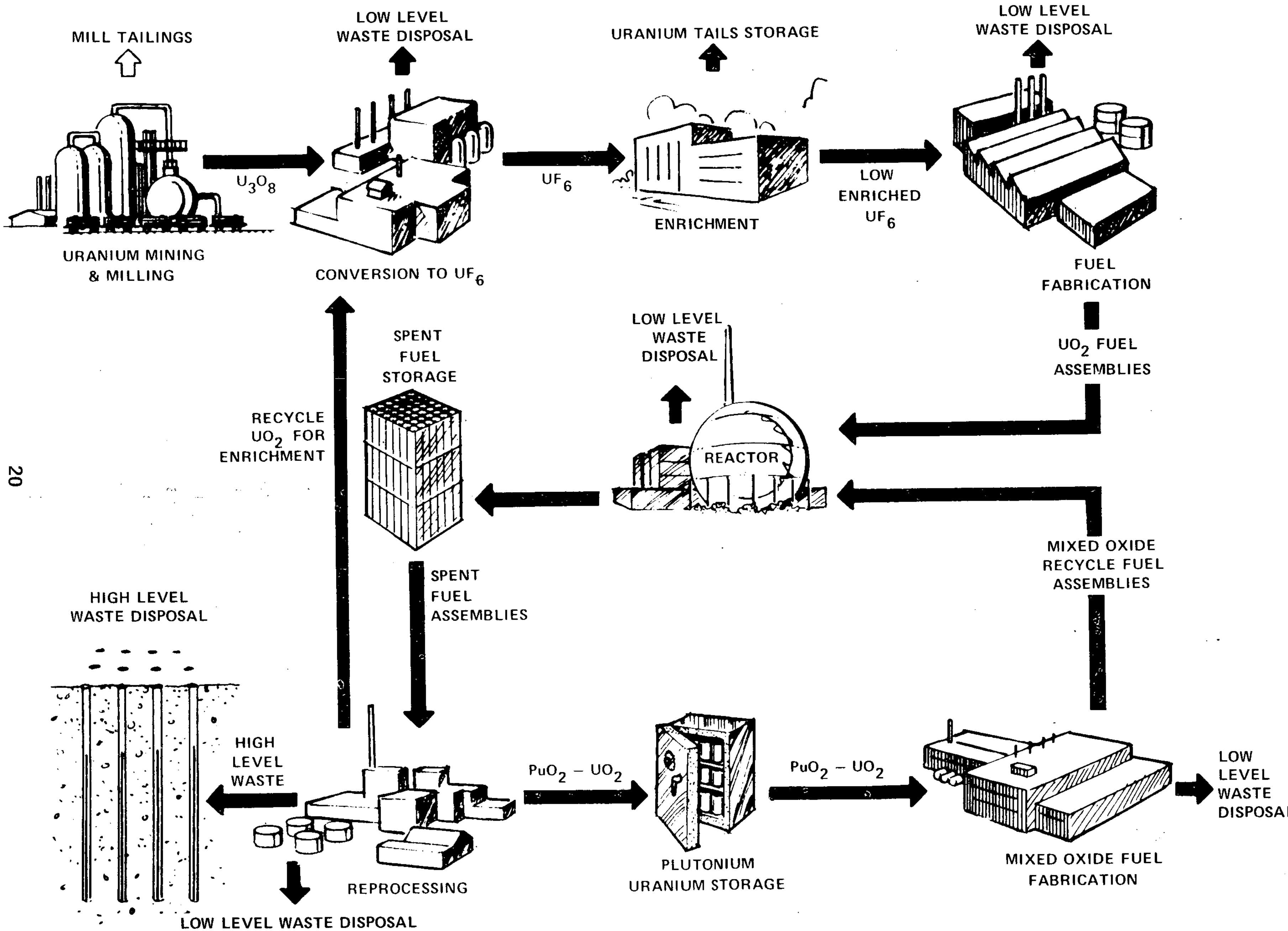

Figure 2. Illustrative Closed Fuel Cycle

Category I systems, expanded to incorporate fuel-cycle options, include today's once-through light-water and heavy-water reactor systems with improved fuel utilization. The light-water reactor was the most important once-through system studied because it is widely used. It was also believed to have good potential for modification in the near future to achieve significant uranium savings. A denatured U-233/U-238-fueled light-water reactor which recycles the U-233 produced from thorium was studied as part of a symbiotic or interdependent system in which the necessary U-233 would come from either a plutonium-fueled light-water reactor or a fast breeder. In this symbiotic system, more proliferation-resistant denatured U-233 fuels would be produced at a few large facilities for use in widely dispersed reactors. The light-water reactor fueled with recycled plutonium/uranium was also included because of the possibility of its use in other countries. Two distinct heavy-water reactor designs were studied: first, the existing Canadian natural uranium reactor, and second, a conceptual design which could use slightly enriched uranium or recycled fuels and would potentially meet U.S. licensing criteria. The heavy-water recycle systems were included for reasons similar to those for including the light-water recycle systems.

Category II, encompassing systems that are now under development, includes resource-efficient once-through systems, and the even more resource-efficient systems that recycle spent fuel. The recycle systems might be deployed later than the once-through systems. Included are the light-water breeder reactor, which is an evolutionary change from existing light-water reactors, and the high-temperature gas-cooled reactor, under development in the U.S. and overseas. These would require further development and the use of a thorium/U-233 fuel cycle. The liquid-metal and gas-cooled fast breeder reactors are included for the longer term because they are the most promising and most developed concepts that essentially eliminate dependence on mined uranium and also are the most efficient systems now under development for transmuting plutonium fuels to U-233. Several advanced fast-breeder fuel types (carbide and metal) were studied to evaluate their effectiveness for transmuting thorium to U-233.

Category III covers advanced conceptual technologies with potential proliferation-resistance and resource-utilization benefits. Included are: the molten-salt reactor, two accelerator-driven reactors, the fusion-driven reactor, the fast mixed-spectrum reactor, and the gaseous-core reactor. The technical feasibility of each of these systems has major uncertainties; consequently, the study concentrated on identifying these uncertainties by first performing conceptual designs and developing better bases for the assessments. The assessment of these alternatives then concentrated on their technical feasibility and on defining research, development, and demonstration needs. The results of this assessment are reported in Volume VIII (Advanced Concepts).

Detailed descriptions of the designs for the reactor and fuel-cycle systems studied by NASAP will be found in Volume IX (Reactor and Fuel Cycle Descriptions) of this report.

1.4.2 Electrical Growth Forecasts

In order to evaluate the merits of alternative nuclear systems, it was necessary to examine them in the context of possible patterns of future electrical demand. Each assessment's results depend, to some extent, on the amount and type of nuclear generating capacity to be installed as a function of time. A range of forecasts was required because experience has shown that estimates of generating capacity are subject to great uncertainty, particularly when projected 20 or more years into the future. When unanticipated traumatic events occur such as those that occurred with the oil embargo and subsequent price increase of 1973 or the recent cutoff of imports from Iran, even short-term projections may prove inaccurate. However, to provide the needed projection of future domestic nuclear generating capacity, 1978 Department of Energy estimates were used. The short-term projections (2 to 3 years) rely on econometric methods applied to present trends in supply and demand. In the mid-term (4 to 13 years), more reliance is placed on the modeling of the economic processes, that is, shifts in population and labor-force growth, and disposable-income changes. The qualitative nature of energy technology is mostly fixed during this period, although the mix can change because of economic trade-offs. In the longer term (14 to 23 years) and beyond, the introduction of new technologies of supply and their penetration into the marketplace become more important, while the demand continues to be based on projections of population and labor-force growth. These projections of the complete domestic energy supply and demand picture form the basis for the projection of domestic nuclear generating capacity.

Projected domestic nuclear generating capacities in the U.S. for the years between 1980 and 2025 are shown in Table 4. These projections were based upon forecasts prepared by the DOE Energy Information Administration (EIA) in May 1978 and submitted to INFCE. The EIA Project Independence Evaluation System was used to forecast over the period 1980 to 2000. Another forecasting method was used for the period 2000 to 2025. It depends on projections of U.S. population, labor force, and total electrical power generation, and was developed by EIA and the DOE Office of Policy and Evaluation.

TABLE 4. 1978 ESTIMATES OF U.S. NUCLEAR POWER GENERATING CAPACITY (GW[1])

Year	High	Low	Median[2]
1980	66	62	64
1985	122	100	111
1990	192	157	175
1995	275	200	238
2000	395	255	325
2005	480	275	378
2010	590	295	443
2015	690	305	498
2020	800	315	558
2025	910	320	615

Source: Department of Energy--Energy Information Administration and Office of Policy and Evaluation, May 1978

[1]GW is the abbreviation for gigawatt, equal to 10^9 watts.

[2]Arithmetic mean of the High and Low cases. Not developed as part of the forecast.

In mid-1979, a range of new DOE-EIA forecasts to 2000 became available, with a single point forecast representing high nuclear growth potential estimated to the year 2020. The High forecast (see Table 5) is slightly below the arithmetic mean of the High and Low forecasts of Table 4, while the Low forecast is slightly lower than the Low forecasts above. Preliminary analyses by the Department of Energy show, in some circumstances, a return to a higher nuclear growth in the post-2000 period. Consequently, most of the NASAP analyses were based on the 1978 arithmetic mean forecast (Median case), but some were performed also for the High growth in the post-2000 period. The wider range above was used in some assessments (e.g., Commercial Potential) and was also used for sensitivity studies in other assessments.

TABLE 5. 1979 ESTIMATES OF U.S. NUCLEAR POWER GENERATING CAPACITY (GW)

Year	High	Mid	Low
1985	118	114	102
1990	171	152	142
1995	225	208	186
2000	300	260	235
2010	450	-	-
2020	675	-	-

Source: Department of Energy--Energy Information Administration, July 1979

In late 1979 and early 1980, while NASAP was being completed, even lower projections through the year 1995 were released by the DOE-EIA. These are shown in Table 6. These projections range from the generating capacity that would be available from only those plants now operating or authorized for construction (Low) to the capacity that could be achieved if there were a moderate resumption of new orders (Mid and High). It should be noted that DOE has not published new projections for the long term beyond the year 2000. However, as discussed in the appendix, the EIA is scheduled to publish new forecasts through 2020 in July 1980. The 1978 projections were used by NASAP because they are the most recent ones to cover the long term, and because they model the option in which there is a renewed commitment to nuclear energy in the U.S., beginning in the 1980's, as well as a lower rate of nuclear growth representative of recent trends.

TABLE 6. 1980 ESTIMATES OF U.S. NUCLEAR POWER GENERATING CAPACITY (GW)

Year	High	Mid	Low
1985	113	106	95
1990	155	140	129
1995	196	179	156

Source: Department of Energy--Energy Information Administration, January 1980

The 1980 forecasts for nuclear power continue the trend of decreasing estimates seen for the past several years. Table 7 illustrates the changes since 1975 in nuclear capacity forecasts for the United States and for the OECD countries including the United States. Because the estimates for 1990 are now based primarily on reactors "in the pipeline," either on order or under construction, future revisions may be expected to be minor. However, forecasts beyond 1990 are more dependent on total energy supply and demand patterns and so are more speculative. Shortfalls in foreign oil supplies, severely constrained use of domestic coal for electricity production, and less than expected success of national energy conservation efforts--any or all of these factors could radically increase the nuclear capacity growth estimates for power from today's systems as well as from more advanced technologies, such as the breeder reactor. The treatment of the uncertainties associated with these estimates is beyond the scope of NASAP.

Figure 3 shows the Department of Energy forecasts to be in the general range of other recent estimates. Depending on the purpose of the estimates and the scenarios considered, industry projections tend to show greater growth, while conservation-oriented studies show lower growth. The projections used for NASAP lie between these extremes. A more detailed discussion of the projected domestic nuclear generating capacity and a comparison with other recent forecasts are presented in the appendix to this volume.

TABLE 7. CHRONOLOGY OF NUCLEAR POWER FORECASTS FOR 1990
(GW of Installed Generating Capacity)

Year of Forecast	U.S.	OECD Including U.S.
1975	285-470 (1)	774-890 (5)
1976	190-250 (2)	---
1977	---	459-640 (6)
1978	157-192 (3)	328-412 (7)
1979	142-171 (4)	281-343 (8)
1980	129-155 (9)	263-327 (9)

(1) Total Energy, Electric Energy, and Nuclear Power Projections, U.S. Energy Research and Development Administration, February 1975.

(2) Basic Forecast Cases, U.S. Energy Research and Development Administration, September 1976.

(3) U.S. Submission to the International Nuclear Fuel Cycle Evaluation (INFCE), April 1978, as prepared by the Energy Information Administration (EIA), U.S. Department of Energy.

(4) Energy Supply and Demand in the Mid-Term: 1985, 1990, 1995, Energy Information Administration, May 1979.

(5) Uranium Resources, Production, and Demand, joint report of the Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA), December 1975.

(6) Uranium Resources, Production, and Demand, joint report of the OECD and the IAEA, December 1977.

(7) Forecasting Subgroup 1A/2A of INFCE, October 1978.

(8) International Energy Assessment, EIA, May 1979.

(9) Commercial Nuclear and Uranium Market Forecasts for the United States and the World Outside Communist Areas, DOE/EIA-0184/24, January 1980.

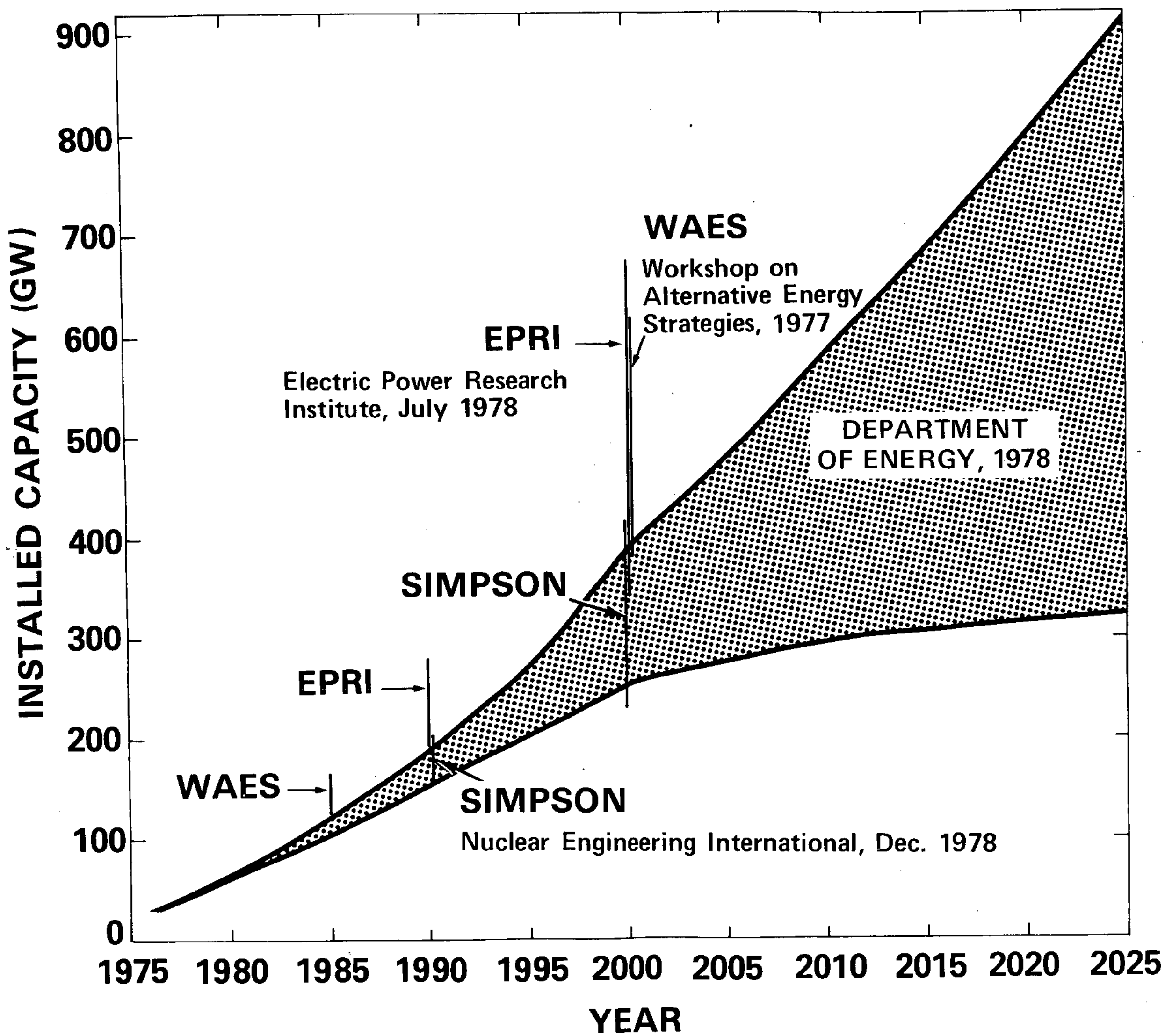

Figure 3. Comparison of Recent Projections of Installed Nuclear Electrical Generating Capacity

2. THE ASSESSMENTS, THEIR FINDINGS, AND THEIR RECOMMENDATIONS

This chapter summarizes the results of assessments by the Nonproliferation Alternative Systems Assessment Program (NASAP) of alternative nuclear power systems. First, it examines the existing situation, comparing the most widely used system, the light-water reactor on a once-through (stow-away) fuel cycle, against other presently available nuclear power systems. The discussion covers four aspects: the relative proliferation resistance of the reactors and fuel cycles, the prospects for their fuel-supply requirements, factors affecting their commercial viability, and some of the pressures to adopt fuel cycles that might increase the availability of sensitive materials and facilities.

Second, the chapter examines NASAP conclusions on some of the nuclear choices that might have to be made in the near future and the more distant future. In doing so, it reviews a broad range of possible technical choices ("resource extenders") which might use available resources more efficiently. The implications for their international deployment, likely resource requirements, and prospects for commercialization in each case are examined. Next, ways that future fuel supplies might be assured to users whose alternative might otherwise be the adoption of less proliferation-resistant technology are also examined. Finally, some of the institutional and technical measures that might reduce proliferation risks are reviewed.

The chapter concludes by summarizing recommendations for research and development.

2.1 TODAY'S NUCLEAR SYSTEMS

Civilian nuclear power is produced today primarily by light-water reactors using fuel that is discharged to interim storage and not reprocessed (the "stow-away once-through" cycle). Other principal types of operating nuclear power plants include the heavy-water reactor used in Canada and marketed worldwide and the MAGNOX and advanced gas-cooled reactors of France and the United Kingdom. In addition, there are several one-of-a-kind power plants in the United States and abroad, including the high-temperature gas-cooled reactor, light-water breeder reactor, and several liquid-metal fast breeder reactors. Worldwide there are over 150 research and test reactors operating at over 10 kW thermal power output in about 30 countries.

While most of today's power systems operate without recycle, there is limited fuel reprocessing capability available commercially. In addition, laboratory or pilot-scale reprocessing facilities exist, or have existed, in several countries. Similarly, uranium enrichment has been developed or is under development in several countries.

This section describes the proliferation resistance, resource use, and commercial potential of today's systems. In addition to assessing those systems now operating commercially, the study of proliferation resistance also addresses research and development programs because they contribute to the vulnerability of these systems.

2.1.1 Resistance to Nuclear Weapons Proliferation

The scope of the NASAP proliferation assessment was deliberately set to try to ensure an analysis and evaluation that would, at a minimum, reflect the breadth of the proliferation problem in dealing with both technical and institutional factors and in taking into account the uncertainties of the evolving situation. While NASAP recognized that the absolute risk of proliferation is an important nuclear power policy issue in itself, this assessment was focused on the differences among the fuel cycles in degree of proliferation risk relative to that of a benchmark light-water reactor. While the assessment emphasizes the relative effects that choosing one nuclear power system rather than another may have on the possible spread of nuclear weapons capability, the discussions also identify the materials and facilities most vulnerable to abuse and consider technical and institutional measures that, developed over time, might be employed to reduce these vulnerabilities and thus increase the proliferation resistance of these fuel cycles.

The assessment procedure used characterizes the proliferation resistance of nuclear power systems in terms of the activities necessary to acquire weapons-usable material. When separated from other materials, both uranium (U) enriched to high concentrations in the isotopes U-235 (more than about 20 percent) or U-233 (more than about 12 percent) and plutonium (Pu) are considered to be nuclear weapons-usable materials, whether in oxide or metallic form. (Uranium enriched to 90 percent or more is often used--and was used by this study--for estimating the relative enrichment requirements for nuclear-weapons purposes. Moreover, while an independent military program to construct nuclear weapons may be considered likely to avoid the use of commercial reactor-grade plutonium containing a significant amount of the higher plutonium isotopes, such plutonium might be used for weapons purposes in certain circumstances. As used in the assessment of proliferation resistance, plutonium means total plutonium, that is, all plutonium isotopes.) The activities examined include the possible removal of materials from the fuel cycle, the modification of an in-system facility to produce these materials, or the construction of an out-of-system (and possibly dedicated) facility for conversion of these materials into a weapons-usable form, and the conversion itself. These required activities and the associated possibilities for detection and deterrence depend both on the technical features of the fuel cycle under consideration and on the safeguards, protective measures, and other institutional provisions that may apply.

The central question to be answered about the proliferation resistance of a nuclear power system is: How easy is it to decide to abuse it or to implement a decision to abuse it? The answer to this question depends upon the answer to three specific questions:

- What resources and efforts does abuse require at the national and subnational level?
- How long will it take?
- Will it be detected, and, if so, what can be the consequences?

The assessment of proliferation resistance depends substantially on the proliferation scenario. For example, a particular isotopic enrichment technique may be hard to implement for a country with a well-developed technological base and experienced personnel, much harder for a less developed country, and essentially impossible for a subnational group. Moreover, the resources required depend on the number and quality of the nuclear weapons sought, and the significance of this resource requirement as a barrier to abuse depends on the situation of the proliferator. Because of the great number of possible combinations of systems, activities, and situations, only a few representative possibilities are treated explicitly.

These and similar considerations have led to the development of a check list to be used in the assessment. Many, but not all, of these considerations are predominantly technical in nature and are descriptive of the fuel-cycle materials, facilities, and technologies. Some of these are intrinsic to the nature of the proliferation activities required, and some are extrinsic, dealing with the international scale and spread of fuel-cycle activities. They are the basis for three major groups of assessment factors used in performing the assessments. These groups are:

- Resources required--the technological base, personnel, and financial resources needed for the specified proliferation activities in light of their inherent difficulty.
- Time required--the approximate times needed for the specified proliferation activities, including preparation, removal, and conversion.
- Risks of detection--the chances and consequences of detection of the proliferation activities, including preparation, removal, and conversion, and the possible timeliness of detection.

Estimates of these factors rely upon many diverse variables which change over time, some of which can be quantified to some extent and many of which cannot. Accordingly, the assessments using these factors are presented as qualitative discussions which focus on the important considerations but which do not usefully lend themselves to methodological tabulations or quantitative rankings.

The approach taken in conducting these assessments has been to treat three generic nuclear power systems and ancillary research activities as simplified, isolated entities. The three systems have been designated by the names of their fuel cycles: once-through, recycle, and fast breeder. Research reactors and critical facilities have been examined separately. Even though there is no "proliferation-resistance index," the NASAP factors have been used in the assessments; and instead of criteria directly related to these factors, a benchmark nuclear power system has been used for purposes of comparison. This benchmark is the light-water reactor using the once-through fuel cycle, in which spent fuel is discharged into interim storage. This system is the one most widely used in the world today; however, its use as a benchmark does not imply that its absolute risk is acceptable. The level of acceptable risk itself is a matter of controversy. In this report, the benchmark itself has been assessed, and desirable improvements to it have been identified.

The approach taken in looking at fuel cycles was to treat a reference system in each generic system and then to treat alternative systems differing in specific ways from the generic system. Moreover, in the case of a particular fuel cycle, two kinds of national deployment were considered. One kind, which requires external enrichment or reprocessing services, involves the national deployment of the reactor and intermediate spent-fuel storage facilities; the second kind, which includes enrichment or reprocessing facilities, involves the national deployment of all fuel-cycle facilities.

The Proliferation Resistance of Once-Through Systems (Stow-Away)

The once-through light-water reactor's fuel cycle involves mining and milling the uranium ore, enriching the uranium to a concentration of about 3 to 5 percent in the isotope U-235, fabricating the enriched uranium into reactor fuel elements, using this fuel to operate a light-water reactor, and then putting the spent fuel into intermediate storage without deciding whether to put it into either long-term storage or to dispose of it permanently. It should be noted that spent fuel from intermediate storage could later be used in a closed (recycle and fast breeder) fuel-cycle system. As a matter of U.S. nonproliferation policy, reprocessing and recycling fuel has been deferred while the nonproliferation risks and economics are being assessed.

Light-water reactors fueled with low-enriched uranium are widely available commercially, generally as boiling-water reactors or as pressurized-water reactors. These two types of reactor differ markedly in physical characteristics but do not differ substantially in their proliferation resistance. Currently, there are more than 58 light-water reactors deployed outside the U.S. in 16 nations. An additional 103 light-water reactors have been ordered by these and 13 other nations. It is anticipated that by 1986 nearly 90 percent of all civilian nuclear power in the world outside the centrally planned-economy (WOCA) areas will be generated by light-water reactors. It is important to note that enrichment plants are much less widely deployed than reactors are. Currently, only one non-nuclear-weapons state, the Netherlands, has a civilian centrifuge enrichment plant deployed, but other centrifuge plants in the Federal Republic of Germany (West Germany) and Japan are planned for in the 1980's. Enrichment facilities will probably become more geographically dispersed than at present, since Brazil and South Africa are also planning for civilian aerodynamic enrichment plants. Moreover, several of these countries already have small-scale or pilot enrichment facilities, and a number of countries apparently are conducting research programs on advanced isotopic separation techniques. On the basis of this existing and planned plant capacity and on current demand projections, enrichment capacity outside the centrally planned-economy areas excluding the United States will begin to exceed aggregate demand in the late 1980's. Including the United States, enrichment capacity is expected to exceed demand at least through the mid-1990's. Against this background of nuclear power deployment, this section assesses the proliferation resistance of the light-water reactor once-through fuel-cycle system within the context of the current nonproliferation regime.

This regime varies from one country to another. By ratifying the Nuclear Non-Proliferation Treaty, more than 100 non-nuclear-weapons states have agreed not to acquire or manufacture nuclear weapons (or explosive) devices and to subject all their peaceful nuclear activities and any nuclear materials or facilities that they export to International Atomic Energy Agency (IAEA) safeguards. These nations have thus agreed to what is sometimes called "full-scope" safeguards. These safeguards require that the IAEA independently verify national systems of material control and accounting to maintain continuity of knowledge and inventory of material. Verification is accomplished through a system of reports, physical inspections, independent measurements, and application of various containment and surveillance techniques.

In addition, as a result of various bilateral supply agreements, some non-parties to the Non-Proliferation Treaty have also agreed to subject specific materials and facilities--but not necessarily all peaceful activities--to IAEA safeguards and not to use those so supplied for weapons purposes. Bilateral and multinational agreements may apply to the transfer of nuclear materials or technologies. An example of a bilateral agreement would be one requiring the application of full-scope safeguards as a condition of sale. A notable example of multinational agreements is the supply system and regulatory regime of the European Atomic Energy Community (EURATOM).

Proliferation Features and Activities

The most significant feature of the reference once-through nuclear power fuel cycle is that directly weapons-usable material is never part of the fuel cycle itself. Fresh fuel contains low concentrations of U-235 (about 3 to 5 percent) diluted in U-238; spent fuel contains low concentrations of U-235 and plutonium (each less than 1 percent), both of which are diluted in U-238 and accompanied by high radiation fields emitted by the products of fission.[1] Refueling of light-water reactors is conducted in a batch mode; approximately one quarter of the boiling-water reactor core and one third of the pressurized water reactor core are discharged annually.

There are three important proliferation pathways by which the reference system may be used to acquire weapons-usable materials: in-system enrichment facilities to produce highly enriched uranium, out-of-system enrichment facilities to produce highly enriched uranium, or out-of-system hot chemical reprocessing (separation) facilities to extract plutonium from the spent fuel.[2] These pathways are examined by noting the activities a potential proliferator would have to undertake and evaluating them when appropriate in terms of the chosen assessment factors. These required activities, including preparation of facilities, removal of material from the fuel cycle, and material conversion, may vary substantially with the scope and kind of the proliferator's nuclear weapons program.[3]

<u>In-System Enrichment</u> -- The key proliferation activity in the abuse of an existing enrichment plant designed to produce low-enriched uranium is the modification of the layout or operation of the plant to permit production of highly enriched uranium. While several methods of enrichment exist, only gaseous-diffusion and gas-centrifuge plants are deployed commercially. Modification of the layout or operation of an enrichment plant depends on the plant type.

In a gaseous-diffusion plant, rearrangement of the cascades designed to produce low-enriched uranium would not be practicable for continuous production of highly enriched uranium because of the size of the equipment. Making multiple passes through the cascades, that is, batch recycle, would yield

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[1]Low-enriched uranium, as defined by the Nuclear Regulatory Commission, is uranium enriched to less than 20 percent; highly enriched uranium is defined as uranium enriched to more than 20 percent and may be weapons usable.

[2]The word "hot" refers to the reprocessing of radioactive materials.

[3]The word "diversion" is used for removal of materials from the fuel cycle if they are under safeguards.

highly enriched uranium over many months or even years, but it would require many years' worth of production material in the first cycle to ensure that the cascade is filled in later cycles. Moreover, production of low-enriched uranium would have to cease. Modifying the operating conditions, that is, a "stretched" off-design operation, is a more attractive technique for producing highly enriched uranium. It is the shortest path for producing highly enriched uranium from a commercial diffusion plant because it uses low-enriched uranium from the plant inventory for direct enrichment. Weapons-usable material can be produced in a few months after the stretched off-design mode is initiated. The length of time depends upon the desired degree of enrichment. In a centrifuge plant, rearrangement of the cascades or batch recycle could yield highly enriched uranium within a matter of weeks if all the separative capacity of the plant were used. Over a longer period, this highly enriched uranium could, in principle, be produced with only a modest reduction in declared production of low-enriched uranium.

<u>Out-of-System Enrichment</u> -- The main activity needed to enrich uranium independently of an existing enrichment plant is building and testing an enrichment facility. Competent personnel without specialized enrichment experience would require several years and about $100 million to build and test a plant capable of producing quantities of highly enriched uranium for tens of weapons per year. If low-enriched uranium fresh fuel were removed from the commercial fuel cycle, the time from removal to weapons-usable material would vary from a few weeks to months, depending on the technology used, the capacity of the plant, and start-up difficulties. If this path were chosen, however, a nation might instead choose to enrich natural uranium rather than use low-enriched uranium fuel to reduce the risk of detection.

<u>Out-of-System Reprocessing of Spent Fuel</u> -- The main activity needed to extract plutonium from spent fuel is building and testing a hot chemical reprocessing plant. Personnel, including chemical engineers but without specialized reprocessing experience, would need one or two years and tens of millions of dollars to build and test a plant that could separate enough plutonium for tens of weapons per year, somewhat smaller commitments for one or two weapons. Once the plant was built and spent fuel was removed from the commercial fuel cycle, the time from removal to weapons-usable material would vary with the competence of the personnel involved. The time could be as short as a few weeks, but it could also be longer if difficulties were encountered in remote reprocessing.

On the basis of the current relative availability of detailed process information and personnel, the isotopic barrier to the production of weapons-usable material from fresh fuel appears greater than the chemical or radiation barrier to the production of weapons-usable material from spent fuel. Several nations have experience with developmental reprocessing facilities in anticipation of recycle or fast breeder systems, and such a facility could perform the function of the out-of-system reprocessing facility described above. The relative difference between the isotopic barrier and the radiation or chemical barrier could change, if, for example, it became common practice for enrichment facilities to be part of national fuel cycles or if enrichment technologies became less difficult.

The activities described above would pose very formidable problems for terrorists or most other subnational groups. At the national level, the necessary construction activities would extend through a lengthy period of time, during which they might be detected by other nations. Moreover, if IAEA safeguards were in effect, the necessary diversion of materials would also be subject to detection, although timely detection could not always be assumed. In addition, the IAEA has had extensive experience in safeguarding thermal power reactors, particularly light-water reactors, but has had little or no experience in safeguarding enrichment plants.

Improvements to the Once-Through Cycle -- A number of measures could be taken to improve the proliferation resistance of the once-through system. Instituting safeguards that would make it easier to detect the diversion of spent fuel in storage or in transit, and combining these safeguards with storage under multinational or international auspices, could significantly reduce the likelihood that this material would be used in weapons. Similarly, safeguards on enrichment facilities would make their misuse more detectable. Limiting the number of such facilities through cooperative arrangements could preserve the current level of proliferation resistance associated with the once-through system. Additionally, restraints on the spread of enrichment and reprocessing technologies coupled with reliable access to enrichment services would make the preparation phase of a weapons program more difficult and time consuming and could make the identification of such preparation less ambiguous. Each of these possible improvements is discussed in more detail below.

1. International Safeguards. Each country has its own regulatory process and procedures. Countries that import nuclear technology may develop

their own regulatory procedures, including safeguards, or they may adopt those of the supplying country. International safeguards procedures may be either those applied by the EURATOM organization in the European community or those of the IAEA.

Proliferation resistance of the once-through system could be improved by wider acceptance of safeguards. In addition, certain structural changes could improve the effectiveness of safeguards for the once-through system, including the following measures:

- Improved methods of material accounting, containment, and surveillance to be applied to enrichment facilities and stockpiles of natural uranium and low-enriched uranium. Methods which achieve near-real-time, tamper-revealing, remote surveillance of spent fuel in storage are technically feasible.

- Surveillance of all nuclear material in a country, whether on site or in transit.

- Assurance of adequate access to the enrichment plant to achieve effective IAEA plant inspection. The plant should be designed to enable IAEA inspectors to verify that there has been no diversion of materials or misuse of facilities. But procedures would also have to be designed to protect sensitive enrichment technology from being transferred.

- Improved mechanisms for prompt inspection and swift reporting of possible diversions.

2. Cooperative Arrangements for Spent-Fuel Storage. International arrangements for storage of spent fuel, including centralized sites, would assist countries utilizing a once-through cycle by relieving pressure on national storage capacity. Such arrangements, implemented under IAEA safeguards, could have the following nonproliferation benefits:

- Effective safeguards could more easily be ensured with fewer resources.

- The impetus for reprocessing could be reduced by providing additional storage capacity.

- The proliferation risk of leaving spent fuel under national control for long periods would be reduced.

Associated with such cooperative arrangements would be the establishment of fuel transport links. Since fuel must eventually be transported from reactor sites in any case, cooperative fuel-storage arrangements should be carefully implemented to minimize the proliferation risk associated with transport.

3. Cooperative Arrangements for Supply of Enrichment Services. Reducing the need for nationally controlled enrichment facilities, the most vulnerable part of the once-through system, would require that the existing capabilities be reliably available at fair prices. New facilities might be established as cooperative ventures under effective multinational control, taking care to avoid diffusion of sensitive enrichment technology.

Other Once-Through Systems -- Another commercially deployed once-through system is the Canadian Deuterium Uranium (CANDU) heavy-water reactor. This reactor has three features that make it somewhat different from the light-water reactor from the point of view of proliferation resistance: (1) Its fuel is natural uranium; therefore, there is no need for enrichment services; (2) as its moderator and coolant, it uses heavy water, a material that can be used in plutonium production reactors fueled by natural uranium; (3) it uses on-line, rather than batch, refueling, and is therefore more difficult to safeguard. The export of heavy-water production facilities is subject to multinationally agreed-upon guidelines for the application of safeguards, but the effectiveness of techniques for safeguarding such facilities remains to be established. The use of natural uranium results in more plutonium production in a heavy-water reactor than in a comparable light-water reactor (500 kg versus 250 kg per GW-year of operation), although the concentration per kilogram of fuel is lower.

High-temperature gas-cooled reactors are also operating as demonstration power plants. For example, the high-temperature gas-cooled reactor designed in the United States and the pebble-bed designs being developed in the Federal Republic of Germany use highly enriched uranium, mixed with thorium, on a once-through cycle. A reduction in their proliferation potential appears possible through the use of low-enriched fresh fuel (less than 20 percent U-235) and through very high burnup. In high-temperature gas-cooled fuel cycles that use low-enriched uranium and no thorium, fissile plutonium discharged annually would be about one third that of a light-water reactor of comparable size. There are other types of gas-cooled reactors (MAGNOX) using natural uranium fuels commercially deployed in a number of countries, particularly the United Kingdom and France; these reactors have plutonium production comparable to that of a natural uranium/heavy-water reactor.

Proliferation Resistance of Closed Fuel Cycles

Fuel cycles involving the reprocessing and recycle of uranium, plutonium, and thorium fuels in either thermal (e.g., light-water, heavy-water, light-water breeder or high-temperature gas-cooled) reactors or fast (breeder) reactors are not presently fully deployed commercially. However, substantial research, development, and demonstration activities are under way in many countries, and commercial deployments before the next century are planned in Japan and several European nations. The countries that are reprocessing or contracting for reprocessing of spent fuel are doing so to obtain plutonium for thermal recycle and fast breeder reactor research, development, and demonstration and/or for waste-management purposes. Waste management is the stated reason for reprocessing in several countries in which there is a linkage between closure of the nuclear fuel cycle and licensing of future nuclear plants. Although the legal implications vary, at least six countries (Austria, Sweden, the Federal Republic of Germany, Belgium, Japan, and Switzerland) have legislation which inhibits the licensing of future plants until progress is made toward safe, permanent waste disposal. In a number of instances, progress in this direction has been construed to mean reprocessing.

More than ten non-nuclear-weapons states have operated some type of spent-fuel reprocessing facility, at least on a laboratory scale. Although some of these facilities have been shut down and in some cases dismantled, the ability to separate plutonium from spent fuel is not uncommon in the world. Belgium, Brazil, the United Kingdom, France, India, Italy, and Japan plan to have commercial facilities for processing oxide fuel from light-water reactors by 2000. The commercial facility planned by the Federal Republic of Germany was recently deferred. Outside the centrally planned-economy areas, Argentina is the only country with announced plans for commercial reprocessing before 2000. By about 1985, Spain plans to make a decision on commercial reprocessing. With the possible exception of Brazil, all countries with announced plans for commercial reprocessing facilities before 2000 have already operated either laboratory or pilot-scale reprocessing facilities.

Of the 660 gigawatts of nuclear power-generating capacity projected by 2000 for the world outside the centrally planned-economy areas, excluding the United States, approximately 90 percent will probably be supplied by light-water reactors. These reactors can operate on fuel from mixed oxides of uranium and plutonium, but plans are indefinite for recycle in most of the countries which plan to have light-water reactors. Nonetheless, substantial testing and research activities related to fuel from mixed oxides of uranium and plutonium are under way in several countries, among them, Belgium, Italy, and Switzerland. Belgium, Italy, Japan, Switzerland, and the Federal Republic of Germany have indicated intentions to preserve the option of recycle in thermal reactors. Japan has an advanced reactor operating on plutonium fuel now and had intended to realize the initial commercialization of plutonium recycle in their light-water reactors by the mid- or late 1980's. This emerging picture of possible imminent deployment of recycle in some nations with advanced nuclear power programs is the basis for assessing the proliferation resistance of the reference recycle system.

There is also a variation in the institutional context in which these programs are situated. Some, for example, are not subject to IAEA safeguards, and some assume a complete in-country fuel cycle while others do not. However, the institutional regime is likely to evolve as these development programs evolve. In the following assessments, it will be assumed that the recycle and breeder fuel-cycle systems are deployed within the context of the current institutional regime.

Recycle Systems -- A system based on conventional PUREX reprocessing of spent fuel from light-water reactors was chosen as the reference recycle system for this assessment. An examination of the potential pathways to weapons through abuse of this cycle found three important technical vulnerabilities in addition to those present in the reference once-through light-water reactor system. The first is that material in transit and in national facilities would be in weapons-usable form and in forms that are relatively easy to exploit for weapons purposes. The second is that the relatively large amounts of plutonium-bearing materials in reprocessing and refabrication facilities, often in bulk form, would be difficult to safeguard effectively. The third is that fuel-reprocessing facilities and facilities for fabricating mixed plutonium/uranium oxide fuel would provide training and experience in plutonium extraction and handling wherever they are deployed. These facilities may be attractive as starting points for a nuclear weapons program or provide an enhanced capability for an independent military program. Moreover, there are potentially attractive proliferation paths for sub-national groups in recycle systems through the seizure of fresh recycle fuel or fresh fuel feedstocks in bulk form.

The most significant proliferation activities that might be used to exploit these vulnerabilities include:

1. Out-of-System Conversion of Already Separated Plutonium. To convert plutonium oxide or plutonium nitrate to plutonium metal requires out-of-system facilities. (Conversion to metal is not now in-system to any civilian nuclear power system; however, it is involved in certain civilian research and development activities.) Converting already separated plutonium in bulk storage or transport to weapons-usable form does not involve unusual procedures and would not present significant difficulties to most nations with trained or experienced personnel. Under these circumstances, preparation activities for tens of metal weapons per year could be completed within a few months at a cost of a few million dollars and could be difficult to detect. Fewer resources would be required if only one or two weapons were required or if oxides were used directly. The period from the time material was first removed from the fuel cycle until significant quantities of weapons-usable material were produced could be a matter of a few days or weeks. A subnational group would find converting plutonium nitrate to metal a more difficult and time-consuming job than converting it to solid oxide.

2. Out-of-System Conversion of Mixed-Oxide Feedstocks or Fuel Assemblies. Out-of-system facilities are also required to convert mixed uranium/plutonium oxide feedstocks, that is, powder or pellets, to plutonium metal. (Again, conversion to metal is not now an in-system activity for any civilian nuclear power system.) Mixed uranium/plutonium oxide powder mixed at the fabrication plant from pure plutonium oxide and uranium oxide would normally contain about 5 percent plutonium oxide for recycle fuels. If these oxides were mixed at the reprocessing plant instead of at the fabrication plant, then feedstock to the head end of the mixed uranium/plutonium oxide fuel-fabrication plant could range up to 10 or 15 percent plutonium oxide. The steps necessary to separate plutonium from uranium are not formidable. After the acquisition of appropriate facilities, which would require up to twice as long as for bulk plutonium oxide and a few million dollars to design, construct, and test, material for tens of weapons per year could be separated in a few months. However, significant quantities of weapons-usable material could be produced in approximately one week.

The proliferation activities required to obtain weapons-usable plutonium from fabricated mixed uranium/plutonium oxide fuel assemblies would be essentially the same, with the addition of a simple sawing operation.

3. Out-of-System Reprocessing of Spent Fuel. The main activities would be the design, construction, and testing of an out-of-system plant capable of hot radioactive reprocessing. These activities would require competent personnel one to two years and a few tens of millions of dollars for a program to build tens of metal weapons per year. The time between removal of spent fuel from the fuel cycle until significant quantities of weapons-usable material are produced can be a matter of a few weeks. Although the handling of radioactive spent fuel is inherently more difficult than that of the fresh fuel or feedstock material discussed above, especially for subnational groups, it is within the means of many nations.

These vulnerabilities and an evolving situation in which many countries, intending to recycle, have acquired preliminary experience with this technology point to an urgent need for strengthened technical and institutional controls. Accordingly, a wide range of potential technical, safeguards, and institutional improvements have been examined.

Improvements to the Recycle System -- Technical measures for improving the proliferation resistance of recycle systems would include coprocessing, co-conversion and introduction of radiation barriers.

Coprocessing to eliminate directly weapons-usable material from the fuel cycle would significantly reduce the vulnerability to theft. While the operator of the plant could easily modify the plant to produce a pure plutonium stream, the detection by IAEA safeguards of pure plutonium anywhere in the cycle could provide evidence of a violation, were there an appropriate agreement.

Co-conversion by blending the originally separated uranium and plutonium nitrates would eliminate separated plutonium oxide from the cycles and provide protection against theft similar to that for coprocessing.

The introduction of a radiation barrier has been considered in order to provide a level of protection to plutonium fuels similar in nature to that of spent fuel. Radiation levels on the order of tens to a hundred rems per hour at 1 meter have been judged sufficient to force a nation seeking to produce tens of weapons to conduct processing in an out-of-system facility similar to a spent-fuel reprocessing facility. This level of protection would correspond to that of spent fuel 100 to 150 years after discharge from the reactor. This radiation barrier could be introduced in a number of ways: spiking, in which a highly radioactive material such as Co-60 could be introduced at certain points in the reprocessing, conversion, or refabrication plants; partial decontamination, in which the reprocessing plant is designed so that a portion of the fission products always remains associated with the plutonium (since use is made of the relatively short-lived fission products in the spent fuel, this measure can be effective only for the processing of spent fuel discharged recently from the reactor); and pre-irradiation, in which the mixed uranium/plutonium oxide fuel element is irradiated before shipment to the reactor site. None of these measures would seem to have much effectiveness against abrupt diversion at the national level in those realizations where a country has a reprocessing plant deployed, since it appears that the plant could be readily modified to produce plutonium in a pure form. Partial decontamination may be somewhat more effective than spiking in this respect, since it would be easy to stop adding the spikant. However, a radiation barrier could delay weapons production by many months if out-of-system facilities had to be built. All of these measures except pre-irradiation may have some advantages with regard to protection against covert diversion by nations, and all of them would provide added protection against theft by the less sophisticated subnational groups. These advantages, however, would have to be evaluated in the light of the technical problems associated with them and of economic, environmental, and safeguards disadvantages. Other concepts involve various engineering design features, for example, to reduce accessibility to plutonium and, more speculatively, to incorporate active measures to deny the use of materials or facilities. None of these concepts appear to be more effective than those concepts already described in addressing the fundamental proliferation vulnerability presented by national control of reprocessing and refabrication facilities. Moreover, since many of these measures involve plant design, they cannot easily be retrofitted to existing facilities.

The IAEA has concluded that current material accountability is not adequate for the large reprocessing plants which are planned to come on line in the next few decades. Increased reliance will have to be placed on containment and surveillance measures, and the IAEA believes that there are good prospects that its goals can be met when specific new measures have been developed for materials accounting as well as containment and surveillance. It appears, however, that these measures may be expensive to implement for the IAEA and the operator, and will require a politically significant level of intrusiveness into facility operations. Moreover, until there is a large-scale demonstration, uncertainties about the technical effectiveness of these measures will remain. Designing new reprocessing and refabrication plants to enhance the application of safeguards is both desirable and important, and can be facilitated through the design review procedure to be exercised by EURATOM and IAEA. The introduction of a radiation barrier would introduce serious difficulties in applying material accounting methods. In addition, inspection and verification would be difficult to carry out in plants in which the highly radioactive environment of the front end was extended throughout the reprocessing facility. And many of the new safeguards measures and procedures under research and development in the U.S. would be rendered inoperative and others, less effective.

Adequate physical security measures are required to prevent diversion by subnational groups. Some of the technical (e.g., coprocessing) and institutional (e.g., colocation) measures considered may effectively contribute to reducing this threat, but their costs and benefits have not been fully evaluated.

One route to reduce the risk of abuse of the fuel-cycle facilities is the development of internationally agreed-upon institutional measures. Basically, the proposals relate to placing sensitive materials and facilities under some form of international control.

One measure would be the construction and operation of only a limited number of large, nationally managed reprocessing plants which, apart from reprocessing fuel for domestic customers, would also provide a reliable reprocessing service on a competitive basis for customers in other countries. This measure has the advantage of limiting the sensitive fuel-cycle facilities to a few sites and nations. Such plants would incorporate advanced instrumentation, and designs, and other features to facilitate safeguarding. The deployment of the fuel cycle in other countries would be limited to the more resistant elements of the cycle--namely, the reactor and the uranium fuel-fabrication facility.

Several measures for multinational participation in nuclear fuel-cycle facilities have advantages and disadvantages like those already discussed, but there are additional considerations. Depending upon their characteristics, these measures may be coupled with stronger "political" barriers against the host nation's abrogating safeguards and with increased assurances that none of the participating nations had diverted material without detection. However, such multinational ventures might facilitate the spread of sensitive technology. While colocation of the plants for reprocessing and for the fabrication of mixed uranium/plutonium oxides might make the fuel cycle less vulnerable to subnational theft by reducing transport requirements, it would have little or no impact on proliferation at the national level except to the extent that safeguards measures may be more effective at an integrated site and indirectly contribute to a trend toward reliance on fewer, larger facilities. This trend may result in fewer nations possessing sensitive facilities.

Plutonium management schemes which would provide for some form of international control over stocks of separated plutonium have been proposed. The advantages of such proposals are that excess plutonium would be removed from national control and its return would be subject to strict release criteria and international oversight.

The results of these assessments are summarized in Table 8.

It has also been suggested that special nuclear materials can be "downgraded" to inhibit their use in nuclear weapons by enhancing the emission rate of alpha particles, gamma rays, neutrons, or heat. Judgments about the use of special nuclear materials must depend on a detailed knowledge of nuclear weapons design and testing. Although producing such details would conflict with U.S. nonproliferation policies, three conclusions can be drawn:

- U-233 is, in principle, as weapons-usable as U-235 or plutonium.
- Increasing the emission rate of neutrons in U-233, U-235, or plutonium would not preclude their use in weapons. This conclusion also applies to the presence of Pu-238.
- The presence of U-232 in U-233 does not provide effective protection against misuse.

What is required is the progressive introduction of features that will substantially improve proliferation resistance in order that, if recycle

TABLE 8. EVALUATION OF MEASURES TO IMPROVE PROLIFERATION RESISTANCE OF CLOSED FUEL CYCLES

Measure	Proliferation Resistance Using Unsafeguarded Facilities or Materials	Proliferation Resistance Using Safeguarded Facilities or Materials	Effect on IAEA Safeguards	Proliferation Resistance to Subnational Threat
Co-conversion	Little or no change		Little or none	Increased
Coprocessing	Increased[1]	Increased[1]	Little or none	Increased
Pre-irradiation	Increased[2]	Increased[2]	Little or none	Increased
Spiking	Increased[2]	Increased[2]	Degraded	Increased
Partial processing	Increased[1]	Increased[1]	Degraded	Increased
Passive measures and physical barriers	Little or no change	Increased	Enhanced	Increased
Active-use denial	Not applicable	Increased	Little or none	Increased
Fuel-service centers (including colocation)	Little or no change	Increased	Enhanced	Increased
Fuel-management and transport control (including storage/ transport as mixed oxide or mixed-oxide assemblies)	Increased[2]	Increased[2]	Little or none	Increased

[1] Depends on how easily the facility can be modified to produce pure plutonium stream.
[2] May not be very effective where reprocessing plant is deployed.

were introduced into widespread use, it should be possible to avoid large differences in proliferation resistance compared to that of once-through systems. Until these measures are developed, however, recycle would introduce the proliferation vulnerabilities already described.

Since light-water reactors are already widely deployed, it is possible that the recycle system could also become widely deployed. However, the effectiveness of combinations of technical and institutional measures to improve the proliferation resistance of the recycle system, as well as their feasibility and acceptability to nations considering the use of closed cycles, is difficult to predict in advance of their actual negotiation and implementation.

Fast Breeder Systems -- Fast breeder nuclear power systems closely resemble recycle nuclear power systems in the sense that spent-fuel reprocessing and recycle of fissile material are intrinsic features of the fuel cycles. Both systems require the same types of ancillary facilities for temporary spent-fuel storage, reprocessing, fuel fabrication, waste management, and transportation. The major differences between breeder and recycle systems lie in the greater flows at higher concentrations of plutonium in the fast breeder system and in the reactors themselves. Current fast breeder reactor designs would produce an excess of plutonium and could lead to the evolution of a nuclear economy which relies almost exclusively on plutonium for the fissile content of the fuel, whereas an economy based on recycle reactors must continue to rely heavily on uranium.

At present, no fully commercialized fast breeder reactors are deployed. Rather, fast breeder programs are under way in a small number of countries--most notably, the United Kingdom, France, Japan, the USSR, United States, and the Federal Republic of Germany--and are at various stages of development ranging from pilot and demonstration reactors to small research and fuel-cycle facilities to support fast breeder system research and development. There is also a variation in the institutional context in which these programs are situated. Some, for example, are not subject to IAEA safeguards, and some envisage a complete in-country fuel cycle while others do not.

The major impetus for reprocessing spent fuel at the present time, in addition to the management of spent fuel, appears to be for fast breeder reactors rather than for thermal recycle. Processing of spent fuel is expected to build inventories of plutonium compounds which can be used to start up fast breeder reactors during the transition period to fast breeder reactor equilibrium. Plutonium for start-up and refueling of planned breeders in the United Kingdom and France will come from gas-cooled reactor (MAGNOX) spent fuel and, in France, from light-water reactor spent fuel as well. French plans call for a 100 t per year plant to be commercial by about 1990, but this would serve only about 3 GW of fast breeder reactor capacity. The cumulative plutonium production in thermal-reactor spent fuel in Japan and the Federal Republic of Germany, as well as the reprocessing capacity to separate that plutonium, far exceeds their pre-2000 fast breeder needs. However, if Japan's plans for a rapid transition to an all-breeder economy by 2025 materialize, this excess reprocessing capacity, and perhaps more, would be needed to meet those plans unless alternative sources of plutonium are found. A number of other countries are conducting research in fast-reactor fuel reprocessing. Aside from several European countries and Japan, India is apparently the only country with near-term reprocessing plans directed toward future support of fast breeder reactor development. India plans to develop plutonium/thorium fast breeder reactors.

Most countries' plans for nuclear power through 2000 call for the deployment of light-water reactors. In 2000, less than 5 percent of the installed nuclear power capacity outside the centrally planned-economy areas is expected to be fast breeder reactors. Most of this capacity will be in France, with some possibly in the United Kingdom, Japan, and the Federal Republic of Germany, and perhaps Italy and India. Belgium, Italy, and the Netherlands have financial interests in the French and German fast breeder reactor programs. It is against this background of fast breeder reactor plans that the proliferation resistance of a reference fast breeder reactor system is assessed.

Reference Fast Breeder Fuel Cycle: Liquid-Metal Fast Breeder Reactor

The reference fast breeder system is the liquid-metal fast breeder reactor. The facilities and materials appearing in the liquid-metal fast breeder reactor fuel cycle are analogous to those of the reference recycle system. The most important proliferation-related features of either fuel cycle stem from the large-scale processing operations and commerce in plutonium-bearing materials. In a typical 1 GW liquid-metal fast breeder reactor, for example, the total plutonium inventory in the core is about 5,000 to 6,000 kg, and yearly, approximately 2,000 kg of plutonium is introduced and about 10 percent more is withdrawn. For each such reactor, at least 2,500 kg (probably several times more) plutonium would be in process, storage, or transport at any given time; by comparison, about 250 kg of plutonium is discharged in spent fuel from 1 GW-year's operation of a once-through light-water reactor.

Since facilities and materials are similar to those of the recycle system, the liquid-metal fast breeder reactor system presents, within a given national context and deployment configuration, essentially the same opportunities for facility modification or for diversion of materials for out-of-system conversion. With the exceptions noted below, the associated proliferation features, activities, and improvements have been discussed in connection with the reference recycle system.

A significant difference between the liquid-metal fast breeder reactor's uranium/plutonium mixed-oxide fuel and recycle mixed-oxide fuel materials lies in the fact that liquid-metal fast breeder reactor fuels would have plutonium concentrations of 15 to 25 percent, which are considered to be weapons-usable, whereas recycle fuels would contain only 4 to 6 percent plutonium. Consequently, it is theoretically possible that a nuclear device could be made directly from fresh liquid-metal fast breeder reactor fuel without need for chemical separation; in recycle systems, plutonium oxide itself is the only material that is directly weapons-usable. This feature would increase the vulnerability of the liquid-metal fast breeder reactor system to subnational proliferation threats, particularly in countries deploying only the reactors. It would also increase vulnerability to national threats, although most nations would probably employ out-of-system facilities to recover plutonium metal.

Otherwise, the high plutonium concentrations and other minor technical differences between breeder and recycle fuels would have a slight impact on out-of-system proliferation activities. The higher plutonium concentrations, for example, would permit somewhat smaller facilities and less feed material to recover plutonium at a given rate. Spent fuel from a liquid-metal fast breeder reactor core is accompanied by higher radiation fields than spent light-water reactor fuel, while that from the blanket would be less radioactive. Both core and blanket spent fuel, however, would still require remote processing. Depending on the point of diversion, out-of-system facilities for processing spent liquid-metal fast breeder reactor fuel might have to provide for removal of sodium or other liquid-metal coolant from the assemblies. While these differences are perhaps worth noting, their impact on the proliferation resistance of the liquid-metal fast breeder reactor system is marginal.

Further proliferation implications of fast breeder systems are related to the dynamics of system development. Whereas recycle systems using light-water reactors could be deployed relatively soon, liquid-metal fast breeder reactors cannot be deployed commercially on a major scale for at least two decades and possibly much longer. Changes in the international institutional framework within which nuclear power systems are operated will clearly evolve during the period of development. However, current reprocessing facilities and plans for their expansion are largely motivated by anticipated fast breeder needs. In other words, the proliferation vulnerabilities of fast breeder systems appear long before actual reactor deployment and must be accommodated in current efforts to establish a satisfactory nonproliferation regime.

Research Reactors and Critical Facilities

Although the above discussion of proliferation resistance has centered on nuclear power plants, research reactors are also a potential source of weapons-usable material.

Research reactors are typically used to study the irradiation behavior of materials of interest in nuclear engineering; to produce radionuclides for medicine, industry, and agriculture; and to promote basic research and teaching. The proliferation implications of research reactors arise from their widespread deployment and their use of potentially significant amounts of highly enriched uranium as fresh fuel (typical annual fuel requirements are 0.6, 8.4, and 121 kg of highly enriched uranium for reactors with thermal power levels of 1, 10, and 100 MW, respectively), while others using natural or low-enriched uranium may produce significant amounts of plutonium in the irradiated fuel.

Critical facilities are very low-power experimental reactors (usually below 10 kw) which operate at low neutron-flux levels (e.g., 10^8 neutrons/cm^2/sec) with no appreciable fuel burnup and little induced radioactivity in the fuel and other core components. They are used as simulators, to provide experimental confirmation of design calculations relating to various reactor characteristics, such as critical mass, kinetics and control, and reactivity coefficients. Critical facilities for use in fast breeder reactor research may use highly enriched uranium or plutonium in various forms, including metal, oxide, and alloys. Since the fuel has little burnup or induced radioactivity, it is usually loaned or leased from the supplier to the operator. Critical facilities for breeder research use plutonium or highly enriched uranium in quantities ranging from a few kilograms to a few metric tons.

France, the United States, the Federal Republic of Germany, and the IAEA have been engaged in studies aimed at preserving the scientific and research advantages of research reactors fueled with highly enriched uranium while reducing their proliferation potential. Some research work suggests that most research reactors can be adapted to less highly enriched uranium (from 20 to 40 percent U-235 with today's technology) with little effect on overall reactor performance. This result is accomplished by increasing the total amount of uranium present in the fuel elements. That is, the amount of U-235 is diluted in larger amounts of U-238. One of the approaches pursued by France is to develop a replacement fuel for its reactors which is 7 percent-enriched uranium. Implementation of such technical measures would substantially diminish the proliferation risk associated with highly enriched uranium research reactors and would permit the possibility of reduced physical security requirements to counter the threat of subnational groups. Operators should find these measures attractive, since relatively free access is important for effective research at such reactors.

Improved international safeguards and a more universal commitment to full-scope safeguards as discussed for nuclear power plants would also be important for reducing the proliferation risks of research reactors. Safeguards procedures need to accommodate the necessary flexibility of research reactor operations.

A longer-term goal that would increase the proliferation resistance of research reactors would be the achievement of a mean level of enrichment of 3 to 20 percent for widely deployed research reactors. Such a level of enrichment would seem to put the greatest distance between research reactors and the problems of highly enriched uranium on the one hand, and of plutonium in spent fuel on the other. Existing technologies can make significant improvements toward this goal.

Natural uranium-fueled research reactors can produce plutonium at the approximate rate of 1 gram per megawatt day (thermal-energy output) of operation. The amount of plutonium produced is reduced as the enrichment level is increased. The proliferation resistance of spent fuel from such reactors would be similar to that of spent fuel from nuclear power plants with the following exceptions:

- Radioactivity from research reactor spent fuel can be one fiftieth that of spent fuel from a commercial power reactor, so problems of shielding personnel from the radiation may be easier to solve.

- Several different chemical forms are typically used for research fuel elements, so steps involved in chemical reprocessing would be altered.

The development, demonstration, and implementation of these new fuels should be pursued.

Major Conclusions

The assessments of the proliferation resistance of various fuel cycles involved the simultaneous consideration of many variables, many of them unquantifiable, and an awareness of the evolutionary nature of fuel cycles and of nuclear programs in different countries. Hence, these assessments could not be purely technical in nature, nor is there a proliferation-resistance "index" that can be applied.

The most important conclusions of the NASAP proliferation-resistance assessments are:

- All fuel cycles would entail some proliferation risks; there is no technical "fix." Nevertheless, the light-water reactor fuel cycle with spent fuel discharged to interim storage does not involve weapons-usable material in any part of the fuel cycle and is a more proliferation-resistant nuclear power fuel cycle than other fuel cycles which involve work with highly enriched uranium or pure plutonium.

- There would also be substantial differences in proliferation resistance among the fuel cycles if they were to be deployed in non-nuclear-weapons states. Some of these differences would be technical in nature (e.g., no reprocessing in once-through fuel cycles as compared with reprocessing in closed fuel cycles), and some would result from institutional arrangements (e.g., the limited deployment of existing international enrichment services).

- Technical and institutional proliferation-resistance features can help. With the progressive introduction of such features, the differences in the relative proliferation risks of alternative fuel cycles might be much smaller by the time the fuel cycles eventually came into widespread use. The differences would remain until the necessary measures had been retrofitted.

- The vulnerability to threats by subnational groups varies between fuel cycles. Recycle systems would be vulnerable to a wide range of threats, whereas current once-through fuel cycles are susceptible to only the most sophisticated threats.

Conclusions about the current deployments are followed by those about near-term decisions that affect proliferation risks with regard to improvements in the current regime and with regard to fuel-cycle choices. Those that would affect longer-term decisions will be discussed later in this chapter.

The Existing Situation -- Today's mixture of nuclear power reactors and technologies has its own set of proliferation characteristics, which can be summarized as follows.

- Given the current relative availability of detailed process information and trained personnel, the isotopic barrier to the production of weapons-usable material from fresh fuel appears greater than the chemical or radiation barrier to the production of weapons-usable material from spent fuel. But this difference could change with time, particularly if enrichment facilities become widespread.

- The light-water reactor fuel cycle with spent fuel discharged to storage has relatively high barriers to proliferation at this time, but it does have vulnerabilities. The two greatest proliferation risks would arise:

  - if the potential proliferator had an enrichment plant, or, since enrichment services are now supplied by only a few nations,

  - if the potential proliferator had an out-of-system reprocessing facility to recover weapons-usable plutonium from spent fuel.

- Facilities for closed fuel cycles potentially increase proliferation risk because plutonium would appear in weapons-usable form and in forms that are relatively easy to exploit for weapons purposes. Without deployment constraints and suitable institutional arrangements, plutonium would appear in substantial and widespread inventories in bulk forms, which are inherently difficult to safeguard.

- Fresh-fuel inventories for many research reactors are a potential proliferation risk because they contain chemically separable highly enriched uranium suitable for fabrication in nuclear weapons.

- All enrichment technologies can be used to produce highly enriched uranium. They differ significantly, however, in the difficulty, cost, time, and visibility of modifying commercial plants or in the time required to produce highly enriched uranium in them or in their use in dedicated facilities. Of currently deployed technologies, the proliferation risks of gas-centrifuge processes appear greater than those of gaseous diffusion.

<u>Near-Term Considerations</u> -- Although the current regime applied to once-through systems (which do not include national reprocessing facilities) has contributed to limiting proliferation, there are trends toward increasing proliferation risks. Planning to strengthen the current regime against proliferation risks must recognize the following five findings about alternative fuel cycles:

- Continued reliance on light-water reactors may call for expanded enrichment capacity. While the development and demonstration of advanced isotopic separation technologies may discourage the spread of centrifuge enrichment technology that now appears relatively easier to utilize for production of highly enriched uranium, their future deployment should be limited.

- Under any realistic deployment schedule for the foreseeable future, the amount of plutonium and the rate of its increase is not likely to differ very much among any of the various fuel cycles. However, these fuel cycles differ greatly in the form in which plutonium appears and in the extent to which it can be controlled and safeguarded. The recycle system involves the production and processing of separated plutonium in reprocessing and fabrication facilities, and its presence in storage and transit.

- While these same difficulties apply in principle to fast breeder systems, major fast-breeder programs are expected to remain confined for several decades to a few nations. The spread of breeder research and development activities, however, continues to be an area of concern.

- A reprocessing technique that cannot be used directly or cannot be modified readily to produce separated plutonium has not been demonstrated. Prospective techniques like pyrometallurgy have been provisionally identified on the basis of preliminary analysis as possibly offering greater diversion resistance for reprocessing fast-breeder fuels.

- No nuclear fuel cycle which can be commercially deployed in the next few decades would offer more proliferation resistance than that associated with realizations of the once-through light-water reactor fuel cycle, in which spent fuel is safeguarded in interim storage facilities and enrichment services are provided by the existing suppliers. Meanwhile, pressures may grow to develop independent, alternative, less proliferation-resistant fuel cycles.

The following measures, which would respond to these proliferation concerns as well as to legitimate desires for security of supply, have been identified:

- Wider acceptance of international safeguards on all civilian nuclear activities (full-scope safeguards) and of the Non-Proliferation Treaty and other treaties (e.g., Treaty of Tlatelolco).

- Application of improved safeguards measures already shown to be technically feasible, in particular, measures to provide timely warning of overt abuse or covert diversion of spent fuel either upon discharge from the reactor or in storage. (Measures could include systems with remote, near-real-time surveillance capability and more frequent inspections. CANDU, the Canadian heavy-water reactor, requires specialized verification systems for on-line refueling.)

- Development of effective safeguards systems, now in the conceptual stage, for enrichment facilities, which themselves should be designed to facilitate safeguards.

- Continued reliance on existing suppliers of enrichment services including ventures under international or multinational auspices. Enrichment research and development should not be undertaken in the absence of a clear demonstration of need.

- Adherence to export controls and the present suppliers' guidelines contained in the IAEA document INFCIRC/254.

- Cooperative arrangements to ensure adequate spent-fuel storage, to provide the options for interim storage, and to leave open the decision regarding recovery of fissile materials or ultimate disposal.

(Commitments for such arrangements will be needed by the early- to mid-1980's, and decisions will be needed soon regardless of decisions about reprocessing.)

- Development of mechanisms for the international management or supervision of stocks of separated plutonium.
- Arrangements to minimize or avoid the storage or transport of undiluted plutonium.
- Cooperative arrangements to share the use of existing large research reactors and critical facilities, and similarly, to provide opportunities for research and development on breeder reactors under international or multinational auspices.
- Limitations on the use of materials in research reactors to enrichment levels which minimize the presence of weapons-usable material.

2.1.2 Resource Utilization

Although no commercially deployed fuel cycle is more proliferation-resistant than the once-through cycle, it utilizes resources less efficiently than other concepts (e.g., recycle) because fissile uranium and plutonium are left in the spent fuel. Some nations, including the United States, had planned to recycle these materials and have instituted major development programs for reactors, such as the fast breeder, that depend upon recycle to greatly increase the energy that can be generated from uranium resources. These programs are being pursued in many countries to avoid resource shortages. Thus, it is important to examine uranium supply and demand relationships and assess the significance of trends on deployment of new and improved technologies. Moreover, enrichment and resources such as heavy water and thorium are also potential constraints and need to be addressed.

This section addresses present and future resource issues from both domestic and worldwide perspectives. Uranium supply and demand have been considered in detail, while other resources have been treated less exhaustively.

The size and reliability of uranium resource estimates pose problems for energy planners. Various resource estimates have been made by the Department of Energy and predecessor agencies. The Nuclear Regulatory Commission; the Ford Foundation/Mitre Corporation report, Nuclear Power: Issues and Choices; and the Uranium Resource Subpanel to the Committee on Nuclear and Alternative Energy Systems of the National Academy of Sciences did not make their own estimates, but commented on estimates by the Atomic Energy Commission and the Energy Resource Development Administration, which are the only comprehensive estimates based on physical evidence. The commenting organizations' projections of uranium availability differ by as much as a factor of two. Contributing to the diversity of thought on the subject of future uranium availability is a lack of distinction between the terms "resources" and "supplies," which often results in an interpretation of resource estimates as supply indicators.[1] Moreover, it cannot be assumed that adequate supplies will be available during a time when estimated reserves or resources equal or exceed the projected cumulative requirements. Equating resources with supplies fails to recognize factors that could constrain the development of uranium supplies. Delineation of new reserves must lead demand by 10 to 15 years for several reasons, to wit: The rate of new discoveries and of delineation of new reserves could be constrained by disincentives for industry to fund exploration and development, inability to identify promising exploration targets, and restricted access to public lands; the rate of net expansion of uranium production capacity could also be a constraint because of disincentives for capital investment, changing regulatory criteria, and lengthening licensing and construction lead times; finally, a shortage of mining labor and declining labor productivity could lead to possible production constraints. Lead times might be shortened, however, and additional uranium might be made available through the development and use of new technologies for exploration and mining, and through increases in uranium price.

The primary source for studies of future uranium supply is the Department of Energy estimates of uranium resources. These are, in fact, the only U.S. uranium estimates developed by systematic evaluation of field data. The

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[1] A resource estimate is not fixed in quantity or time, but rather is continually changing, reflecting past exploration and production, market price, and the state of production technology. Supply is the amount of uranium that is produced and available in a given period of time.

latest estimates and the associated forward cost[1] estimates, published January 1, 1979, are given in Table 9. However, the limitations of the Department of Energy estimates must be recognized, and the figures should not be viewed out of context. In particular, these estimates represent not the totality of the nation's uranium endowment, but only the quantities presently indicated or believed to exist. The estimates for the different resource categories--namely, "reserves" and "probable," "possible," and "speculative" resources--have significantly different degrees of reliability. Equally uncertain is the amount of time necessary to transform a quantity of estimated resources into produced uranium.

The Department of Energy uranium-resource estimates are largely based on surface drilling data from industry sources and detailed geologic studies of favorable and potentially favorable areas. For purposes of this report, these resources have been categorized as (a) high-grade resources, estimated on the basis of forward costs of up to $50 per pound of U_3O_8 (equivalent to a market price of about $100 per pound of U_3O_8), and (b) resources of lower grades that might be produced at higher costs. These lower-grade resources have uranium contents generally of less than about 250 parts per million (ppm). Some of these resources are lower-grade portions of the conventional sandstone high-grade deposits; others are contained in the mill tailings from previous production, and could be produced economically at higher market prices. Other low-grade resources are known to be in different types of geological deposits such as Chattanooga shales (55 to 85 ppm), phosphates (50 to 200 ppm), some coals (25 to 110 ppm), and copper ores (4 to 50 ppm). Even sea water contains about 3 parts per billion of uranium. Although some of the low-grade and by-product uranium resources are very large, as can be seen from Table 10, there is no assurance that they could all be developed into acceptable economic sources of supply. These low-grade resources are considered to be producible only at prices considerably higher

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[1]For purposes of this report, forward costs are the yet-to-be-incurred costs of producing U_3O_8 from a given resource, and include the direct costs of developing and operating a mine and building and operating a uranium mill. They are commonly used to indicate the economic availability of a uranium resource. A forward cost category includes all resources at or below the stated forward cost. Forward costs are not to be confused with price, which includes past costs, cost of money, marketing costs, rate of return, profit, some taxes, etc. For this study, a rough rule of thumb is that price is approximately twice forward cost. Because the forward cost category includes all the resources at or below its stated value, the average price of all the resources being used at any time will depend on the relative amounts of the lower-cost resources included in the production.

TABLE 9. JANUARY 1, 1979, DEPARTMENT OF ENERGY ESTIMATES OF DOMESTIC URANIUM RECOVERABLE RESERVES AND POTENTIAL RESOURCES[1] (Short Tons of U_3O_8)

Forward Cost ($/lb U_3O_8)	Reserves[2]	Potential Resources		
		Probable	Possible	Speculative
≤ $15	290,000	415,000	210,000	75,000
≤ $30	690,000[(3)]	1,005,000	675,000	300,000
≤ $50	920,000[(3)]	1,505,000	1,170,000	550,000

[1]Quantities given for the different forward cost categories are cumulative, not additive; i.e., material in the ≤ $30 category includes that in the ≤ $15 category.

[2]An additional 120,000 short tons have been estimated to be recoverable by the year 2000 on a by-product basis from phosphate rock (100,000 short tons) and copper leach (20,000 short tons) sources.

[3]Estimated ± 15% uncertainty at 90% confidence level for the ≤ $30 reserves, and ± 17% uncertainty at 90% confidence level for the ≤ $50 reserves.

TABLE 10. U.S. LOW-GRADE URANIUM RESOURCES

		Short Tons of U_3O_8
1.	Conventional deposits of $\geq$ 100 ppm associated with high-grade ores (>$50/lb to <$100/lb U_3O_8 forward costs)	461,000
2.	Phosphate by-product uranium	26,000,000
3.	Copper leach by-product uranium	not available
4.	Mill tailings	19,000
5.	Chattanooga shale	5,000,000
6.	Lignite coal ash	30,000
7.	Sea water	5,000,000,000

than today's market price, or as by-products tied to production of a primary product. To date, all domestic low-grade production has come from by-product operations. While there has been little experience on which to base supply estimates, these lower-grade resources do give additional assurances of the long-term availability of uranium, although at considerably higher costs. The potential supply from low-grade resources will probably be limited by economics, regulations, and available manpower.

In order to assess the adequacy of uranium resources to meet the demands of any particular future nuclear generating system, the factors to be considered are the rate of discovery and delineation of new resources, the physical scale of operations (tons of ore mined and milled annually), and the requirements for miners. Two estimates of U.S. supply capability of high-grade resources were used, one by the Department of Energy's Office of Uranium Resource Assessment Operations (which will be referred to as "Resource Assessment" below), the other by the S. M. Stoller Corporation. While these groups used similar techniques to develop the estimates, each used different assumptions for discovery rates, ore grade, and productivity. The Resource Assessment projection is not a supply forecast, but rather an estimate of the maximum feasible production capability which could be obtained from the resources under consideration, given adequate time to develop these resources. The Stoller projection is influenced by expectations of demand as forecast by the 1978 Median Nuclear Growth estimates. As such, the Resource Assessment projection shows a higher peak rate than the Stoller Corporation projection as well as a more rapid decline in annual production past the year 2010. The Resource Assessment projection implies that a maximum annual production capability of around 80,000 to 86,000 short tons of U_3O_8 could be attained from currently identified high-grade resources in the period 2000 to 2010, declining to 30,000 to 50,000 short tons of U_3O_8 per year by 2025. If demand were to be lower than this supply capability through the period to 2010, the decline in production from high-grade resources would be delayed.

Two projections of production capability from low-grade resources were also used in this analysis: (1) a maximum capability, achievable by accelerated development of shale resources and phosphate by-product uranium, estimated by the Office of Resource Assessment Operations; and (2) a more conservative estimate by NASAP based on slower development of shale and a leveling off of phosphate by-product uranium. This Resource Assessment projection suggests that with a vigorous development effort, production of 3,000 short tons of U_3O_8 per year from shale could occur by 2000, and could build up to as much as 35,000 short tons of U_3O_8 per year by 2025, assuming an adequate market demand, adequate price, and resolution of technological and environmental problems. If produced as a by-product of shale-oil production, the recovery of uranium could be economical at today's prices for oil and uranium. One such oil-shale plant, now in the conceptual design stage, would produce 1,200 short tons of U_3O_8 per year, and about 50,000 barrels of oil per day, from 100,000 short tons of shale per day, at an investment cost of about $2 billion. If uranium production from phosphates were accelerated, a level of 7,000 short tons of U_3O_8 per year could be obtained from this source by 2000, and close to 40,000 short tons per year by 2025, assuming a high 7 percent annual growth rate and recovery of uranium from all phosphoric acid operations. Another smaller supply of uranium as a by-product of copper ore refining is projected to reach 1,500 short tons of U_3O_8 per year by 2000 and 3,000 short tons per year by 2025; rework of mill tailings would supply another 1,500 short tons of U_3O_8 per year in 2000, but would be fully reworked before 2025. Thus, the maximum total production capability from all low-grade resources could reach 13,000 short tons of U_3O_8 per year in 2000 and 78,000 short tons per year by 2025.

The NASAP projection of uranium from low-grade resources, indicates annual production of 7,000 short tons of U_3O_8 in 2000, increasing to 11,000 short tons by 2025; production from shale is projected to begin shortly after 2000 and reach 5,000 short tons of U_3O_8 per year by 2025.

To provide forecasts of total uranium supply, the Resource Assessment estimates of production capabilities from high- and low-grade resources were combined as the maximum supply estimate in Figure 4, ranging from 90,000 short tons of U_3O_8 in 2000 to 125,000 short tons of U_3O_8 in 2025. The more conservative Stoller high-grade projections and the NASAP low-grade projections are also shown. Combined, the lower projections give an annual supply capability of 65,000 short tons of U_3O_8 in 2000 and 90,000 short tons of U_3O_8 in 2025.

Nuclear energy forecasts are at best uncertain, as evidenced by the almost annual change in these forecasts. The reasons for this have been examined elsewhere and do not need restatement here. However, this uncertainty in the size of future markets has been the greatest impediment to investment in exploration and mine development by mining companies. As described in Chapter 1, this assessment has used a range of projections based upon 1978 Department of Energy analyses to cover the range of possible futures. These projections of installed nuclear electrical-generating capacity are described in the appendix to this volume. In 2000, the 1978 Low and Median nuclear-growth estimates approximate the entire range of the 1979 Department

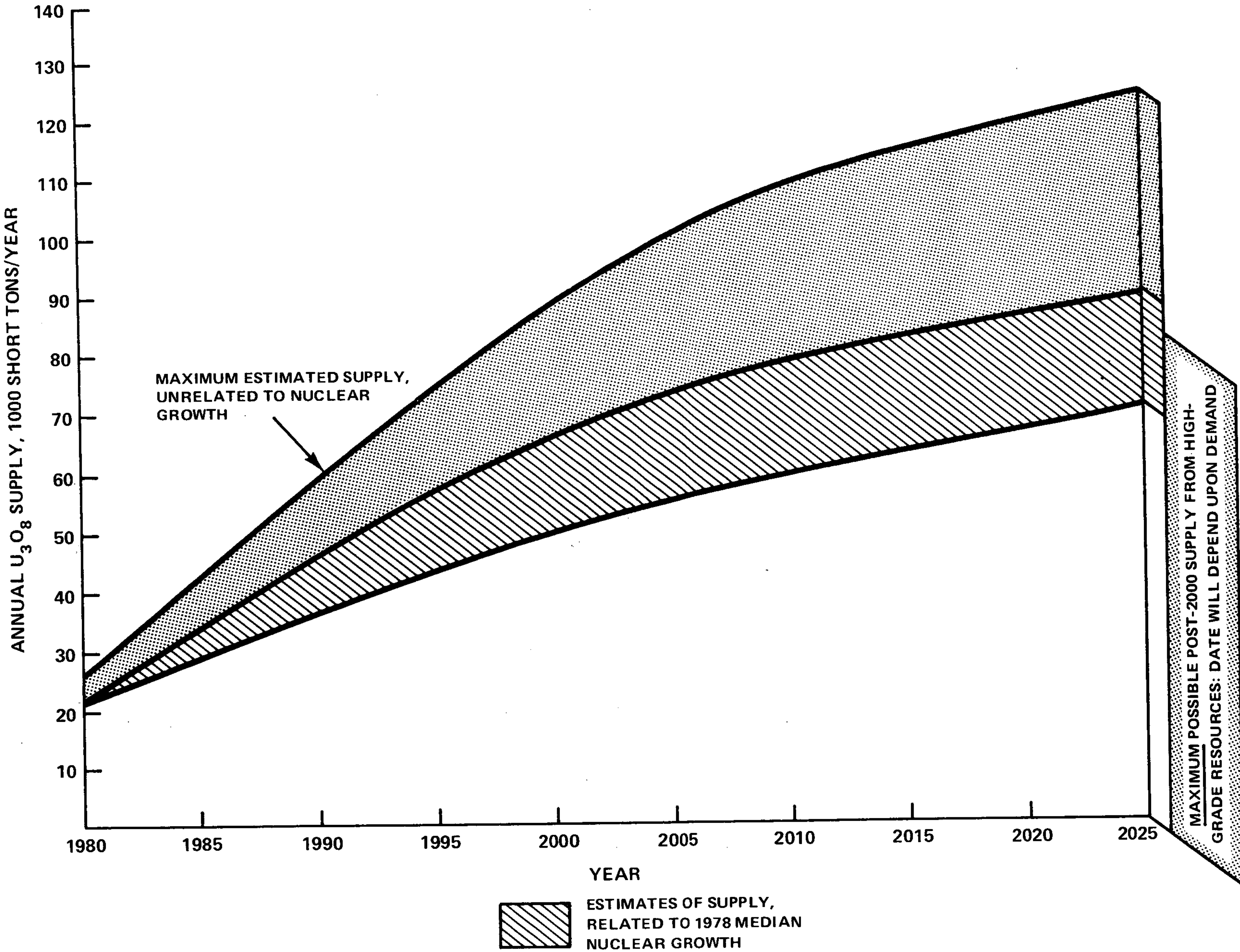

Figure 4. Annual U_3O_8 Supply Capability Estimates

of Energy projections (which assume a continuation of the 12 GW per year growth rate after 1995), as shown below, in which the 1979 Median and High projections are entirely above the range of the 1980 estimates.

		1978 Estimate	1979 Estimate	1980 Estimate
Low Nuclear Growth	-	255 GW	235 GW	150 GW
Median Nuclear Growth	-	325 GW[1]	260 GW	200 GW
High Nuclear Growth	-	395 GW	300 GW	250 GW

The 1978 High nuclear growth projection was submitted by the United States to INFCE, and has been included here to represent an upper level of nuclear growth rate that could result in the post-2000 period from a reversal of current trends and an increasing demand for nuclear power. It is generally only under the latter conditions that new reactor systems and fuel cycles would become of interest. For such systems, the 1978 High and Median growths were used in the assessment.

The uranium requirements associated with these forecasts have been calculated for the U.S., assuming a continuation of the present nuclear system, and are shown in Table 11 and Figure 5 below for the 1978 growth projections. A continuation of the present nuclear system means that the light-water reactor operating on the once-through fuel cycle would remain the only nuclear system in use, that the fuel utilization of this reactor would remain at today's design goals, and that the enrichment plant tails assay would be 0.2 percent U-235.

TABLE 11. ANNUAL U.S. U_3O_8 REQUIREMENTS IN THOUSANDS OF SHORT TONS FOR THE CURRENT LIGHT-WATER REACTOR SYSTEM

	in 1980	in 1990	in 2000	in 2010	in 2025
1978 Low Nuclear Growth	15	32	48	56	62
1978 Median Nuclear Growth	16	37	64	88	121
1978 High Nuclear Growth	17	42	79	119	181

[1]The average of the high and low forecasts used for purposes of description by NASAP.

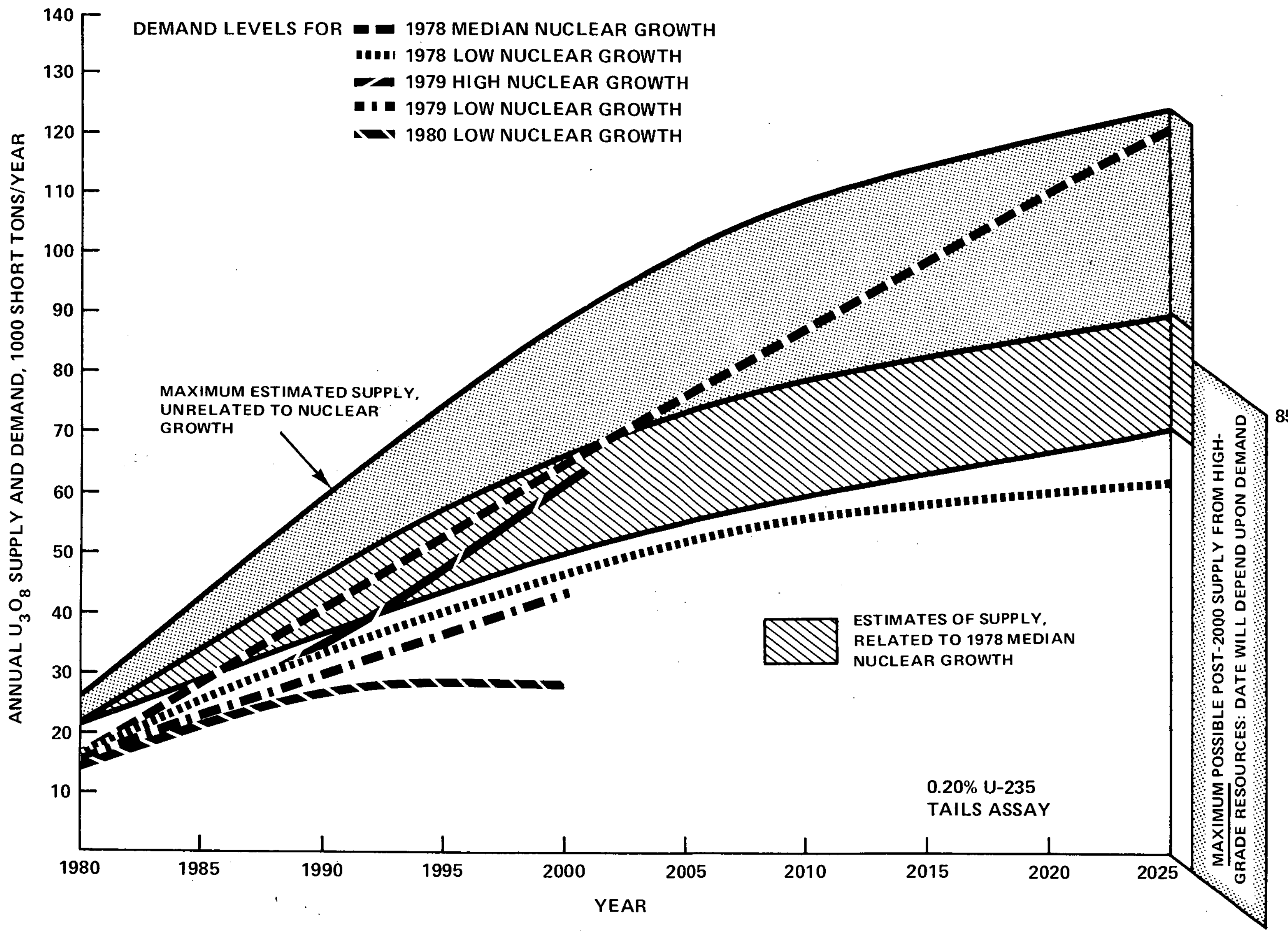

Figure 5. Comparison of U_3O_8 Supply Capability and Demand Using the Current Light-Water Reactor on the Once-Through Fuel Cycle

As a point of reference, 18,500 short tons of U_3O_8 were produced in the United States in 1978 from a production capacity of about 20,000 short tons. Additional committed or planned production capacity could bring the total to about 25,000 short tons of U_3O_8 in 1980 and nearly 40,000 short tons in 1985, according to Department of Energy projections of domestic production possibilities. Other estimates suggest that uranium production-capacity expansion will reach a more modest total of about 28,000 short tons of U_3O_8 in 1985.

The uranium that would be required by the above nuclear growth forecasts (assuming the continued use of the light-water reactor in the once-through cycle at current fuel-utilization efficiency and enrichment plant tails assay of 0.2 percent (U-235) is compared with possible uranium supply capability in Figure 5. The 1978 Median nuclear growth would require the largest estimated supply capability by 2025, (i.e., 85,000 short tons of U_3O_8 from high-grade resources and 36,000 from the low-grade) but less than the maximum capability before that time. Median nuclear growth could be supported through about 2020 by high-grade resources but would require aggressive development of high-grade resources and significant production from low-grade resources thereafter. The uranium demands resulting from the 1978 Median growth, while not impossible to meet, would challenge the capability of the uranium industry. The annual uranium demands resulting from the 1978 Low nuclear growth appear not to be a problem. Since all of the 1980 projections are less than the 1978 Low growth projection, these would also not be expected to create an imbalance.

This assessment has considered the prospects for depending solely on U.S. resources, but uranium is a commodity in international commerce that is both imported and exported by the U.S. Such a condition will likely continue, so that shortfalls in domestic supply might be made up by imports, while, on the other hand, excess production could be exported.

Worldwide U_3O_8 Supply/Demand Relationships

The principal source of data on resources used in this assessment is the report "Uranium Resources, Production, and Demand," December 1977, by the Nuclear Energy Agency (NEA) of the OECD, and the International Atomic Energy

Agency. This report was prepared by the Joint NEA/IAEA Working Party on Uranium Resources from data supplied officially by various countries.[1]

The Department of Energy resource classifications that describe domestic uranium sources can also be used to describe world resources. The NEA/IAEA-based estimates of resources in the world outside centrally planned-economy areas include reserves, at a forward cost of up to $50 per pound of U_3O_8, that total about 2.9 million short tons of U_3O_8 and "probable potential" resources that would total an additional 2.8 million short tons. Excluding the U.S., more than 80 percent of these resources would be in Australia, Canada, Niger, South Africa, and Sweden. Estimates of additional potential resources in the WOCA were prepared by the International Uranium Resources Evaluation Project under NEA/IAEA sponsorship. Initial studies of 185 countries, including the U.S., have led to an estimated range of from 8.5 to 19.2 million short tons of U_3O_8 in speculative resources (i.e., undiscovered but inferred) that could be produced at a cost of up to $50 per pound of U_3O_8.

Uranium production capacity in the world outside centrally planned-economy areas, excluding the U.S., was about 30,000 short tons of U_3O_8 in 1978. Canada, France, Gabon, Namibia, Niger, and South Africa represented over 90 percent of this capacity. The 1977 NEA/IAEA study estimated essentially the maximum future world production capacity that could be produced from known resources under favorable economic and political conditions. These projections include production through 1985 from resources with a forward cost of less than $30 per pound of U_3O_8, although some higher-cost material up to $50 per pound is likely to be produced during this period. The production of foreign countries outside centrally planned-economy areas could reach a level of nearly 40,000 tons of U_3O_8 in 1980 and about 70,000 tons of U_3O_8 by 1985.

NEA/IAEA data on the production levels that might be attained after 1985 suggest that only a few countries have known resources sufficient to justify increases in production capacities beyond those levels projected for 1985. Moreover, some countries with adequate resources for continued expansion may not fully exploit their resources because of political, environmental,

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[1] The Peoples' Republic of China, the USSR, and associated Eastern European countries did not provide data and have not been included.

and economic restraints. Based on currently estimated resources, foreign production capacity for countries outside the centrally planned-economy areas, excluding the United States, could be increased from about 70,000 short tons of U_3O_8 in 1985 to about 83,000 short tons of U_3O_8 in 1990. One country, Australia, would account for almost all of the potential increase in production capacity outside the U.S. by 1990.

As in the U.S. analysis, estimates of supply from both high-grade and low-grade resources have been used to provide projections of total foreign U_3O_8 production capability. Figure 6 shows the range of supply projections for the world outside the centrally planned-economy areas, including the U.S., which result from combining the high-grade and low-grade resource projections made by the NEA/IAEA Joint Working Group with estimates made by the Department of Energy's Office of Uranium Resource Assessment Operations.

The upper pair of curves, called the "High supply" for purpose of this analysis, assume accelerated development of a high base combined with the higher estimates of supply from low-grade resources. The high base of high-grade resources assumes the upper bound for speculative resources. The lower pair of curves--the "Low supply"--result from assuming the delayed development of a low base of speculative high-grade resources as well as a low estimate of low-grade resources. Together, these curves represent upper and lower bounds of potential uranium supply based on current knowledge of foreign and U.S. resources.

The High supply estimate for the world outside the centrally planned-economy areas projects a production capability of 235,000 short tons of U_3O_8 in 2000 and 508,000 short tons of U_3O_8 in 2025; in 2000, 10 percent of the supply capability would come from low-grade resources; by 2025, this proportion would grow to about 30 percent. The "Low supply" estimate for these countries projects production of 192,000 tons of U_3O_8 in 2000 and 247,000 short tons of U_3O_8 in 2025, drawing approximately the same proportion of supplies from low-grade resources as does the High supply estimate.

The majority of high-grade uranium supply between 2005 to 2010 would have to come increasingly from uranium currently in the "possible" and "speculative" resources categories. Production of uranium from these categories is uncertain, and this situation is complicated by the long lead times associated

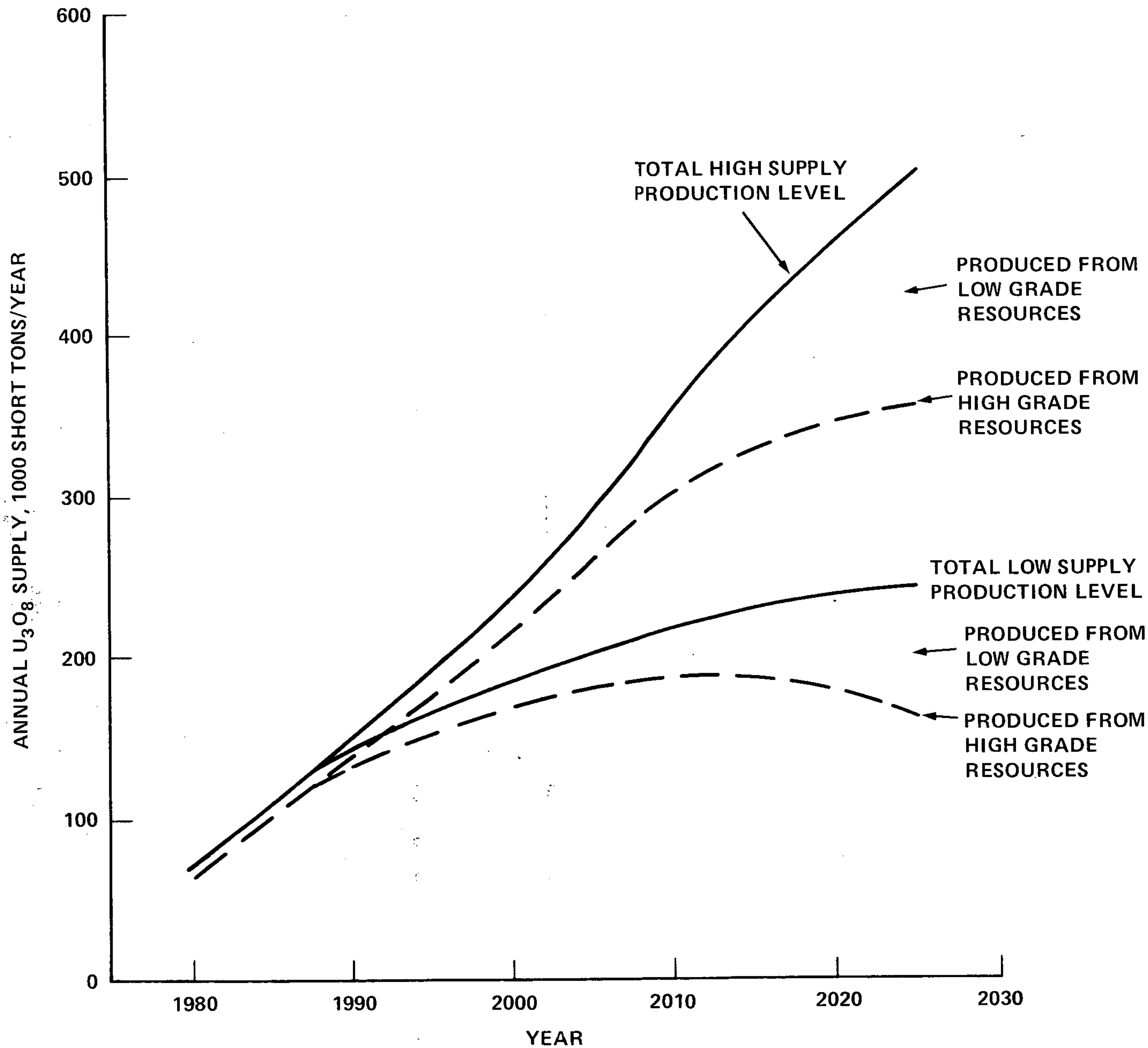

Figure 6. Estimates of WOCA Annual U_3O_8 Supply Capability

with exploration, delineation of reserves, and development of mines and mills in a variety of overseas areas.

Outside the U.S., uranium by-product from phosphoric acid production is expected to be the only significant source of supply from low-grade resources through 2025. In the U.S., substantial production capability from Chattanooga shale is believed to be possible in the post-2000 period if economic factors permit and environmental impacts can be made acceptable.

There are various projections of installed nuclear electrical-generating capacity for the world outside the centrally planned-economy areas which present an even more uncertain picture than for the U.S. alone. Forecasts which have been reported in the International Fuel Cycle Evaluation (INFCE) studies range[1] from 850 GW in 2000 to 1,200 GW, depending on whether a Low or High growth rate is assumed. A recent Department of Energy analysis identifies a present trend in which the rate of nuclear growth in countries outside the centrally planned-economy areas is about 40 percent lower than the Low growth projection. Therefore, the discussion in this volume is limited to a forecast countries outside the centrally planned-economy areas made up by combining the INFCE Low nuclear-growth projection for these countries, excluding the United States, nations with the Department of Energy 1978 Median-growth projection for the U.S.

The uranium demand[2] corresponding to this nuclear growth is compared in Figure 7 with the production capability projection and suggests that a uranium supply/demand imbalance might occur shortly after the year 2000. However, if the most recent nuclear-growth trend (about 40 percent lower) identified by the Department of Energy continues, this possibility would be postponed until about 2010. If the High supply scenario for the world outside the centrally

[1] The U.S. 1978 Low- and High-growth projections presented earlier are part of these forecasts.

[2] Assuming that in foreign countries the proportion of heavy-water reactors fueled with natural uranium continues at its present level of 5 to 7 percent of the total (there are no heavy-water reactors in the U.S.) that the light-water reactor system continues to operate with present fuel-utilization efficiency and that enrichment plants operate at a tails assay of 0.2 percent U-235.

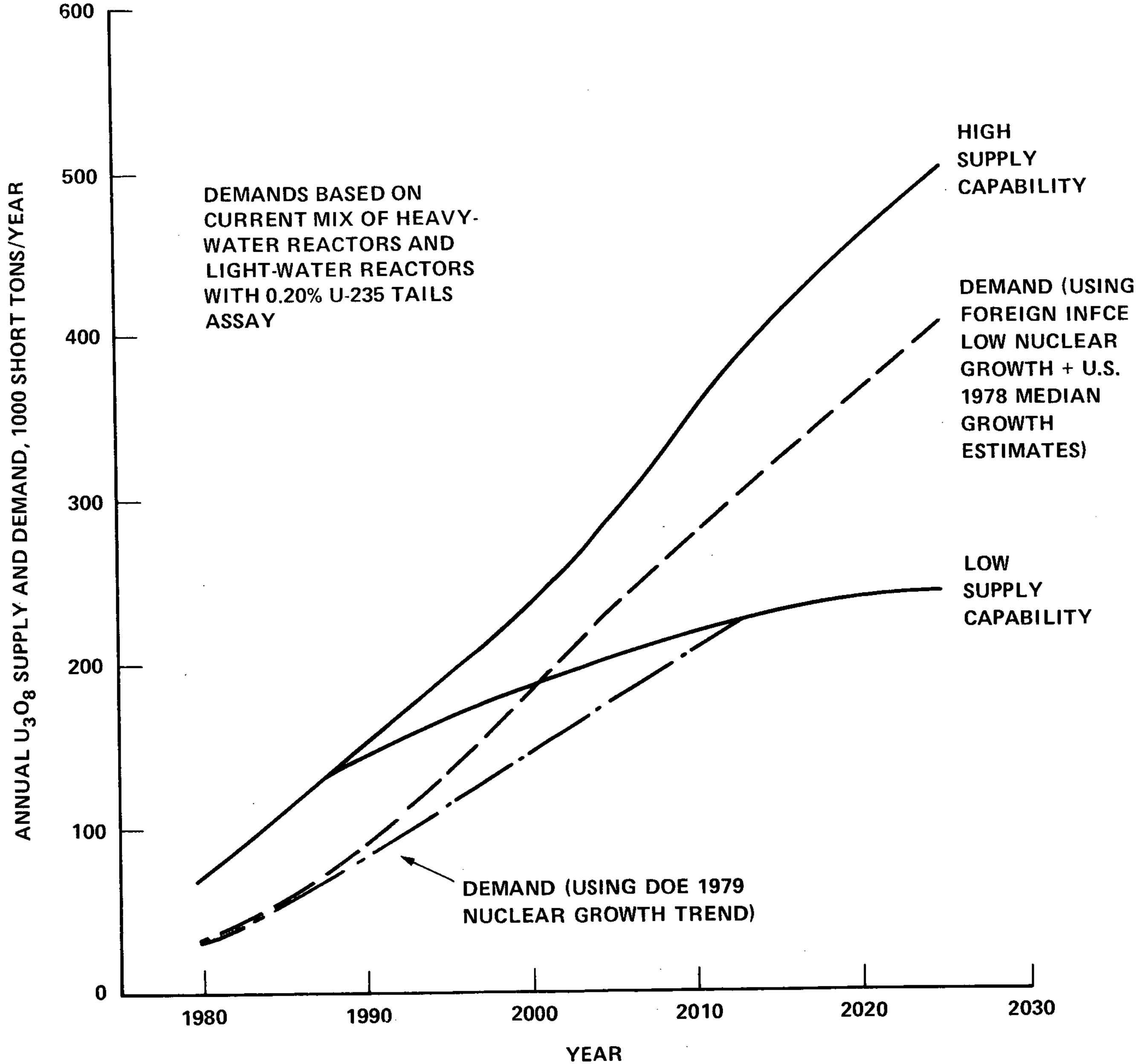

Figure 7. Comparison of WOCA Annual U_3O_8 Supply Production Capability and Demand for Current Light-Water and Heavy-Water Reactors

planned-economy areas could be achieved, a supply/demand imbalance would not occur until after 2025.

Although the uranium resource bases of some countries are so small that they will always be net importers, they can reduce their uranium demand through various improvements to their reactors, as will be discussed later. With the additional impact of uneven geographic distribution of resources, some countries may feel pressures to reprocess spent fuel and recycle in thermal reactors or fast breeder reactors earlier than others.

<u>Other Resources: Heavy Water, Enrichment Services, and Thorium</u>

Heavy water is used commercially as a moderator and coolant in the heavy-water reactor. At present, the only proven method for large-scale production is the Girdler Sulfide process used in Canada and the U.S. The basic aspects of this technology are fairly complex but well known. Plant construction and operation at high capacity without adverse environmental impact are demanding because of the toxic and corrosive nature of the working substance. In addition, significant aspects of this technology remain under proprietary control, and it would take a time-consuming and expensive program to develop the technology indigenously. Moreover, governments have been cautious in transferring such technology because of its potential use in weapons programs, and the transfer of commercial heavy-water production facilities and technology triggers safeguards under the guidelines of the Nuclear Suppliers Group.

Future demand for heavy water will in turn depend on the acceptance of heavy-water power reactors. Relative to its use in heavy-water reactors, other uses of heavy water should continue to be minor until well into the next century.

As of September 1976, over 9,000 metric tons (t) of heavy water had been produced in the world outside the centrally planned-economy areas. In 1978 production capacity of heavy water was about 2,000 t/yr. While the projected Canadian capacity (2,400 t/yr) by 1980, supplemented by supplies from the U.S. and the USSR, seems sufficient to meet the projected demand for CANDU reactor inventories through the end of the century, the political acceptability of relying on essentially one source for large-scale supplies is problematical.

There are only imprecise data on which to judge the future supply situation; however, it appears that supply should be adequate into the 21st century. The prerequisites for adequate heavy-water supply are access to technology and the willingness to make investments to construct the heavy-water plants in a timely manner.

The enrichment requirements for the world outside the centrally planned-economy areas have been supplied almost entirely by the U.S., and to some extent by the USSR, until 1979. During the 1980's major enrichment capacity is expected to come on line in France, the United Kingdom, the Netherlands, the Federal Republic of Germany, and Japan; smaller capacities are planned to come on line in Brazil and South Africa. The United States has a major expansion of enrichment capacity under way to increase the design capacity, measured in separative work units per year, from about 17 million at present to 29 million by 1990. By that date, planned expansions would bring total enrichment capacity in countries outside the centrally planned-economy areas to about 63 million separative work units per year.

Requirements for the world outside centrally planned-economy areas were about 20 million separative work units per year in 1979 compared to capacity of about 25 million. These requirements are expected to grow to 40 to 50 million separative work units per year by 1990.

The U.S. requirements for enrichment services will continue to increase. Table 12 gives the annual requirements for separative work, assuming current light-water reactor fuel designs and 0.2 percent U-235 tails assay.

TABLE 12. U.S. ANNUAL ENRICHMENT REQUIREMENTS (10^6 Separative Work Units) (at 0.20 Percent U-235 Tails Assay)

	in 1990	in 2000	in 2010	in 2025
1978 Median Nuclear Growth	22	38	52	72
1978 Low Nuclear Growth	19	29	34	37

The U.S. enrichment capacity which exists, is under construction, or is being initiated will be adequate to meet both U.S. requirements and some foreign requirements in addition to those already contracted for. If the current plans for expansion in countries outside centrally planned-economy areas are carried through on schedule, excess capacity will exist until the early or mid-1990's. Neither U.S. nor foreign enrichment requirements appear likely to increase more rapidly than the ability to expand capacity; indeed, compared to the effort required to expand the nuclear generating capacity, the effort required to expand enrichment capacity should not be prohibitive.

Thorium is used as the fertile material in a number of fuel-cycle alternatives to be discussed later. Thorium use, at about 3 short tons per year, is being demonstrated in the U.S. in the operation of the 330 MW Fort St. Vrain high-temperature gas-cooled reactor and the 60 MW Shippingport light-water breeder reactor. The potential for satisfying domestic thorium requirements is good. A relatively large resource base has been established for both monazite sands and vein deposits. The current demand for thorium (about 10 short tons per year) is very small, and crude thorium products resulting from rare earth separation from monazite sands are being stockpiled for future needs. No additional demand has been foreseen until after the year 2000. Industry already has the capacity to supply thorium for several more reactors; with present technology and facilities, capacity could be expanded to several hundred tons per year. This easily expanded capacity could supply the initial cores for more than four reactors per year. If additional reactors were converted to thorium fuel cycles, techniques for milling vein ores would have to be developed, and the industry would have to expand to fill requirements. Nonetheless, thorium supply should not be a deterrent to thorium fuel-cycle deployment.

The foreign supply and demand for thorium are similar to those of the U.S. Only one small demonstration reactor now uses thorium, and a second reactor is to start up in the early 1980's. Total demand from these reactors is about 3 short tons per year, and little increase before 2000 has been foreseen. The extent of eventual foreign requirements for thorium is not known. A relatively large resource base is known to exist, and there is a potential to greatly expand this resource base through exploration. Large deposits of monazite sands are believed to exist in a number of developing countries. Moreover, the extraction of thorium from monazite and the purification of the thorium are generally straightforward. The technology and equipment for these operations could be made available to other countries as incentives to exporting an upgraded product. With these incentives, there would be enough thorium to support thorium fuel-cycle deployment.

2.1.3 Commercial Considerations

Continued commercial success of the light-water reactor operating on the once-through fuel cycle is contingent on its economic attractiveness and operating reliability relative to competing baseload nonnuclear options; on the ability and willingness of the nuclear power industry to provide necessary reactor products and fuel-cycle services; on resolution of any outstanding safety and environmental issues; and, as a result of heightened public awareness because of the Three Mile Island accident, on continued public acceptance of nuclear power.

These factors will be discussed to provide a context for assessing the merits of emerging technologies and to highlight pressures for change.

Today, most of the electricity generated by nuclear power comes from light-water reactors on a once-through cycle. Even if alternative reactors and fuel cycles were already available, the light-water reactor would be the most economical. Moreover, current nuclear systems are cost-competitive with other commercial power-generating technologies, such as coal and oil. However, the cost of nuclear power generated by light-water reactors on a once-through cycle is affected by the price of U_3O_8. For example, an increase of $14 per pound of U_3O_8 would raise the cost of a kilowatt hour from a light-water reactor by 1 mill--a 7 percent increase over the 1978 national average cost of 15 mills for nuclear-generated electricity. Even if coal prices were to remain constant, the current approach to nuclear-powered electricity production would be likely to remain cost-competitive with coal at prices up to $70 per pound of U_3O_8 in most parts of the country, and even at prices as high as $110 per pound of U_3O_8 in some geographic regions (for example, in the Northeast).

Utilities are adjusting their new plant-ordering patterns to reflect forecast reductions in future electrical-demand growth. At the same time, planning must take into account high investment costs and more stringent financial terms and conditions, and challenges during the licensing process by concerned citizens. Plant manufacturers also are faced with uncertainties, including a paucity of new orders as a result of continuing deferrals and cancellations of existing orders, and a lack of new reactor business. Sustaining the effective and economic use of existing manufacturing facility capacity and trained manpower will represent a growing problem in the next few years for most vendors. In addition, the financial institutions that invest in electrical utilities see increasing uncertainties with regard to nuclear growth and financial risk.

At the national level, major questions remain concerning the resolution of the waste-disposal issue, licensing reform, and the rights of states to limit severely or eliminate nuclear-plant siting within state boundaries. The accident at the Three Mile Island Plant in Pennsylvania has cast additional doubts on the level of public acceptance for nuclear power and on the extent of safety and licensing changes that may be required in existing and subsequent plants. The NASAP analysis was completed before publication of the report of the Presidential Commission on Three Mile Island, and it would be premature to judge its effects now.[1] No one can predict with certainty the impact of these events on questions of eventual public acceptance, on the operation of existing plants or new plant orders, on planned construction schedules, and, ultimately, on costs to build and operate nuclear plants.

Quite simply, the overriding concern in the commercial sector now is assuring that the existing nuclear technology remains a viable competitor and that the underlying industry infrastructure remains intact. Questions regarding which new nuclear technology to pursue are of lesser interest.

No reactor or fuel cycle is commercially viable unless it is licensable for operation by the Nuclear Regulatory Commission. The scope of the NASAP licensing assessment was limited to safety and environmental issues only. It does not include the need for power, economics, antitrust issues, safeguards, and institutional and social factors, all of which are considered in the licensing process. Safety issues common to all of the alternative reactor and fuel cycles relate to protecting the general public and the nuclear facility operating staff from radiation exposures exceeding legal standards and guidelines that might result from unplanned events or accidents (equipment failures, operator errors, or external forces such as earthquakes). Environmental issues common to all of the assessed nuclear alternatives include a

[1] The highlights from the Nuclear Regulatory Commission's Three Mile Island 2 Lessons Learned Task Force Status Report and Short-Term Recommendations are included in Volume VI, Safety and Environmental Considerations for Licensing.

broad spectrum of physical and social impacts such as commitment of land and water resources; heat rejection; radiation exposure to the operating staff and general public; and social and direct costs.

After more than 25 years of evolution, licensing requirements for light-water reactors are considered to be comparatively well defined in the form of regulation criteria and guides. However, there are still some unresolved safety issues which were identified and are subjects for ongoing industry and Nuclear Regulatory Commission actions to enhance safety. The accident at Three Mile Island has led to major reviews of the basic technology and the whole licensing process, including licensing criteria, design requirements, operating procedures, and operator qualifications by the Nuclear Regulatory Commission, The President's Commission on the Accident at Three Mile Island, several Congressional committees, and industry. Significant changes will undoubtedly result, but the full impact of this accident on reactor licensing cannot be known until reviews are completed in late 1979 and in 1980.

The principal environmental impacts associated with normal operation of the once-through cycle stem from the mining and milling of uranium for reactor fuel and, to a lesser extent, enrichment, fabrication, and reactor operation. The primary impacts of uranium mining and milling are on population exposure due to the release of radioactive radon gas to the atmosphere, and on water and land use, since much of the exploration and extraction of uranium occurs in arid regions in the western U.S. Also of importance is the storage of spent fuel discharged after reactor operation. Unless further capacity is installed, lack of on-site storage could result in some reactor shutdowns past 1985. These environmental problems will require continued attention in order to assure continued safe operation of nuclear power reactors. Small reductions in the amount of fuel mined, milled, and discharged may be achievable by the year 2000. The means for achieving these reductions are discussed in subsequent sections.

Fulfilling safety and environmental requirements will be more difficult to demonstrate for some alternative reactor concepts than for others, and the risks of serious delays or setbacks in the development and licensing process will vary with the extent to which existing technology can be extrapolated. Changes in the Nuclear Regulatory Commission's General Design Criteria and design requirements for light-water reactors will also affect the alternative reactors. As a measure of the difficulty each alternative would have in meeting safety and environmental requirements, estimates were made of the minimum time it would take to resolve technical issues which are currently preventing commercial license application. Reactor plant concepts that have a demonstrated basis for proceeding with a definitive commercial design for wide deployment would need a minimum of 2 to 3 years for design completion and Preliminary Safety Analysis Report preparation. (Submission of a Preliminary Safety Analysis Report is one of the first major steps taken by a utility seeking a construction permit from the Nuclear Regulatory Commission.) Reactor plant concepts, which still require a demonstration reactor to be operated so that the safety basis can be established, would require at least 15 to 20 years before a commercial-size plant Preliminary Safety Analysis Report could be submitted. Some fuel concepts would need qualification before loading into commercial reactors; for them, the minimum time to reach this stage would be 7 to 12 years. For each of the alternative reactor and fuel concepts selected for this analysis, several issues remain to be resolved through research, development, and demonstration programs.

2.1.4 Pressures to Select Less Resistant Systems

In light of uncertainties about the adequacy and accessibility of uranium supplies and in anticipation of growth in demand for nuclear fuel, some nations are moving toward sensitive fuel-cycle activities, some toward enrichment, and some toward plutonium-based fuel cycles. Some nations are making the same moves to reduce operational, economic, and political dependency on foreign nations for supplies of uranium or enrichment services. A number of nations are concerned with the environmental implications of spent-fuel storage and disposal. For example, Austria, Belgium, Japan, Sweden, Switzerland, and the Federal Republic of Germany have statutory requirements linking the licensing of nuclear power reactors to demonstrated progress toward solving the waste-management problem. In some cases, this demonstration has been construed as a requirement for reprocessing. Moreover, doubts about the reasons for choices of less proliferation-resistant fuel-cycle technologies by neighboring nations may encourage similar choices based on considerations of national security. In short, some nations have indicated the start of a partial transition from today's once-through system, a few to recycle and several to fast breeder systems, although only a small percentage, less than 5 percent of the projected installed capacity, is projected to be provided by fast breeder reactors in the year 2000.

Thus, there are a number of pressures, whether correctly or incorrectly, influencing nations to adopt or plan for less proliferation-resistant technologies. Although there has been a consistent downward trend in all nuclear energy forecasts for the past several years, so that the spread of sensitive materials and facilities is less imminent, the underlying pressures remain. However, there are countervailing forces that can alleviate each of these pressures. Such considerations enter into the development and assessment of measures and alternatives likely to improve the nonproliferation regime.

Perhaps the most critical pressure to be alleviated is that of security of supply. Nations assert that the level of their economic development and economic independence is of paramount importance to their political independence and international influence. In some instances, it appears that deployment decisions regarding plutonium fuel cycles are being taken for strategic reasons as well as for conventional commercial and economic considerations, even though such decisions may not have an appreciable impact on security of supply for many decades.

2.2 ASSESSMENT OF FUTURE CHOICES AND APPROACHES

A number of approaches are available to deal with the pressures discussed in the preceding section. Some would afford greater proliferation resistance and economics benefits than others. Some of these longer-term approaches have already begun to be actively pursued, and pilot and prototype facilities already exist in some countries. This section of the NASAP report evaluates the various alternatives for the future, to identify those that would be in the best interests of the U.S., considering proliferation resistance, resource use, commercial and economic factors, and international acceptability. The alternatives fall into three categories:

- Resource extenders: nuclear systems and technologies that use scarce uranium resources more efficiently or rely upon other nuclear fuels to generate power;
- Supply improvements: measures to increase the assurance of fuel supplies which address both the continued accessibility of uranium and the adequacy of uranium resources to meet long-term nuclear growth;
- Institutional and technical measures: approaches relating to fuel cycle materials and facilities which are designed to enhance security of supply and nonproliferation effectiveness through a framework of prevailing procedures and practices (such as safeguarding spent-fuel storage) and internationally concerted activities or arrangements (such as a spent-fuel storage facility under multinational auspices).

It is important to point out that the development of these approaches will be evolutionary. The technology of the present--for the most part light-water reactors--will continue to dominate nuclear power production for the next 30 to 40 years. This is true because of the large number of such reactors that are currently deployed and coming on line, and because of a prevailing attitude of caution on the part of the nuclear industry, primarily the utilities and the supplier industries, regarding deployment of new, as yet commercially unproven nuclear power systems.

This attitude of caution with regard to new systems could extend to public acceptance as well. Alternative nuclear systems which introduce large differences from the current light-water reactor system could face public acceptance uncertainty, resulting in continued, and perhaps more widespread, debate over both potential nuclear power benefits (e.g., assurance of long-term electrical-energy supply with breeder reactors) and over potential problems (e.g., abuse of reprocessing facilities or materials). Other categories of possible concerns include the operation of facilities, the process of making decisions about nuclear power, and the long-term social effects of recycle and reprocessing decisions, nuclear system choices, and waste management plans. As with the evolutionary nature of systems, public concerns will change as choices are made.

Current technology will be slow to give way to new technologies and will do so only when clear-cut advantages as perceived by the users exist. The technology's evolutionary nature provided the backdrop against which new alternatives were projected by the NASAP analysis--a set of conditions that may be characterized as follows:

- Changes in aggregate uranium-resource use beyond those of light-water reactor improvements and economic factors will be small, at least through the balance of this century, since more efficient reactors and fuel cycles cannot be deployed in significant quantities until well into the next century.

- Current problems and concerns (e.g., spent-fuel stockpiles) associated with the operating light-water reactors will continue to mount.

- It will take time to develop and implement technical and institutional countermeasures that would affect the proliferation vulnerabilities of new technologies and fuel cycles. While this time appears to have become available, it must be well spent, and long lead-time activities must be begun in the near term.

In addition, commercialization of any new nuclear technology would face major barriers, as perceived by the private sector. These include:

- Today's lack of knowledge about future demands for electric power, coupled with a near-term overcapacity in manufacturing facilities--specifically, steam-supply-system fabrication.

- The unpredictability of changes in Federal and State laws and regulations governing utility rates, health and safety, the environment and other matters. Moreover, there is opposition to nuclear power among some public groups and skepticism among others.

- Possible restrictions on available private-sector and risk-capital financing.

- A perceived lack of national commitment to increased nuclear growth and to resolving key policy issues such as waste disposal.

Utilities have historically had strong incentives to invest in new plants. These incentives were improved technology, the growth of their electric power systems, and the supportive political and regulatory climate. The new plants benefited from economies of scale and indications that unit costs for the electricity they produced would be declining compared with the cost for nonnuclear alternatives. But today, due primarily to changes in perceptions about a host of institutional concerns and their impact on power-plant economics, utilities have little incentive either to express commitments for new nuclear technology or to invest in it.

In light of these barriers, the private sector has virtually no commercial (financial) interest in new nuclear technology at this time, neither the manufacturers as suppliers, nor the utilities as users. Improvements to light-water reactors are a likely exception to this, as they involve smaller business risks; are natural extensions to existing products; are relatively inexpensive to complete the necessary research, development, and demonstration; and offer economic and resource benefits. The private sector, with some Federal Government stimulation, can be expected to adopt these improvements. Should a national requirement exist for a new nuclear technology, such as advanced converter or breeder reactors, the Federal Government would have to bear most of the costs to commercialize these systems.

User interest in specific new reactor systems is being expressed formally and in concert through utility groups organized specifically on behalf of such systems. These groups represent a segment of the utility market which may be interested in unique features of a reactor system. However, even where such programs exist, the potential for funding from the private sector is still quite limited. Further, it remains to be seen whether the participating utilities, without substantial Government assistance, would be prepared to commit the more significant funds required for constructing demonstration plants and creating the initial market demand for the early plants.

2.2.1 Resource Extenders

Light-water reactors operating on a once-through cycle do not use uranium as efficiently as would some alternative reactors and fuel cycles. While the past few years' downward changes in nuclear-growth projections have alleviated some concern over the adequacy of uranium resources, considerable uncertainty about the adequacy of supply in the next century remains. A number of alternatives are available to further alleviate potential supply problems. The most important ones, those aimed at improving the efficiency of uranium utilization, are discussed below--light-water reactor fuel-utilization improvements; reduced enrichment plant tails assay; recycle in light-water reactors; deployment of advanced converter reactors; deployment of breeder reactors; and a group of conceptual designs for reactor systems.

Light-Water Reactor Fuel-Utilization Improvements

It appears possible to improve uranium utilization, that is, to reduce the U_3O_8 requirements per unit of energy produced, in light-water reactors on a once-through fuel cycle by 15 to 30 percent or more through modifying current fuel designs, altering plant operating procedures, improving fuel-management schemes, and redesigning plant systems and components. Some of the improvements--called 'retrofittable'--could be applied to operating plants or to plants now being designed and constructed. Other improvements, (nonretrofittable) would involve system and component changes and could be installed only in new plants. Improved uranium utilization would also reduce the amount of fuel that would have to be fabricated and the amount of spent fuel that would have to be stored. The retrofittable improvements examined by NASAP could increase uranium-utilization efficiency in individual reactors by 15 percent by 1990 and by an additional 5 to 10 percent by 2000.

Technical feasibility could be demonstrated for many proposed retrofittable modifications by 1985, and the combined impact of these near-term modifications, if all were fully exploited, would reduce annual uranium demand below that of the NASAP reference light-water reactor by 15 percent. The balance of the retrofittable improvements--those not expected to have been demonstrated by 1985--might be available for utility use by the mid-1990's and could be fully deployed by 2000.

More than two thirds of the resource savings from the pre-1990 retrofittable improvements could come from higher burnup. Some increase in burnup is expected to be accomplished with no fundamental change in fuel design, but would require demonstrating that existing designs can be irradiated longer than currently warranteed by vendors. Demonstration experiments being performed in commercial reactors involve burnup increases from the roughly 30 to 33 megawatt-days per kilogram of fuel (MWd/kg) reflected in current warranties, to perhaps 36 to 40 MWd/kg. This increased burnup could be demonstrated before 1985. Other near-term modifications are also under active study and, as a class, have good prospects of technical success. Modifications include such things as improved fuel management, lattice changes and axial blankets.

Additional retrofittable uranium savings would come from an extension of burnup beyond 36 to 45 MWd/kg. It appears that routine burnups in the range of 45 to 55 MWd/kg for commercial fuel assemblies could be technically feasible in the early 1990's, and the first experiments of this type are now being planned. Naturally, fuel with extended burnup must be licensed by the Nuclear Regulatory Commission, and licensing can be expected to proceed in parallel with ongoing development.

The nonretrofittable improvements are more speculative at this time because less work has been done for their development and they involve changes in plant systems and components. Advanced rapid refueling is expected to be the most significant improvement in this group. Implementation of the nonretrofittable improvements can perhaps bring the total uranium savings in new light-water reactors to something over 30 percent after the end of the century.

<u>Implications for International Deployment: Proliferation-Resistance Assessment</u> -- The proliferation resistance of improved light-water reactors

on the once-through fuel cycle would be very similar to that of the current light-water reactor once-through cycle (discussed in the proliferation assessment of the present system). The most significant proliferation resistance characteristic of the system, which would not be affected by improved fuel utilization, is that there is no material that is directly weapons-usable in any part of the fuel cycle.

The only facility required by this fuel cycle that would be capable of producing weapons-usable material is the uranium-enrichment plant. While currently operating enrichment plants and those for which there are firm commitments are located in relatively few countries and will be adequate to meet demand at least through the mid-1990's, additional enrichment capacity will likely be required about the time that the fuel-utilization improvements are being implemented. Gas-centrifuge technology might well be used for this new capacity, and, as discussed earlier, gas-centrifuge enrichment plants can be modified more easily than gaseous-diffusion plants to produce highly enriched uranium. In addition, gas-centrifuge technology would be more amenable to use in small clandestine facilities. The requirement for additional enrichment capacity would be reduced by implementing fuel-utilization improvements and would reduce the proliferation vulnerability of the future nuclear power regime. New enrichment capacity should be added only when the need is clear and could be limited to expansion of existing facilities or joint ventures under international auspices. In addition, safeguards approaches need to be developed and implemented for enrichment plants, and the plants themselves should be designed to facilitate safeguards.

Another vulnerability of the light-water reactor once-through fuel cycle is the spent fuel from which plutonium could be extracted in an out-of-system reprocessing facility. This vulnerability would remain with the implementation of the fuel-utilization improvements but at a somewhat reduced level, since higher fuel burnups, if an annual refueling cycle were to be maintained, would result in the annual discharge of 40 percent less spent fuel and about 25 percent less plutonium. The pressures on many countries to deal with ever-increasing inventories of spent fuel would also be reduced. The countermeasures and actions applicable to spent-fuel storage under the current system will nonetheless have to be pursued, even if light-water reactor modifications were to be incorporated in the future.

<u>Resource Utilization: The Impact of Light-Water Reactor Improvements Domestically and Worldwide</u> -- In the U.S. through the year 2000, the nuclear power system will consist almost entirely of light-water reactors. Thus, the

implementation of retrofittable fuel-utilization improvements--that is, higher fuel burnup and changed fuel management--would apply to the whole system and would result in 15 percent lower annual uranium requirements and about 5 percent lower enrichment requirements than those of systems using light-water reactors at current fuel-utilization efficiency.

For the 1978 Median growth projection, a supply/demand imbalance appears possible late in the first quarter of the next century, even with implementation (beginning in 1990) of a 15 percent improvement in fuel utilization of light-water reactors if the enrichment tails assay is held at 0.20 percent U-235, as indicated in Figure 8. Such an imbalance could be avoided only with significant production from low-grade resources (about 18,000 short tons per year in 2025). If the 1979 growth trend continues at about 12 GW per year, the annual uranium demand in 2025 would require maximum production from high-grade resources and moderate production from low-grade resources (10,000 to 15,000 short tons of U_3O_8 per year). Moreover, production from the Chattanooga shales probably would not be required before 2025.

The annual requirements for enrichment services to support the 1978 median growth could be reduced by about 2 million separative work units in the year 2000 and by 4 to 6 million separative work units in 2025, as compared to that required for the current light-water reactor with a 0.20 percent U-235 tails assay. This projected reduction in requirements represents several billion dollars less investment in enrichment capacity over the whole time period.

A 40 percent reduction in the annual discharge of spent fuel would also result from implementation of these improvements, due to higher fuel burnups and smaller fuel batches. However, the impact on total storage requirements would not be significant for several decades after introduction of the improvements. Reductions in spent-fuel storage away from reactor would be a few percent smaller in 2000 and about 35 percent smaller in 2025. The reduction in quantities would be about 1,000 metric tons in 2000 and 96,000 metric tons in 2025 for the 1978 Median growth projection as compared to the current light-water reactor.

A further 15 percent reduction in uranium requirements for each new reactor, in addition to the 15 percent retrofittable reduction just discussed, might be implemented beginning in the year 2000. Assuming a rapid introduction schedule which would begin in 2000 and result in these improvements in all new reactors by 2010, annual uranium requirements for the system could be reduced by about an additional 7 percent in 2010, up to 13 percent in 2025.

As shown in Figure 8, if a 30 percent reduction in fuel utilization can be achieved, the 1978 Median demand projection is not likely to result in a uranium shortfall until after 2025; this is even more likely if the 1979 growth trend persists.

Commercial Potential -- The proposed improvements in fuel utilization appear to be commercially practicable, and most of them would lead to lower fuel-cycle costs. However, though they might reduce fuel-cycle costs, any modifications that would affect plant operations and thereby lead to increased total operating costs may not show an overall benefit. In their practical application, these improvements would lead to higher burnups and shorter refueling cycles but might conflict with the interests of some utility operators which dictate using higher burnups to permit longer operating cycles--from annual refuelings to 18-month cycles, for example--for capacity factor improvements.

Plants operating with longer intervals between refuelings would require more uranium to sustain them than would be required when they operated on annual refueling intervals, as long as the fuel burnups were held constant. As long as the utilities perceive that the longer cycles will improve plant capacity factors, they can be expected to purchase the extended burnup fuel to improve plant economics in this mode of operation. Consequently, the initial step in burnup extension may not be seen in resource savings. However, if very high burnups were eventually to be demonstrated and commercialized--perhaps in the range of 40 to 50 MWd/kg of uranium--resource savings would be realized over current requirements, even with longer intervals between refuelings. One vendor is already offering an optional fuel design of 36 to 38 MWd/kg fuel burnup.

The improvements have good prospects for rapid market capture (deployment) when market demand develops, as they involve only the fuel, and the fuel-supply infrastructure is already in place. In addition, the utilities are participating in ongoing development programs with the Department of Energy and the Electric Power Research Institute and thus are familiar with some of

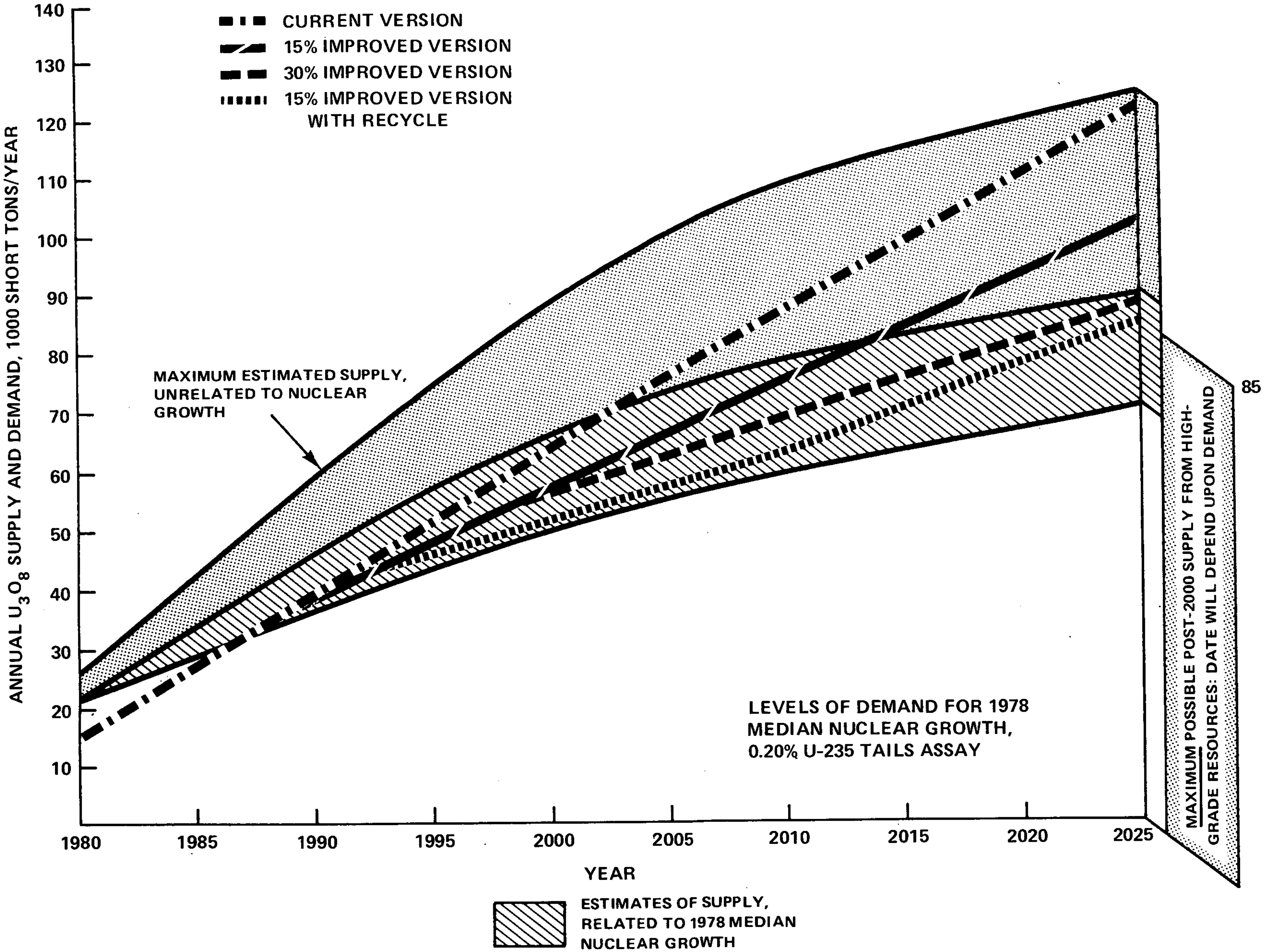

Figure 8. Effects on U_3O_8 Demand of Using Light-Water Reactor Self-Generated Recycle Compared with Improved Once-Through Light-Water Reactors

the modifications. Licensing risks are perceived to be smaller for these improvements than for any new system. Once successful demonstration, including licensing, has been achieved, these modifications could be deployed rapidly, and are expected eventually to capture the whole market.

Since these improvements would be evolutionary changes to the present product line, vendors would perceive investment in this technology as being less risky than investments in alternative reactors and fuel cycles. There would also be little impact on business relationships as they now exist in the nuclear industry. In setting a price for any fuel of a new design, the vendor can be expected to include compensation for added effort in fabrication, to earn a return on the research and development investment, and to maintain profit levels that would otherwise have been reduced because of lower requirements for fabricated fuel. To the degree that extended burnup would reduce the fabrication market, an area that has been profitable, the vendors would probably be less aggressive in marketing some of these modifications, except as a measure to protect their market share of nuclear-steam-supply-system business. A risk facing vendors would be reversal of Federal policy prohibiting reprocessing and recycling of plutonium. Improvements that can be implemented in the near future, which would likely yield a resource efficiency improvement of up to 15 percent, would be unaffected by such a policy change. These improvements, together with a few others--all of which can be utilized in currently operating reactors--could potentially extend the combined resource efficiency gain up to 20 to 25 percent. However, this gain could not be achieved until after 1990. Recycle could be available about ten years after the decision to proceed with it was made. Thus, even with recycle, the incentive to use most of these improvements would remain, although it would be somewhat diminished. The schedule for their market entry would be about the same as that for recycle. Ultimately, however, the combined resource efficiency gain from the improvements and recycle is not significantly better than that which could be achieved by recycle alone. Since it is likely that the light-water reactor fuel would be reoptimized for recycle operation, manufacturers of reactor fuel might have no incentive for extending the performance of the improvements beyond 15 percent, once the decision to recycle was made. On the other hand, should the improvements be demonstrated before a decision to use recycle has been made, the market lifetime would be sufficient to provide incentive to vendors to market them.

For the utilities, the increased fabrication costs should be more than offset by uranium-cost savings. Since these gains would accrue to the utilities, they can be expected to encourage vendors to make these improvements.

Successful demonstration of retrofittable improvements would require a development program that would be modest in comparison to that required for any new system. The total research, development and demonstration effort would include detailed fuel design, pre-irradiation mechanical tests, irradiation experiments and safety studies, irradiation of partial to full batches of fuel assemblies, and post-irradiation tests. Most of this effort would be needed to establish that the modified fuel will perform reliably before it is used on a large scale by utilities. Also, some of the effort would be devoted to developing the information required for generic licensing by the Nuclear Regulatory Commission.

With a national program, enough duplication could be eliminated so that the total research, development and demonstration effort for the retrofittable improvements would cost $150 to $300 million, if carried out under Department of Energy auspices by all of the five current light-water reactor fuel vendors, and tailored to demonstration of each product line. If the retrofittable improvements were to be independently pursued by all five vendors, the costs could be $350 to $550 million.

The potential benefits to the utilities, and ultimately to electricity consumers, from research, development and demonstration associated with reduced uranium requirements in retrofittable light-water reactor improvements could total several billons of dollars by the end of the century, at current projected electrical-demand growth. They could amount to several hundred millions of dollars in the year 1990 alone.

The estimated cost of research, development, and demonstration of the nonretrofittable improvements is more speculative because components have not yet been tested for technical and economic feasibility. Preliminary estimates of $0.6 to $1.0 billion or more have been made. Following identification of the most promising concepts in the mid-1980's, the necessary development and demonstration programs for these improvements might be completed toward the end of the century, whereupon deployment could occur in new plants.

Reduced Enrichment Plant Tails Assay

The dominant enrichment technologies are, and for the next several decades will be, gaseous diffusion and gas centrifuge. At current prices for U_3O_8 and separative work, enrichment plants using these technologies can economically reduce the U-235 concentration from 0.71 percent in natural uranium to about 0.20 percent in the tails stream. These plants could operate at lower tails assay, but the cost of their product would be higher. The choice of tails assay for lowest-cost enriched product would involve the trade-off of natural-uranium feed price against the price of separative work. At a uranium price of $40 per pound of U_3O_8 and an enrichment services charge of $100 per separative work unit, the least-cost low-enriched uranium product would be produced at a tails assay of 0.23 percent U-235. Should the uranium price increase to $100 per pound of U_3O_8 (equivalent to using uranium with $50 forward cost), while the enrichment services charge remained at $100 per separative work unit, then the least-cost low-enriched product would be produced at a tails assay of 0.13 percent U-235. However, the enriched-product cost would be relatively insensitive to using slightly lower tails assay and would increase only a few percent. Reducing tails assay to 0.1 percent U-235 might require increased uranium-enrichment capacity, which could be provided by existing technology or, more economically, by improved gas-centrifuge technology.

The development of advanced isotope separation processes such as laser and plasma separation, with their potentially lower separative work costs, could lead to more economical extraction of U-235 from the tails stream. The mode of operation could be within an independent advanced isotope separation plant or an integrated plant in the existing enrichment complex. In either mode, the natural-uranium feed requirements would be reduced by the same amount. If uranium price were $100 per pound of U_3O_8 and enrichment services charges from advanced isotope separation technology were $40 per separative work unit, then the least-cost, low-enrichment product could be produced at a tails assay of 0.05 percent U-235.

Reducing the tails assay from 0.20 percent to 0.05 percent U-235, which will probably require advanced isotope separation techology to be economical, would reduce uranium requirements by about 20 percent, and would require about 80 percent more separative work.

Implications for International Deployment: Proliferation-Resistance Assessment -- The advanced isotope separation processes are at an early stage of development. A detailed proliferation-resistance assessment based on the presently known science and technology has concluded that the U.S. is not embarking on an obviously proliferating set of technologies in the advanced isotopic separation program. As with other enrichment technologies, however, specialized designs for highly enriched uranium could be developed. Whether a plant configured for civilian production of low-enriched uranium could be adapted to produce highly enriched uranium without substantially redesigning the plant is a matter of some controversy. The current assessment is that such a configuration would be costly, time consuming, and detectable. However, the means by which these processes could be adapted to highly enriched uranium production is still poorly understood, and the perception that adaptation would be difficult must be subject to continued expert scrutiny. Of course, the threat of a technological breakthrough sometime in the future exists, as it does with any technology that is not yet fully understood. More important, when these technologies have been developed to the point of implementation, their deployment should be limited by appropriate institutional arrangements. The same would be true of new gas-centrifuge enrichment capacity should it be required.

Resource Assessment -- Table 13 summarizes, for the 1978 Median nuclear growth, the uranium and separative work requirements associated with implementation of several reduced tails assay options in conjunction with improvements in light-water reactor fuel utilization. The Low nuclear-growth case is not shown, since it does not represent a uranium supply problem. Annual uranium requirements resulting from Median nuclear growth and the combination of fuel-utilization improvements and tails-assay reductions could probably be met through 2025 from high-grade resources. Of course, the annual requirements for enrichment services increase as tails assay is reduced.

Furthermore, if advanced isotope separation techniques are successfully developed and enrichment tails assay is reduced to 0.05 percent U-235, there is little likelihood of a uranium shortfall until after 2025. Since the technical details for achieving this further 15 percent fuel-utilization improvement have not been defined, the potential effects on separative work demands and spent-fuel storage requirements cannot be predicted with precision; however, if the improvements do not require higher burnup, then enrichment requirements should be decreased by about 15 to 20 percent.

TABLE 13. THE EFFECTS IN THE U.S. OF REDUCED ENRICHMENT TAILS ASSAY ON U_3O_8 USE IN LIGHT-WATER REACTORS--MEDIAN NUCLEAR GROWTH

ANNUAL U_3O_8 REQUIREMENTS
(Thousands of Short Tons)

	in 1990	in 2000	in 2010	in 2020	in 2025
Light-Water Reactor - Once-Through					
- 15% Improvement - 0.2% U-235 Tails Assay	37	54	75	93	103
- 0.1% U-235 Tails Assay[1]	32	47	64	80	89
- 0.05% U-235 Tails Assay[2]	32	44	61	75	83
- 30% Improvement - 0.2% U-235 Tails Assay	37	54	69	81	88
- 0.1% U-235 Tails Assay[1]	32	47	59	70	76
- 0.05% U-235 Tails Assay[2]	32	44	56	66	71

ANNUAL ENRICHMENT REQUIREMENTS
(Millions of Separative Work Units)

	in 1990	in 2000	in 2010	in 2020	in 2025
Light-Water Reactor - Once-Through					
- 15% Improvement - 0.2% U-235 Tails Assay	22	36	49	62	68
- 0.1% U-235 Tails Assay[1]	30	50	68	85	94
- 0.05% U-235 Tails Assay[2]	30	66	89	113	124
- 30% Improvement - 0.2% U-235 Tails Assay	22	36	46	54	58
- 0.1% U-235 Tails Assay[1]	30	50	64	75	81
- 0.05% U-235 Tails Assay[2]	30	66	84	98	105

[1]Reduction from 0.20% to 0.10% U-235 tails assay assumed in 1990.

[2]Reduction from 0.10% to 0.05% U-235 tails assay in 2000.

Considering only the foreign countries outside centrally planned-economy areas, as a group, the implementation of a 15 percent improvement in light-water reactor fuel use and a reduction in tails assay to 0.10 percent U-235 if the INFCE Low growth occurred, accelerated development of high-grade resources and significant product from low-grade resources would still be required. If the nations outside centrally planned-economy areas, including the U.S., are considered as a group, the outlook is about the same. Again, it should be noted that the supply in the post-2000 period would be increasingly tied to production from speculative high-grade resources and low-grade resources.

Assuming a 30 percent reduction in U_3O_8 requirements and a reduction in tails assay to 0.05 percent U-235 by 2010, a supply capability about 20 percent greater than the Low supply would avoid an imbalance until 2025 with additional improvements in light-water reactor fuel utilization. In summary, improvements to reduce uranium requirements for light-water reactors by about 15 percent and a reduction in enrichment plant tails assay to 0.10 percent could probably avoid a supply/demand imbalance through at least 2020, if uranium supplies are considered as an aggregated resource for countries outside the centrally planned-economy areas and the current nuclear-growth trend persists. Additional improvements to light-water reactor uranium utilization could provide further assurance that demand would not exceed the lowest projection of supply capability through 2025. Expansion of foreign uranium supply is more important to foreign countries than to the U.S, although an expansion of U.S. production capability for export could alleviate this situation.

Commercial Potential -- Uranium-enrichment services are provided by the Government on a commercial basis with established contracting terms. The pressure to reduce enrichment plant tails assay will come mainly from the desire of utilities to buy a "least-cost" product, considering uranium price and separative work costs. If the price of uranium were to rise faster than the cost of enrichment services (which now appears likely), pressures to reduce tails assay would be strong. The enrichment-plant operator would respond to these pressures because more sales would result. The only uncertainty faced by the enrichment-plant operator would be in raising capital and building adequate capacity to meet nuclear-demand growth. In short, normal market forces should provide an adequate stimulus for tails-assay reduction to be implemented.

The advanced isotope separation technologies are in too early a stage of development to assess their potential to replace or be used in conjunction with existing processes. Successful technical development, combined with demonstration of economic performance, would lead enrichment operators to adopt the technology to meet new capacity requirements. These technologies are expected to have been technically demonstrated by about 1990, with implementation beginning shortly thereafter, depending upon economic and financing considerations. The estimated cost to complete the necessary research, demonstration and development could range from $500 to $800 million.

Recycle in Light-Water Reactors

Resource-utilization improvements can also be achieved by recycling uranium and plutonium from spent fuel in light-water reactors. The technical base for fueling light-water reactors with mixed oxides of uranium and plutonium is well advanced, although no fully commercialized system exists. Commercial deployment of recycle systems based on the currently conceived PUREX process could begin in the 1990 time frame, assuming completion of the technical work as well as licensing reviews in a timely manner. An equilibrium system of light-water reactors operating so that they recycled uranium and plutonium in amounts equivalent to that in their own spent fuel would utilize up to 40 percent less uranium than the NASAP reference light-water reactors on a once-through cycle and around 15 percent less than light-water reactors with all retrofittable improvements. Such a system would include enrichment facilities, reactors, facilities for spent-fuel storage, reprocessing, fuel fabrication and refabrication, waste management, and the transportation links between them.

Implications for International Deployment: Proliferation-Resistance Assessment -- As previously discussed, the most apparent new proliferation characteristics of recycle in light-water reactors (compared to those in once-through cycles) result from the addition of sensitive reprocessing facilities and widespread commerce in plutonium-bearing materials. Separated plutonium may be present in storage and in transport in forms that may be directly usable for nuclear weapons. Fresh mixed-oxide fuel itself could be converted to weapons-usable form through chemical processes requiring special handling, but not the massive shielding needed for spent-fuel reprocessing. In short, the recycle system represents a major step away from the more proliferation-resistant once-through cycle. Given the large number of light-water reactors likely to have been deployed throughout the world by 1990, proliferation resistance could deteriorate rapidly if recycle were to be adopted on a wide scale. Under such circumstances, implementation of proliferation-resistance improvement measures would become of paramount importance.

Resource Assessment -- The pace at which plutonium recycle could occur in light-water reactors would be dependent upon the rate at which reprocessing and plutonium fuel-fabrication plants could be placed in service. No such commercial facilities are operational in the U.S. today, and it would be at least ten years before the remaining technical and licensing issues surrounding the Allied General Nuclear Services (AGNS) reprocessing facility at Barnwell, South Carolina, could be resolved and the plant could be operational. If current U.S. policy to defer commercial reprocessing were to be changed, then plutonium recycle could begin about 1990, based on use of the Allied General Nuclear Services (AGNS) plant and recycle starting in a few reactors. The capacity of the AGNS plant would become fully utilized over the following decade, with additional capacity becoming operational after the year 2000. It has been assumed that the implementation of the near-term 15 percent improvement in once-through fuel utilization from higher fuel burnup and fuel-management changes would also begin in 1990 and would eventually be adopted for all light-water reactors.

These annual U_3O_8 requirements are compared in Figure 8. The annual U_3O_8 demand for the recycle system is about 21 percent lower than the once-through system with a 15 percent improvement and only 7 percent lower than the 30 percent improved once-through light-water reactor system. It should be noted that the annual uranium demand for all these systems can be further reduced by 13 percent if the enrichment tails are reduced from 0.20 percent U-235 to 0.10 percent U-235 and by 18 percent if the tails are reduced from 0.20 percent U-235 to 0.05 percent U-235.

Commercial Potential -- Recycle in light-water reactors in the U.S. would involve a higher level of commercial risk than once-through operation. Given current policy and licensing uncertainties, and because a reprocessing facility has no alternate commercial application, the private sector would be unlikely to pursue this technology without strong Government policy assurances. Even with a policy change, private investment in a reprocessing facility would not come without strong support by the Government and utilities alike. Assuming that the first commercial facility would be the AGNS plant, about $600 to $950 million would be required to put the plant in operation. Resolution of remaining technical and institutional issues would take about ten years. Thus, recycle could be available, if needed, around 1990.

The economic benefits of recycle may not be sufficient to justify the investment risks. The economics of recycle is closely tied to the cost of reprocessing; low-cost reprocessing favors recycle and high-cost reprocessing does not. Also, as the fuel-utilization efficiency of the light-water reactor once-through fuel cycle improves, the economics of recycle appears less attractive. Although there is no established U.S. commercial price for reprocessing services, NASAP cost estimates lead to the conclusion that, within the uncertainties, the comparative costs of recycle and once-through operation would be almost equal over a wide range of U_3O_8 prices, ranging from $100 per pound of U_3O_8 to more than $200 per pound. But much higher uranium prices might be required to justify the economic risks of adopting recycle.

Advanced Converter Reactors

Additional improvements in fuel-utilization efficiency can be achieved through use of advanced converter reactors. All nuclear power reactors that employ both fissionable (fissile) material, such as U-235, U-233, or Pu-239, and fertile material, such as U-238 or thorium, convert the fertile material to new fissile material while producing power. The measure of the efficiency of this process is called the conversion ratio (new fuel made in the reactor per unit of fuel fissioned), and is about 0.6 in today's light-water reactors.

The difference between the fissile content of fresh fuel and that of spent fuel approaches zero as the conversion ratio approaches unity. Because of losses in fuel processing, which can be a few percent, the conversion ratio must be a few percent over unity in order to achieve zero fuel make-up. Also, the initial fuel inventory required to start the system would tend to be larger as the conversion ratio increased.

Those systems with conversion ratios somewhat higher than that of the light-water reactors have been designated advanced converter reactors; those with conversion ratios greater than unity can produce more fissile material than they consume and have been called breeder reactors. These reactor types will be discussed separately.

The two advanced converter reactors discussed here are the heavy-water reactor and the high-temperature gas-cooled reactor. The heavy-water reactor considered by NASAP is similar to the natural uranium-fueled CANDU reactor, although the design has been modified to satisfy U.S. licensing standards and to improve the economics under U.S. conditions. Low-enriched fuel was substituted for the natural uranium in the CANDU design, primarily because uranium-oxide fuel enriched to 1.2 percent U-235 in combination with higher system pressure and temperature would improve uranium-resource utilization, would reduce fuel-cycle costs, and would reduce the rate of plutonium production. The high-temperature gas-cooled reactor studied is the design under current development in the U.S. Two versions of the system were considered--the steam (indirect) cycle and the gas-turbine (direct) cycle. These reactors would operate with a helium-cooled, graphite-moderated core, using a high-burnup uranium/thorium fuel which produces very little plutonium.

Reductions in uranium requirements on the order of 35 to 45 percent over a standard light-water reactor (5 to 15 percent over the improved version) could be achieved using advanced converters on a once-through cycle, and 40 to 70 percent, using recycle. In general, these reactors could not be brought into commercial use until about the first decade of the next century, given the long lead time necessary to develop and demonstrate the systems. The steam cycle version of the high-temperature gas-cooled reactor could be made available earlier than the direct cycle version, since the remaining development and demonstration steps are fewer in number and less complex technically.

Implications for International Deployment: Proliferation Resistance of Advanced Converters -- For once-through systems, various alternatives are currently under consideration. Most of these would seek to improve uranium utilization, to ease some concerns for security of supply and to reduce the impetus for reprocessing. Some modifications in the fuel for the standard CANDU heavy-water reactor may marginally improve its proliferation resistance. The use of uranium fuel enriched to 1.2 percent would improve uranium utilization substantially by reducing uranium requirements about 25 percent below requirements for the standard CANDU heavy-water reactor using natural uranium. It would reduce the amounts of plutonium in the spent fuel to about the level in current light-water reactors and reduce the amount of spent fuel generated from more than 4 to 1 1/2 times that of a light-water reactor. But while the use of such fuel would reintroduce a dependence on enrichment services, it could also provide a pretext for developing an independent enrichment capability.

The use of a once-through fuel cycle using 20 percent enriched uranium and the introduction of thorium have been considered for heavy-water and high-temperature gas-cooled reactors. As in the once-through light-water reactor cycle using low-enriched uranium fuels, the isotopic barrier would be retained, but it would reduce to about one tenth the separative work required to enrich fresh fuel for use in nuclear weapons. There would also be large amounts of similar material in the spent fuel, including U-233 of equivalent enrichment. On the other hand, the amount of plutonium in the fuel would be decreased, and the difficulty of extracting it would probably be increased. The use of highly enriched uranium feed in any of these reactor types would, of course, greatly decrease the proliferation resistance of the once-through cycle. In the case of the presently deployed and planned conventional light-water reactors, three elements--the cost and development time required for introducing new fuel types, the lack of clear market acceptance, and the nature of the differences in proliferation resistance--substantially reduce the attractiveness of choosing any of the once-through alternatives to the light-water reactor solely on the basis of proliferation resistance.

Alternative recycle systems were examined to assess their relative proliferation-resistance features. The proliferation resistance of plutonium recycle in heavy-water reactors would be essentially the same as that of the reference light-water reactor system, whether or not the fuel-utilization improvements were incorporated. Advanced recycle systems typically incorporate thorium to reduce consumption of uranium resources and to make the denaturing option available. Adoption of a relatively pure uranium/thorium cycle (with U-233 and no U-238) would have proliferation risks comparable to those of ordinary plutonium recycle systems, since fissile concentrations would be comparable and since weapons-usable material would become available through chemical separation (hot reprocessing, if the material is protected by a radiation barrier).

However, proliferation resistance may be increased if the fresh fuel is denatured. Isotopic enrichment would then be required to obtain weapons-usable U-233. Reprocessing and other recycle facilities could be placed in international centers operating in suitable locations under appropriate controls. In these centers, the extracted plutonium could be combined with thorium to fuel reactors which could then produce U-233. This U-233 would be denatured and used to fuel dispersed reactors, which would return their spent fuel to the international centers. But this system, which would require recycle facilities and interdependence between two reactor types, would not be preferable from a proliferation-resistance standpoint to an interdependent system which has reactors operating on low-enriched uranium fuel in dispersed locations and returning spent fuel to international centers. It would be preferable to a system which used mixed uranium/plutonium oxides to fuel the dispersed reactors.

Resource Use of Advanced Converters in the Once-Through Cycle -- Advanced converter reactors, such as the heavy-water reactor and the high-temperature gas-cooled reactor, use uranium more efficiently than the current once-through light-water reactor fuel cycles; an individual heavy-water reactor uses 42 percent, and a high-temperature gas-cooled reactor uses 30 percent, less uranium over a 30-year operating lifetime. However, the effect of any individual reactor on the uranium consumption of the total nuclear system is dependent on its ability to penetrate the market. For purposes of this analysis, the advanced converter reactor would be introduced in 2003, and would be able to capture an increasing fraction of new capacity plus replacements each year thereafter. However, a new reactor could not capture all new capacity plus replacements until about 30 years after its introduction. The introduction of advanced converters on the once-through cycle following a 15 percent improvement in light-water reactor fuel utilization would reduce uranium demand by about 10 percent, as shown in Figure 9. This alternative would be almost as effective as the potential 15 percent further improvement to the light-water reactor with once-through fuel utilization.

It is important to emphasize that the impact of advanced converter reactors on uranium requirements reflects the NASAP market penetration analysis and the continuing use of the once-through fuel cycle. With commercial introduction of an advanced converter beginning in 2003, the light-water reactor would still comprise over 70 percent of the operating nuclear capacity in the year 2025.

Resource Use in Advanced Converters with Recycle -- Further improvements in fuel utilization are possible if advanced converters recycle spent fuel. In general, advanced converter reactors recycling fuel are expected to use the thorium fuel cycle. This cycle involves the production of U-233 which is, from a physics standpoint, a better fuel for these reactors than uranium enriched in U-235. Two approaches to the making of U-233 were analyzed: (1) use of enriched (20 percent and 93 percent U-235) uranium/thorium fuel in light-water reactors and (2) use of plutonium/thorium fuel, also in light-water reactors. It was assumed that either fuel type could be used in light-water reactors beginning in 1990, and that the U-233 would be used in the advanced converters. However, recovery and recycle of the U-233 would not occur before 2000, and probably not until later.

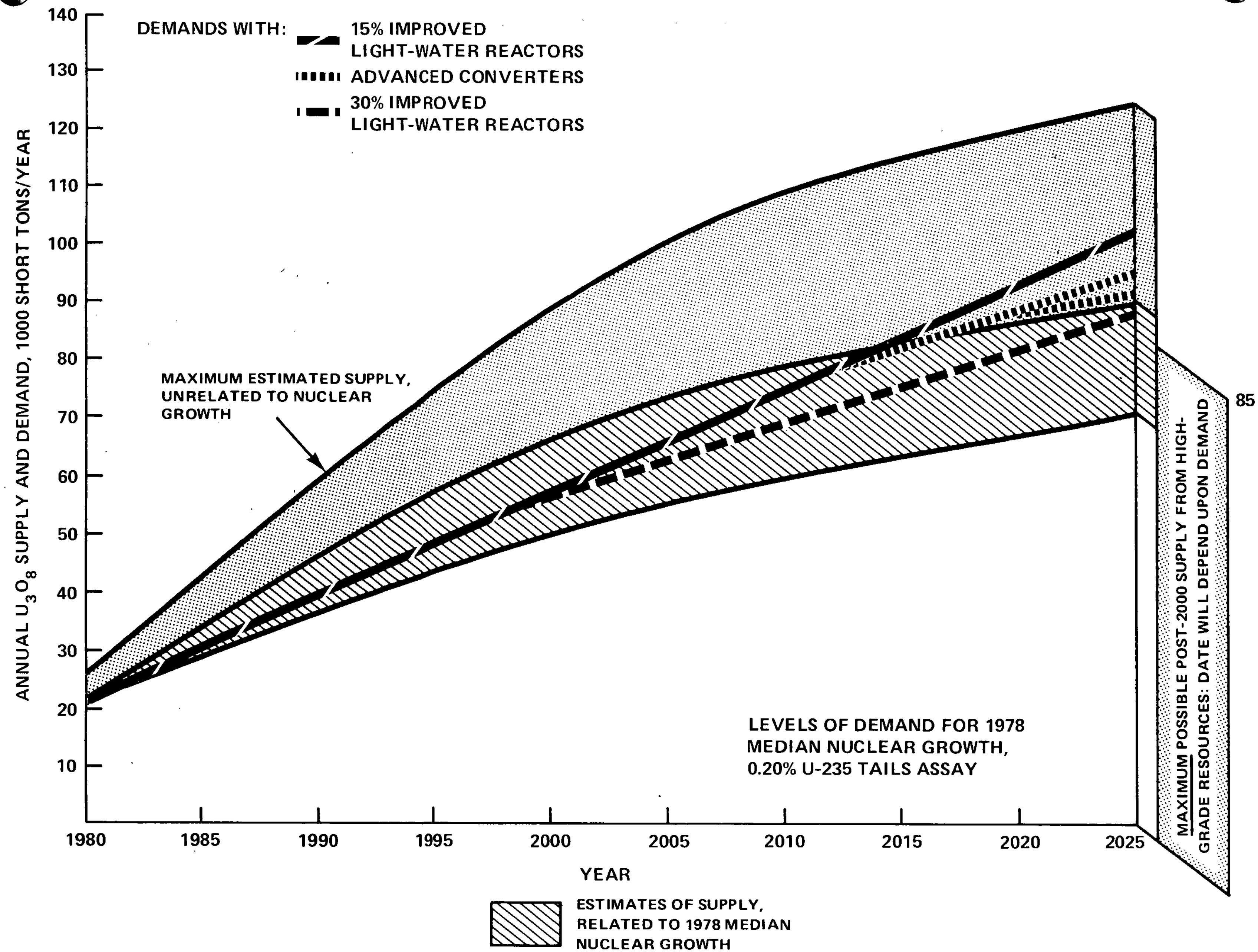

Figure 9. Effects on U_3O_8 Demand of the Introduction of Advanced Converters into a System of Improved Once-Through Light-Water Reactors

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

Enrichment plant tails assay would be 0.20 percent U-235 in all scenarios. If the U-233 were to be produced by fueling reactors with U-235 and thorium, large initial inventories of enriched uranium would be required. As U-233 was produced and recycled, uranium demands would diminish. U_3O_8 demand in 2010 would be nearly twice that for self-generated recycle in light-water reactors. With either the 1978 Median or High growths, there would be a supply/demand imbalance during the initial deployment stage. By 2025, there would be significantly reduced uranium requirements, but the earlier High requirements could preclude rapid deployment of this fuel cycle.

Should advanced converters penetrate the market at a slower rate, then the High peak uranium demand would be avoided, but the longer-term uranium demand would be higher than the demand with a more rapid market penetration.

Using plutonium obtained by reprocessing spent fuel from light-water reactors and combining it with thorium to produce U-233 in light-water reactors could avert uranium supply/demand imbalances through the year 2025, even with rapid introduction of advanced converter reactors. For both 1978 High and Median growth, the annual U_3O_8 supply would be adequate or nearly adequate if the large backlog of light-water reactor spent fuel were to be used as a source of plutonium until 2025, or probably shortly after, when the spent-fuel backlog would have been consumed.

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

Commercial Potential -- In contrast to evolutionary changes to existing technologies such as the light-water reactor improvements discussed earlier, advanced converters would represent a higher level of commercialization effort with attendant technical, financial, operational and possibly public acceptance risks, especially if reprocessing and recycle were utilized. Advanced converters would take longer to become available and, given the amount of time required to demonstrate new technologies, could not be introduced commercially, as a class, before the turn of the century and could not be commercially deployed in significant numbers much before 2025. None of these systems would offer significant economic advantages over light-water reactors unless uranium prices were in the range of $100 to $200 per pound of U_3O_8. Thus, natural market forces alone could not be expected to commercialize any advanced converter.

Commercial deployment could be effected only through heavy Federal involvement in the stages of research, development, demonstration, and precompetitive deployment. First would be a series of activities designed to ensure that the reactor system and the fuel-cycle facilities were advanced enough technologically to be a reliable electric power-generation system, one that could eventually be offered competitively to the utilities. The precompetitive deployment would begin when the demonstration of the technology had been completed and would involve deploying a series of reactor plants which would not yet be economically competitive with the existing system. It is anticipated that substantial manufacturing and construction learning would occur during this initial deployment. The reactors deployed during this phase might require subsidies, such as incremental investment costs over the existing light-water reactors, to induce private sector investment in the new system.

The estimated cost of research, development, and demonstration for advanced converters ranges from $2 to $5 billion, depending on the system, and the pace, or risk, of the program undertaken. In addition, precompetitive subsidies such as incremental investment costs above a light-water reactor system, could add $1 to $2 billion to the total cost of commercializing any new advanced converter system. Recycle operation would require additional research, development, and demonstration cost--$1.8 to $2.6 billion for the high-temperature gas-cooled reactor, for example. This initial investment cost for facilities would be partially repaid through the sale of electricity or fuel-cycle services. Lead plant costs, for example, could be almost fully recovered, as could lead fuel-cycle facility costs.

The steam-cycle high-temperature gas-cooled reactor has received most of the attention from the Federal Government, utilities, and vendors in the United States. Although it could operate on uranium, the high-temperature gas-cooled reactor has been designed for the thorium cycle, thereby decreasing the pressure on uranium resources. Also, according to some, the safety characteristics of this reactor might offer potential improvement over the light-water reactor, such as the thermal properties of the graphite moderator and lower expected radioactive releases. Interest in this reactor concept has recently shifted to direct-cycle version, a system with potential for process-heat applications, and, with dry cooling, for use in water-poor regions of the United States. The features of this fuel reactor system would be adaptable to both electric power generation and process-heat applications. The market potential for process-heat applications was not analyzed by NASAP.

The potential of the direct cycle in electrical markets would be determined primarily by how the market would perceive and react to this system's unique characteristic of low water consumption, its potential for improved safety characteristics, and the utilization of thorium resources.

At the current time, the sum of all these factors does not offer a clear advantage over the existing light-water reactor and its near-term improvements. Yet, assuming that this system were to be deployed after successful demonstration, could penetrate the baseload nuclear electrical-generating market (similar to the penetration experienced by the light-water reactors), and could eventually achieve a maximum annual market share of 50 percent, it could make as much as a 13 percent contribution of the installed nuclear capacity in 2025, if electrical-demand growth were high.

Because the heavy-water reactor could be deployed earlier, its potential market contribution by 2025 could be greater, given a similar set of market-penetration assumptions. However, the advantages of this system over the current light-water reactor, with its planned improvements, are so marginal that they would not be sufficient to generate significant market demand, at least until uranium cost becomes very high. Also, there is no significant private-sector domestic interest in this system.

Breeder Reactors

Of all the resource extension techniques being considered, breeder reactors are unique, since they have the potential to decouple power production from uranium supply. A number of concepts are currently under development both in the U.S. and abroad. Of those being investigated, the liquid-metal fast breeder reactor is clearly the front runner in terms of overall promise, from the standpoints both of technical and economic performance, and of timing as to when the technology could be available. The gas-cooled fast reactor, using the same fuel cycle as that of the liquid-metal fast breeder reactor, is perceived by some to have potential economic performance advantages also. This system is significantly behind in development, so that the effect of its deployment by 2025, even if research, development, and demonstration are pursued aggressively, would not be significant. Other reactor concepts may warrant increased development attention in the future. For example, the light-water breeder reactor may be a candidate for more extensive development because it is an extension of the light-water reactors presently in use and thus represents an evolutionary technology change. The light-water breeder is discussed separately in this report. Also, the gas-cooled fast breeder reactor could be a backup breeder technology, and any domestic effort could benefit from international interest. There are, for example, gas-cooled breeder programs in the Federal Republic of Germany and in Switzerland.

Breeder reactors produce more fissile material (Pu-239 or U-233) than they consume in the process of generating electricity. A typical liquid-metal fast breeder reactor design will generate about 1.2 to 1.4 atoms of fissile material for each atom fissioned. To achieve this performance, the reactors require the reprocessing and recycle of the fissile isotopes in the spent fuel.

These fast breeders operate at high temperatures, and the fuels operate at high power density and require a level of technology beyond that of the current light-water reactor fuel. However, a great deal of research and development work has been done both domestically and internationally on these systems. With an early decision to proceed with a demonstration plant, fast breeders could be deployable on a commercial scale in the U.S. before 2010. A later commitment to the next major facility along with proof of operation for each remaining major development step could result in a 2020 to 2030 commercial introduction.

<u>Implications for International Deployment: Proliferation-Resistance Assessment</u> -- While breeder reactor systems would afford a potentially inexhaustible nuclear-fuel supply, they would also represent a major departure from once-through light-water reactor systems in terms of proliferation risk. In many respects, the proliferation resistance of breeder systems would be

similar to that of recycle systems; however, there would be differences due to the increased flows of plutonium at higher concentrations.

Fast-breeder mixed-oxide fuels would have plutonium concentrations of 15 to 25 percent, considered to be weapons-usable, whereas recycle mixed-oxide fuels would contain only 4 to 6 percent plutonium, not considered to be weapons-usable. This feature would increase the vulnerability of the nuclear power system to subnational proliferation threats, particularly in countries deploying only the reactors. It would also increase the vulnerability of the breeder system to national threats, although most nations would probably employ out-of-system facilities to recover plutonium metal. Otherwise, the higher plutonium concentrations and other technical differences between breeder and recycle fuels would have only a marginal impact on out-of-system proliferation activities. The higher plutonium concentrations, for example, would permit the use of somewhat smaller facilities and less feed material.

Finally, because research and development activities, largely motivated by anticipated fast breeder needs, are already taking place, the proliferation vulnerabilities of fast-breeder systems could appear long before actual reactor deployment and must be accommodated in current efforts to establish a satisfactory nonproliferation regime.

A number of breeder systems have been investigated as alternatives to the liquid-metal-cooled design. Gas-cooled reactors and/or thorium-blanket concepts have a similar degree of proliferation resistance to that of the liquid-metal fast breeder reactor with uranium/plutonium fuel and would not appear to reduce significantly the prospects of proliferation. Advanced system concepts, such as the molten-salt breeder, are discussed later.

<u>The Impact of Fast Breeder Reactors on Domestic and World Resources</u> -- The fast breeder reactor does not require the mining of new uranium, but is dependent on plutonium recovered from light-water reactor fuel to provide initial inventories of fuel. The fast breeder reactor can also produce an excess of fuel over its lifetime which can be used to fuel new reactors in a growing nuclear power system without the need to mine uranium. Thus, electric power-generating systems which employ significant numbers of fast breeder reactors would require substantially less mined uranium than systems which do not. On the other hand, reprocessing is absolutely essential.

The introduction of the fast breeder reactor into a system of 15 percent-improved light-water reactors on the once-through cycle would result in a leveling off and then a decline in annual U_3O_8 demand; the peak of the annual demand would occur within about ten years after introduction, as shown in Figure 10.

This effect would depend on the rate of introduction of the breeder, which in turn would depend on the rate of reprocessing to obtain the plutonium for the breeder initial inventory. The uranium recovered from the reprocessed light-water reactor spent fuel contributes substantially to the reduction in uranium demand. In the 1978 High-growth case, about 21 GW of breeders would be introduced starting in 2006, before the uranium demand peaked at about 90,000 short tons of U_3O_8 per year in about 2015; reprocessing requirements would increase to about 7,600 t/yr by that time, equivalent to the annual spent-fuel discharge from about 500 light-water reactors. If the deployment of the fast breeder reactor did not begin until 2014, the peak in uranium demand would occur about seven years later, amounting to more than 100,000 short tons of U_3O_8 per year and lasting about a decade. Thus, with a high nuclear growth, early fast-breeder introduction would be an alternative to large-scale development of low-grade resources.

Should the High nuclear growth occur, the fuel utilization of the light-water reactor once-through fuel cycle might be improved more than 15 percent, and the enrichment plant tails assay could be reduced. Also, high-grade and low-grade uranium resources could be exploited to the maximum. However, since the fast breeder reactor would tend to significantly decrease the demand for enriched uranium within ten years after its introduction, maximum development of uranium supply facilities and added enrichment-plant capacity for reduced tails assay might result in surplus facilities before the end of their useful life. Thus, rapid deployment of fast breeder reactors may reduce the incentive to invest in uranium mining and enrichment facilities.

Assuming the 1978 Median nuclear demand and fast-breeder introduction in either 2006 or 2014, uranium supply should not be a problem, and in either case, annual demand would be declining by 2025. The resource-conservation incentive for introducing the fast breeder reactor is that it is an essentially inexhaustible source of electrical energy.

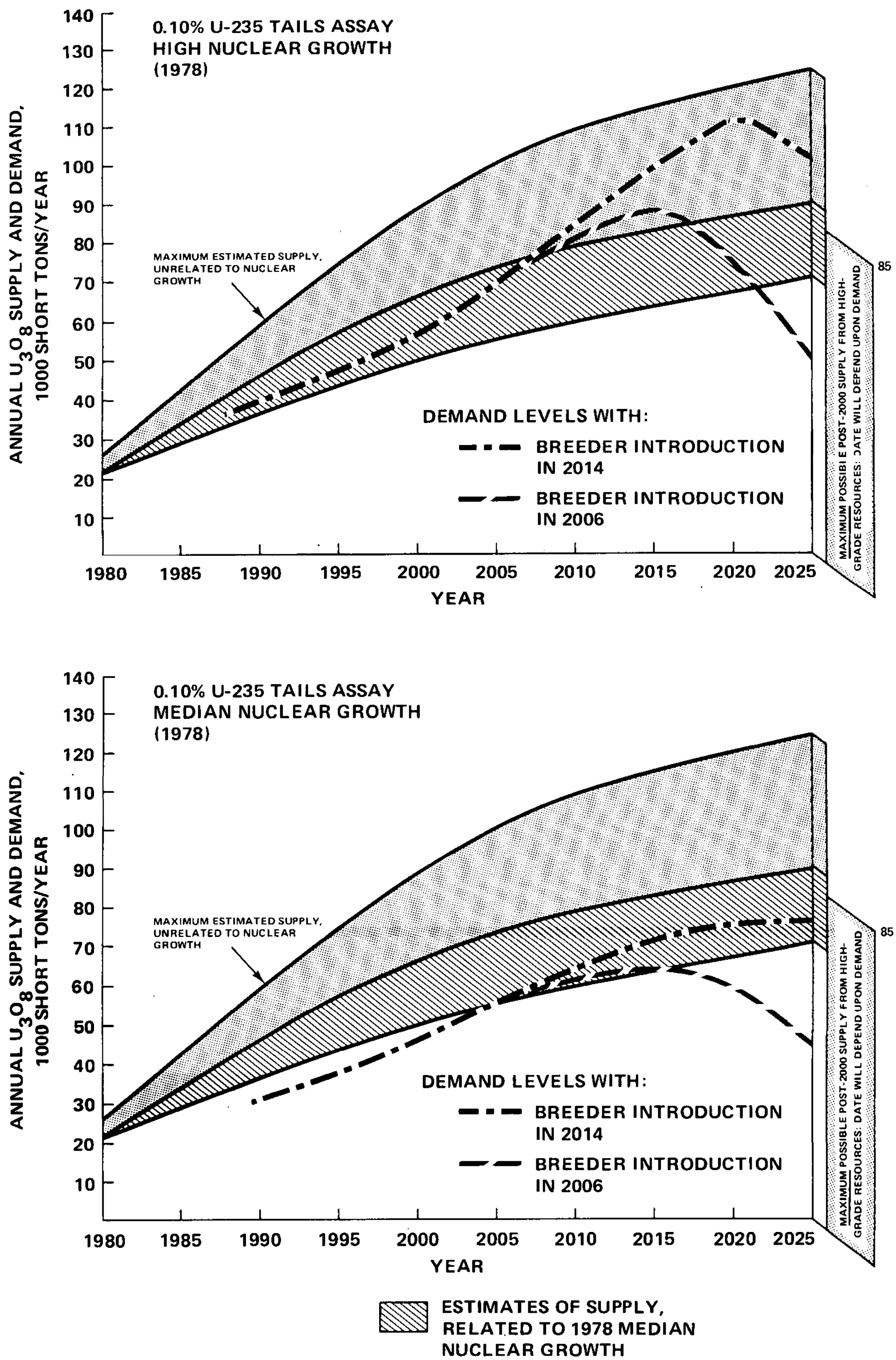

Figure 10. Effect of Breeder Introduction Date and Nuclear Growth on U_3O_8 Demand in the U.S. (for a System of Liquid-Metal Fast Breeder Reactors and 15% Improved Light-Water Reactors)

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

Internationally it was assumed that the breeder would probably be introduced into a system consisting primarily of 15 percent-improved light-water reactors using an enrichment tails assay of 0.10 percent U-235. Two scenarios were assumed leading to liquid-metal fast breeder reactor deployment of about 10 percent of installed foreign capacity by 2025 in the slow scenario and 20 percent in the rapid scenario; deployment in the U.S. was assumed to begin in 2014 in the slow scenario and 2006 in the rapid scenario. The impact of a slow deployment of the fast breeder reactor through 2025 would be about the same as that for the 30 percent-improved light-water reactor on the once-through cycle with 0.05 percent U-235 tails assay; the rapid breeder deployment would have greater impact, particularly after 2025. The difference between the slow and rapid breeder reactor deployment rates does not apear to be significant through 2025 if the current nuclear-growth trend, which is 35 to 40 percent below the INFCE Low growth projection, persists.

Achieving the maximum improvements in light-water reactor uranium utilization on the once-through cycle could reduce the urgency for rapidly deploying the fast breeder reactor to avoid foreign uranium supply/demand imbalances through 2025, if uranium supply and demand are considered on a worldwide aggregated basis. However, rapid deployment of the fast breeder reactor might be more important for higher growth rates and for the long-term needs beyond 2025.

The introduction of the fast breeder reactor into the U.S. would further reduce the possibility of a global supply/demand imbalance. The achievement of the maximum light-water reactor fuel utilization improvements in countries outside the centrally planned-economy areas would keep the demand below the Low supply capability even with a slow fast breeder reactor deployment.

Commercial Potential -- Breeder reactors such as the liquid-metal fast breeder have high long-term commercial potential, since they can provide a virtually inexhaustible supply of electrical energy, and their economic competitiveness would improve as the price of uranium increased. As with advanced converter reactors, however, the commercialization of breeder reactor systems would represent higher initial risk--financially, operationally, and possibly from an institutional (public acceptance and licensing) standpoint. As with the advanced converters and other new systems, the private sector would perceive major barriers to commercialization, such as uncertain future electrical demand and economic performance and a perceived lack of a national commitment to deployment of advanced nuclear systems.

International research, development, and demonstration of the liquid-metal fast breeder reactor system has progressed to the point where it has now been well demonstrated at 300 MW of rated electrical capacity, a relatively small size for commercial application. A larger breeder is now under construction in France, so it remains to be proved that the system can operate reliably and economically at sizes comparable to the light-water reactors with which it must eventually compete.

The sodium-cooled fast breeder reactor system is generally more complex than the light-water reactor. The technology needs to be demonstrated long enough (1) to learn how the materials used in the expected operating environments would behave; (2) to establish the required fuel performance; (3) to ensure that the large components for plants of commercial size would operate reliably and predictably; and (4) to ensure that the level of safety and environmental impact would be acceptable. The entire system must prove effective and must generate electricity in a utility system long enough to show some indication that it could do so economically. Reprocessing and fabrication facilities, too, must be demonstrated. Finally, the reactor system and the associated fuel-cycle facilities must be shown to be licensable by the U.S. Nuclear Regulatory Commission.

The estimated cost of completing the required research, development and demonstration is $9 to $11 billion for the reactor plant and $1.5 to $2 billion for the fuel-cycle facilities. If deployment of the system were to be aggressively pursued, the necessary research, development and demonstration steps could be completed in time for the first commercial plant to operate in 2006. A more conservative program, one involving less technical and economic risk, would target operation of the first commercial plant for 2014 and a later commitment to the next development facility would result in commercial operation in 2020 to 2030.

Based on NASAP's estimates of breeder capital cost and uranium price and supply, the fast breeder reactor may first become economically competitive with the existing light-water reactor between 2010 and 2020. The commercialization of the fast breeder would probably require deployment of reactor plants before they were commercially competitive. Two to five such plants might be needed, depending upon the scope and pace of research, development and demonstration. Breeders would entail a higher capital cost than the competing light-water reactors: These breeders would be candidates for a Federal subsidy estimated at $1 to $4 billion. Lead fuel-cycle facilities would probably be constructed before natural market forces induced private capital investment in fuel-cycle facilities; hence, these would also be possible Federal subsidy items. The cost of these facilities has been estimated at $2 to $3 billion. Investments in the precompetitive phase could potentially be recovered through sale of electricity and fuel-cycle services.

Historically, private industry and the Federal Government have viewed the liquid-metal fast breeder reactor as the advanced technology most likely to replace the light-water reactor when uranium scarcity and economics dictate such a transition. Based on this perception, the Government's plans for research, development, and demonstration, and industry's manufacturing infrastructure and venture plans were designed for the eventual transition. For example, some manufacturing facilities were designed and built in sizes that would facilitate modification for the breeder's needs. Should the current lower nuclear-growth estimates prove to be correct, vendors would find themselves with excess manufacturing capacity, and alternate uses for these facilities may have to be found. For some time, significant effort and expenditure have supported a fast-breeder program; no other system has benefited in this way from both great commercial interest and strong Government sponsorship.

Although the private sector remains interested in the liquid-metal fast breeder reactor, sponsorship, as measured by financial commitment, has been largely the Government's. The private sector did commit funds to previous demonstration projects, but the amounts were small compared with the total bill for research, development and demonstration. Given today's climate, the prospects for private sector sponsorship are virtually nonexistent, and the Government would have to fund most of the $10 billion or more that would be required.

In summary, while its commercial development potential is currently low, the long-term market potential of the liquid-metal fast breeder reactor is good. Its market outlook is strongly enhanced, first, because its economic competitiveness will improve substantially as the cost of uranium increases, and, second, by its ability to extend uranium resources almost indefinitely. Private sector interest would be a strong motivating force. Once it has been perceived to be economical, the system could be deployed rapidly unless moderated by institutional constraints or the utilities' continuing problems with raising capital.

Assuming that the system were deployed immediately after successful demonstration, and penetrated the nuclear market as the light-water reactor penetrated the baseload electrical generating market, and that it eventually captured a maximum annual 50 percent market share, its potential contribution would, in the case of high electrical demand, be as much as 13 percent of the installed nuclear generating capacity in 2025. The contribution of the breeder reactor could be higher in some foreign countries than in the United States.

The commercial potential of the gas-cooled fast reactor was also assessed. This reactor was conceived as a back-up to the liquid-metal fast breeder reactor, and as such, it was to have taken advantage of developments in allied technologies--the liquid-metal fast breeder's fuel, fuel-cycle facilities, and the resolution of generic licensing, safety, and environmental issues related to fast breeders; and the high-temperature gas-cooled reactor's components and systems such as the reactor vessel, steam generators, and helium-purification and helium-handling systems. As currently conceived, it has the potential for lower capital cost and for better overall economics than the liquid-metal breeder using the same fuel. However, significant engineering questions remain to be answered to support these potential attributes.

Being dependent on the developmental progress of two other technologies, the gas-cooled fast reactor system as a whole has been less developed. The first major step would be to show that, in a small plant, the entire system works. Following this step, the system must prove its performance characteristics in a plant of commercial size and demonstrate its operating reliability and, ultimately, its economic competitiveness. This could be accomplished with one or two reactor plants, depending upon the level of risk underlying the approach to research, development, and demonstration. If deployment of the gas-cooled fast reactor were to follow that of the liquid-metal fast breeder as currently planned, the fuel-cycle facilities required for this system would be available. However, if it were to be developed without the parent technologies, the effort would need to be substantially increased, and would include demonstration of the fuel-cycle facilities.

The estimated cost of completing the research, development, and demonstration required for the gas-cooled fast reactor as a back-up breeder is $5.3 to $7.3 billion. Like the liquid-metal fast breeder reactor, the gas-cooled fast reactor would require precompetitive deployment of reactor plants, which, if aggressively pursued, could be introduced between 2015 and 2020; precompetitive costs would come to several billion dollars. With a high-risk, accelerated approach to research, development, and demonstration, the earliest date the first commercial (precompetitive) plant could operate has been estimated to be in 2016. A more conservative, risk-balanced plan would schedule the first commercial plant for operation in 2024.

The overall market potential of the gas-cooled fast reactor would be low if the liquid-metal fast breeder were to be pursued, since it would have to share the breeder market and the liquid-metal reactor could be introduced earlier. It would be higher if the liquid-metal fast breeder reactor were not pursued. As a back-up breeder, it is not clear whether, or how, the gas-cooled fast reactor might enter the market. If it were to compete with the liquid-metal fast breeder for the fast breeder reactor's share of the nuclear market, then its penetration would probably be significantly slower than if the gas-cooled fast reactor were deployed in competition with the improved light-water reactor. In this situation, the liquid-metal fast breeder reactor would already be deployed, possibly with more than one reactor supplier, and its cost would reflect operating experience. The gas-cooled fast reactor would essentially be competing without benefit of learning. The precompetitive cost would have to be subsidized in some way if it were to compete on the basis of its mature peformance characteristics. Penetrating the nuclear market as the light-water reactor did the baseload electrical generation market, and assuming an eventual annual maximum market share of 50 percent, its potential contribution to the nuclear electrical generation capacity could be as much as 4 percent in 2025 under a high electrical demand growth scenario.

Water-Cooled Breeder Reactor

A number of different water-cooled breeder reactor concepts (including a heavy-water version) are being investigated by the Department of Energy's Division of Naval Reactors. However, NASAP's analysis has focused on the light-water concepts, which are more developed than the heavy-water concepts. One of the light-water breeder systems is being demonstrated at the Shippingport Atomic Power Station.

The light-water breeder reactor is an extension of light-water reactor technology, and would be designed to operate at a conversion ratio of 1.0 or slightly higher. The plant components and equipment would be essentially the same as those of pressurized-water reactors, but the fuel design would be different. This system would make use of thorium-based fuels and breeding is anticipated, using a fuel cycle based on highly enriched U-233 and thorium. The light-water breeder reactor would require reprocessing and recycling of fuel, and since U-233 is not found in nature, it must be produced in a reactor. Thus, the introduction of light-water breeder reactors would require the production of U-233 and would occur in two phases, a prebreeder phase and a breeder phase. These phases could involve two separate reactor designs or a single reactor design with two sequential fuel types. In one of the latter options, the second phase is to operate the reactor as a high-gain converter, which has a conversion ratio of less than one.

The prebreeder would be characterized by relatively high uranium consumption, since the prebreeder would use a uranium/thorium fuel with a relatively high U-235 content. The U-233 produced by prebreeders would be used to fuel reactors in the breeder phase which could have little or no requirement for natural uranium. Both prebreeders and breeders would use essentially the same reactor and plant components as the pressurized-water reactor, but would substitute different core, fuel, and control-system designs. One of their advantages would be extensive use of the existing manufacturing facilities of the light-water reactor.

Prebreeders could use plutonium/thorium fuels to produce U-233 for breeders. Use of plutonium in this manner would assume that the reprocessing proliferation and safeguard issues had been resolved. In addition, it is also possible to produce U-233 in current light-water reactors by substituting thorium for U-238 as the fertile material.

Implications for International Deployment: Proliferation-Resistance Assessment -- In contrast to denatured recycle systems, the light-water breeder reactor relies on highly enriched U-233 and would probably be relatively low in proliferation resistance, although perhaps comparable to the plutonium recycle in a light-water reactor, which uses plutonium in the fresh fuel. Like that of the plutonium recycle systems, the proliferation resistance of systems using highly enriched uranium might be improved somewhat by technical measures and by confining reprocessing and fabrication activities to plants under international auspices.

Since the light-water breeder reactor fuel-cycle systems require reprocessing and depend on the recycle of highly enriched U-233, their proliferation resistance would certainly be no greater than that of the recycle system if they were deployed under national control in non-nuclear-weapons states.

One modification of the light-water breeder, mentioned earlier, is a concept using denatured U-233/thorium fuel; it cannot breed and has been termed a high-gain converter. The denatured U-233 high-gain converter would have the same proliferation characteristics as other denatured cycles requiring reprocessing.

The Impact of Water-Cooled Breeder Reactors on Domestic and World Resources -- The water-cooled breeder reactor has been advanced as a reactor system that would significantly reduce future uranium consumption. The rate of deployment of the prebreeders in the system determines the U_3O_8 consumption, if the prebreeder uses a uranium/thorium fuel with a relatively high U-235 enrichment. However, if a plutonium/thorium fuel is used in prebreeders, there is no U_3O_8 requirement for those reactors, assuming the plutonium is obtained by reprocessing light-water reactor spent fuel. The U-233 produced by prebreeders is used to fuel reactors in the light-water breeder-reactor phase, so the breeder has little or no requirement for U_3O_8. Although light-water breeder reactors generate new U-233 at approximately the same rate that they consume it, some portion of a growing system must always consist of prebreeders. These prebreeders could furnish the additional U-233 to make up for losses, and to provide for system expansion. It was assumed that the light-water breeder reactor concept was introduced into a system of 15 percent-improved light-water reactors. A seed/blanket type of light-water breeder was used for the uranium/thorium-fueled scenarios, and a high-gain converter was used for the plutonium/thorium-fueled scenarios.

Rapid deployment of a light-water breeder reactor system based on initial production of U-233 in U-235/thorium-fueled prebreeders would have high initial requirements for uranium, but within ten years of introduction of the breeder, annual uranium demand would peak and begin to decline. If the prebreeder reactors are deployed more slowly, the U_3O_8 demand peak associated with rapid deployment can be avoided. However, this results in the deployment of fewer light-water breeder reactors by 2025 and, consequently, higher long-term annual and cumulative uranium consumption. A range of deployment rates was considered by varying the fraction of new and replacement reactors which are prebreeders. For the 1978 Median-growth rate, it was found that if 30 percent of new reactors are prebreeders, the large peak in demand during initial deployment could be avoided and over the long term, annual uranium requirements would rise at a slower rate, eventually beginning to decline. The annual U_3O_8 requirements for a system of prebreeders and light-water breeder reactors is presented in Table 14. The prebreeders are deployed into a system of 15 percent-improved light-water reactors beginning in 1990 for two prebreeder introduction rates. The rapid deployment scenario results in a faster buildup and faster decline in uranium requirements. With the

TABLE 14. ANNUAL U_3O_8 DEMAND FOR SYSTEMS OF LIGHT-WATER REACTOR PREBREEDERS AND BREEDER REACTORS[1]
(Thousands of Short Tons)

	in 1990	in 2000	in 2005	in 2015	in 2020	in 2025
Rapid deployment (begin deployment 1990, 100% of market by 2000)	52	66	83	45	34	33
Moderate deployment (begin deployment 1990, 30% of market by 1995)	50	56	66	79	77	73

[1] 1978 Median nuclear growth, 0.20% enrichment plant tails assay

moderate deployment rate, uranium supply would appear to be adequate through 2025; a nuclear growth of about 12 GW per year could be sustained for at least several decades thereafter. If the higher uranium supply range is achieved, supply would not be a problem for the rapid deployment scenario.

If a high nuclear growth rate resumed in the post-2000 period, the same uranium demand trends would occur, but supply would be a much greater problem, particularly with rapid deployment of prebreeders, and the concomitant sharp increase in requirements during initial deployment. With the moderate deployment rate, a supply/demand imbalance would occur around 2025 even with maximum production from high-grade resources and near-maximum production from low-grade resources.

In summary, it is possible to use enriched uranium in a uranium/thorium prebreeder to make the transition to a U-233/thorium-fueled light-water breeder reactor without encountering a uranium supply/demand imbalance with a Median growth rate of about 12 GW per year; this growth rate could be sustained for several decades after 2025. However, aggressive uranium-resource development, improvement in the fuel utilization of light-water reactors, and possibly reduction in enrichment plant tails assay would be required; otherwise, the deployment rate of prebreeder reactors would be constrained, and light-water breeder reactors would have marginal impact on uranium requirements during the period through 2025. The nuclear system growth rate that can be sustained with the uranium/thorium approach to introducing the light-water breeder reactor may be limited to about 12 to 15 GW per year.

A uranium supply/demand imbalance could also be avoided with prebreeder light-water reactors using plutonium/thorium fuel. If plutonium-fueled prebreeder reactors were introduced in the 1990's with 1978 Median nuclear growth, the annual demand would not reach 60,000 short tons U_3O_8 per year until 2025. If a High nuclear growth rate resumed after 2000, demand would grow to about 100,000 short tons U_3O_8 per year by 2025, and large-scale development of low-grade resources would be required to sustain this growth rate. Uranium supplies would not appear to be a problem until about 2025.

It appears that the plutonium/thorium strategy leading to the light-water breeder reactor may not be able to sustain a growth rate much larger than the Median nuclear growth of about 12 to 15 GW per year and that this growth rate could be sustained with a production of about 50,000 to 65,000 short tons U_3O_8 per year for several decades after light-water breeder reactor introduction.

Commercial Potential -- Factors in the commercial potential of the light-water breeder reactor include its evolutionary status relative to the existing light-water reactor technology and its requirement for bred U-233; industry interest in commercial prospects of the current research and development programs under way at the Department of Energy; and the use and availability of reprocessing and fabrication facilities for U-233 fuel. If plutonium is used to augment U-235 as prebreeder fuel, there is a requirement for reprocessing and fabrication facilities for this fuel as well, adding to the uncertainty regarding assurance of recycle technology to support the desired deployment rate.

NASAP's economic analysis of light-water breeder reactor concepts indicates that, at the present time, the high-gain converter is the most promising concept for competing economically with the improved light-water reactor. Therefore, this concept was chosen for the commercial assessment. Some of the other concepts have better characteristics for resource utilization and could be selected if uranium resource scarcity was the main decision factor. The high-gain converter has a conversion ratio of about 0.9 and is therefore not a breeder. However, it would be much more resource-efficient than the current light-water reactor. Other light-water breeder reactor concepts may prove to have commercial potential in the future. Industry's interest in the results of the underlying research and development programs for such concepts will help determine this potential.

Since the systems and components of the high-gain converter reactor are essentially the same as those in the pressurized-water reactor, no plant-related demonstration would be required. Fuel performance, reactor control systems, and recycle facilities would need to be demonstrated, however.

The fuel design of the high-gain converter is based on the Shippingport U-233/thorium fuel now undergoing extensive testing. A companion program has been designed to establish needed information for U-235/thorium fuel, which will be used for the prebreeder phase. Plutonium is not included in this program, so that if it were to be used, subtantially more development work would need to be done.

Fuel-performance data from actual system operation is a prerequisite to utility acceptance, such as is the case in the extended burnup fuel for light-water reactors. Experience with at least one batch of fuel assemblies of the proposed commercial U-235/thorium and U-233/thorium fuels would be required. However, if fuel designs using U-235 and U-233 that would be offered for commercial applications are essentially the same as those being demonstrated at Shippingport and associated programs, then it is likely that very little, if any, additional irradiation tests would be required to establish generic fuel performance. However, the nuclear steam-supply-system vendors, as fuel fabricators and offerers, would need to conduct programs to ensure licensability and to provide technical bases for performance warranty of fuel designs specific to each of their systems.

Batch or full-core fuel-performance demonstrations can be conducted in a lead plant, which would either be a retrofitted operating pressurized-water reactor or a new pressurized-water reactor modified for high-gain converter operation. While use of an operating pressurized-water reactor as the lead plant would reduce capital investment, subsidies would probably still be required. These subsidies would cover the owner's costs for possible downtime and replacement power. It might also be necessary to subsidize other items that the utility might feel were essential to protect its interest, since it would be agreeing to convert what would normally be a baseload plant, with predictable capacity factor, into an experimental facility.

Recycle technology, including facility operation would need to be demonstrated for this system. Demonstrations would be needed for uranium/thorium fuel facilities, for the system using U-235 for prebreeders and U-233 for the high-gain converter. Additional recycle facilities for plutonium would also be required if it were used for the prebreeder phase. All recycle facilities would need processes demonstrated in hot pilot plants to establish performance parameters, although the technology for plutonium-recycle facilities is more advanced.

The schedule for research, development, and demonstration of fuel-performance and fuel-cycle facilities is the primary determinant in positioning the high-gain converter reactor for deployment. If the present program continues to 1985 and the decision to proceed is made at that time, the estimated cost of completing the required research, development, and demonstration is $1.1 to $2.4 billion for the reactor plant, and $1.7 to $2.5 billion for the fuel-cycle facilities with the U-235 prebreeder fuel. Use of plutonium in prebreeders would increase these costs to $2.6 to $4.0 billion. If a decision were to be made earlier, say in 1980, the cost could be less. The low end of the range for the reactor plant cost is for retrofitting an operating plant. Subsidy costs, as discussed earlier, might also be needed.

The time when the high-gain converter could become competitive with the improved light-water reactor depends primarily on nuclear energy demand and uranium supply projections, given the NASAP estimates on fuel-cycle facilities costs. For a High nuclear energy demand, Low uranium supply scenario, the transition point at which the high-gain converter could be economically competitive might occur before 2000. On the other hand, Low nuclear energy demand and High uranium supply would put this date at around 2025 or beyond. The High nuclear energy demand scenario must be considered a low-probability event at this time.

If the system were competitive with the improved light-water reactor by the time it is deployed, no precompetitive plants would be required. However, it would be necessary to construct recycle facilities before any substantial market demand could occur. A subsidy for this front-end investment for lead facilities may be required to induce the investment of private capital in fuel-cycle facilities. The assured availability of these facilities would make the fuel-cycle cost more certain, an important factor in obtaining utility commitments to the high-gain converter during this period. The estimated cost for the lead light-water facilities ranges from $5 to $7 billion for plutonium/thorium and uranium/thorium recycle requirements. This investment could potentially be recoverable from operation of these facilities.

The market potential of the high-gain converter reactor would be heavily influenced and made more favorable by its enhanced resource-utilization characteristics. In addition, the system's economic competitiveness would improve as uranium cost increased, and the system would enable the use of thorium resources. Since it is not a breeder, however, the high-gain converter reactor does not eliminate dependency on uranium resources. With the supply network for the plant already in place, the reactor vendors need build up only the fuel-fabrication facilities. This has not stimulated private sector commercial interests to date, however. The fuel-cycle facility and other infrastructure requirements during transition from completion of research, development and demonstration to commercial deployment of the high-gain converter reactor are substantial and could be an obstacle to private sector acceptance of the system.

Assuming that this system would be deployed following completion of research, development and demonstration; would penetrate the nuclear market as the light-water reactors did the baseload electrical generating market; and would eventually achieve a maximum annual market share of 50 percent, then its potential contribution to electrical generation would be up to about 30 percent of the installed nuclear capacity in 2025. These potential contributions are higher than those of other new systems discussed previously and reflect the sensitivity of market share to the system introduction date. Because it could be introduced earlier than other systems, the light-water breeder reactor might have made a greater contribution by the end of the study time horizon.

The market potential of the other water-cooled breeder reactor designs being analyzed by the Department of Energy is uncertain at the present time and must await results of the research and development programs. While the high-gain converter would appear economical relative to improved light-water reactors at uranium prices of about $100 per pound U_3O_8, other versions of the light-water breeder reactor would appear to be uneconomical until U_3O_8 prices reached $200 per pound.

Symbiotic Systems

Thermal reactors (advanced converter as well as light-water reactors) can be operated in a symbiotic strategy with fast breeder reactors. That is, fast breeders would produce fissile material to be used to fuel converter reactors, and breeders could use plutonium from converter reactors and the spent fuel stockpile. Thus, breeders would be used in a complementary fashion to converters, in principle, supplying all their fissile requirements. The mix of breeders and converters--called a symbiotic system--could be optimized to produce an overall system effectiveness (lower system cost) which is higher than either breeders or converters operating alone. The objective of developing advanced converters in conjunction with fast breeders is to provide maximum flexibility in breeder deployment. Flexibility arises from the capability to meet different demand projections while maintaining minimal dependence on fast breeders.

Assuming that current Federal and private sector roles are maintained (that is, the private utilities own and operate the nuclear plants), symbiotic strategies could imply a much higher level of cooperation among utilities aimed at overall system (interregional) mix and optimization. This cooperative decision-making could come at the expense of an individual utility's flexibility to create generating mixes for its own service area. If Government ownership and/or management of utilities with breeder reactors and converter reactors were utilized, national optimization schemes might be more workable in practice. Such ownership/management arrangements would represent a significant change in the current roles of the Federal Government and the private sector.

If advanced converters, which would have reduced fissile requirements, particularly if operated on the thorium cycle, were among the thermal reactors deployed, fewer breeders would be required to support a fixed generating capacity. However, symbiotic systems with advanced converters like high-temperature gas-cooled reactors or heavy-water reactors on the thorium cycle would require the development of two major fuel cycles, one based on plutonium and another on thorium. Thus, the research, development, and demonstration and investment costs and the system complexities involved would be increased over a strategy which emphasized only one fuel cycle.

For these reasons, symbiotic systems would not be expected to be deployed in the time period covered by the NASAP report--from now to 2025. In the long term, the importance of such strategies would depend on breeder economics and uranium scarcity.

Advanced Concepts

A number of less-developed nuclear concepts were studied because of their apparent potential for contributing to the long-term supply of electrical energy in a proliferation-resistant and resource-efficient manner. The fast mixed-spectrum reactor and the denatured molten-salt reactor would not require external reprocessing facilities. The mixed-flow gaseous-core reactor would have very low fuel inventories and high fuel utilization. Fuel-producing concepts, such as the linear-accelerator fuel-regenerator reactor, the electronuclear fuel-producer reactor or the fusion-fission hybrid reactor, have been suggested as ways to produce significant quantities of fuel for use by dispersed reactors. These systems are, for the most part, in the earliest stages of research, and in some cases, technical feasibility has not been demonstrated.

Fast Mixed-Spectrum Reactor -- The fast mixed-spectrum reactor would differ 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 reactor would initially be loaded with low-enriched uranium fuel; and at equilibrium, make-up fuel would be either natural or depleted uranium.

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 denatured molten-salt reactor would use a uranium/thorium fuel with U-233 and U-235 at low enrichments, and the plutonium that would build up in the circulating salt would be physically inaccessible for diversion.

Mixed-Flow Gaseous-Core Reactor -- The mixed-flow gaseous-core reactor is characterized by the use of a fissioning gas mixture as its fuel source with the continuous removal of fission products. 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.

Linear-Accelerator Fuel-Regenerator Reactor -- The linear-accelerator fuel-regenerator reactor would produce fuel for other reactors rather than 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. The reactor would be designed to produce fuel by increasing the fissile plutonium content of light-water reactor fuel elements arranged to form a subcritical fission blanket, that is, a fission blanket which is unable to maintain or increase fission power without the use of an external source of neutrons.

Electronuclear Fuel-Producer Reactor -- The electronuclear fuel-producer reactor would use a linear accelerator to produce a beam of high-energy protons which would strike a liquid-sodium target to produce neutrons that subsequently would react with a subcritical blanket of fissile and fertile materials. 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. One fuel-producer reactor would provide the fuel for about five similarly sized light-water reactors. The concept differs from the fuel-regenerator reactor in that it would require a reprocessing cycle to recover the U-233 that is produced, and would use plutonium fuel.

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. The blanket could produce sufficient fissile fuel to operate several fission reactors and simultaneously produce electrical power. The hybrid reactor would produce its own tritium from lithium-bearing fuel. The hybrid reactor fuel cycle would require reprocessing and fuel fabrication and would involve the handling of substantial quantities of weapons-usable materials.

Implications for International Deployment: Proliferation-Resistance Assessment -- Commercial introduction of any of these systems is expected to take 40 years or more. After initial introduction, any concept would require additional time for deployment before contributing in a major way to energy production. Meanwhile, a large number of more fully developed systems would be deployed, and, accordingly, even though some of the reactor concepts considered may offer possible benefits for proliferation resistance, none can influence the overall level of proliferation risk for a long time.

Both the molten-salt and gaseous-core reactors are perceived to have similar proliferation-resistant features, in particular, the limited access to fissile material and the difficulty of removing it undetected from the two fuel cycles. The fast mixed-spectrum reactor fuel cycle would be slightly more vulnerable to proliferation because its spent fuel would contain substantially more plutonium than spent fuel from light-water reactors operating in the once-through mode. However, the institutional controls needed to minimize proliferation risk with the fast mixed-spectrum reactor are similar to those required for the once-through light-water reactor system and would therefore be in place. Similar to that of the fast mixed-spectrum reactor, the fuel that would be used in the fuel-regenerator reactor would contain substantial quantities of plutonium after regeneration; the accelerator would also have to be carefully safeguarded to prevent its being used as a covert source of weapons-usable material.

The other fuel-producing concepts, the fuel-producer and the hybrid reactor, would produce significant quantities of fissile fuel for use by dispersed reactors. They could be converted easily to the production of weapons-usable materials, and only institutional controls could keep them in the nuclear power fuel-generation mode. Accordingly, their deployment should be limited and under appropriate international auspices. The dispersed reactors fueled with regenerated plutonium/uranium or denatured uranium would be somewhat less proliferation resistant than reactors with once-through cycles using low-enriched uranium because of the greater accessibility of weapons-usable material in the fabrication and reprocessing facilities.

Resource Assessment -- All six advanced concepts would use uranium more efficiently than the light-water reactor. The gaseous-core reactor could substantially reduce dependence on mined uranium because all fertile and fissile material loaded into the reactor would be burned. This would yield an increase of more than an order of magnitude beyond the present light-water reactors, in the amount of electrical energy generated per unit of U_3O_8 used. The other concepts would be less resource-efficient, but would still give a two- to four-fold improvement in uranium utilization. Also, alternate fuel-management schemes could substantially increase the fuel efficiency for these concepts (for example, reprocessing of fuel for the molten-salt reactor or reconstituting fuel from the fuel-regenerator without reprocesssing it).

Commercial Potential -- Because of the preliminary status of the designs for these advanced concepts, assessment of future commercial potential is highly uncertain. However, all of the six advanced reactors would have difficult paths to follow with considerable uncertainties in demonstrating technical feasibility and commercial acceptability. Cost estimates for the required research, development, and demonstration programs for the advanced systems range from minimums of $6 to $12 billion to maximum estimates of $9 to $20 billion, exceeding those of other systems studied. Preliminary evaluations indicate no economic incentive for these systems until U_3O_8 costs are in the range of $160 per pound or more. Thus, none of these concepts appear to offer a viable, competitive means of improving proliferation resistance in the period of interest. However, one or more of these concepts may be more proliferation resistant than the fast breeder over the long term and may therefore warrant further investigation.

Summary Assessment: Resource Extenders

Improved fuel utilization in the once-through light-water reactor system appears, on balance, to be the best short-term choice for extending uranium resources while maintaining a high level of proliferation resistance. These improvements would have the greatest positive impact on resources between now and the year 2025; they appear to have economic advantages, are commercially attractive, would improve rather than degrade the proliferation resistance of the once-through cycle, and could be achieved at relatively low research, development and demonstration cost. In short, the case for aggressively pursuing both the retrofittable and new reactor improvements, with an aim toward early commercial introduction, is compelling.

Reducing enrichment plant tails assay is the next logical choice for extending uranium resources. Unlike light-water reactor fuel-utilization improvements, however, reducing the enrichment tails assay could increase proliferation risks; if increased enrichment capacity were required it would be preferable to accomplish the increase in enrichment capacity by expansion of capacity in countries with existing facilities under IAEA safeguards. Moreover, the economics of reduced tails assay is strongly tied to the relative prices of enrichment services and U_3O_8. Lower tails assay can be encouraged when economically justified. Thus, if uranium were in short supply, the price would rise, thereby making tails-assay reduction an economical prospect. Tails assay reduction, combined with improved fuel utilization in light-water reactors, should preclude supply/demand imbalances well into the 21st century, even if nuclear growth were to parallel that in the 1978 Median nuclear-growth scenario (325 GW in 2000, 615 GW in 2025).

While the combination of light-water reactor fuel-utilization improvements and tails assay reduction would ease supply/demand imbalances in the U.S., resource constraints could occur if uranium supplies were to be lower than the current estimates or if light-water reactor modifications were not to be as efficient or commercially acceptable as currently predicted. Recycle of uranium and plutonium in light-water reactors can improve resource-utilization efficiency, but at the cost of increased proliferation risk. Some, but not all, of the uranium savings of recycle would come from recycling fuel into improved light-water reactors. Assuming reprocessing would begin in 1990 (at the Allied General Nuclear Services plant) and capability would be added by 2010 to serve all domestic operating light-water reactors, annual U_3O_8 demand in 2025 would be reduced by about 20 percent compared to the 15 percent-improved once-through light-water reactor (7 percent compared to 30 percent-improved version). As such, recycle could provide about ten years of added fuel. This time might be valuable if nuclear growth were higher than is now projected, if supply capability were lower than currently projected, or if light-water reactor improvements proved to be infeasible. However, the likelihood of such scenarios occurring is judged to be small at the current time, and when compared to the potential increase in proliferation risks, and the apparent absence of an economic penalty associated with foregoing reprocessing, continued deferral of commercial reprocessing for plutonium recycle appears warranted.

As a class, advanced converters on the once-through cycle seem to offer only modest benefits in resource use. While they use much less uranium than current light-water reactors, their efficiency is not significantly better than 30 percent-improved light-water reactors (about 40 percent for heavy-water reactors, 30 percent for high-temperature gas-cooled reactors) when operated on a once-through cycle. Given their development schedule, annual demand would be reduced less than 10 percent in 2025 compared to 15 percent-improved light-water reactors, and would be negligible when compared to 30 percent-improved light-water reactors. Moreover, they do not appear to offer any significant economic advantage compared to light-water reactors, and would be expensive to commercialize. The proliferation resistance of the high-temperature gas-cooled reactor would be similar to that of the light-water reactor, while the heavy-water reactor would be less proliferation-resistant. A system with potential value, however, appears to be the direct-cycle high-temperature gas-cooled reactor system. This system is likely to be economically competitive with light-water reactors and could be commercially attractive if the markets in water-scarce regions and for process heat applications materialize.

While light-water reactor fuel-utilization improvements and tails-assay reduction appear adequate to support U.S. nuclear power needs at least through the first decade of the 21st century, breeder reactors may prove desirable and necessary before the first quarter of the next century is over. Of the breeder systems that could be commercially available by then, none were found to be significantly more proliferation resistant than the liquid-metal fast-breeder reactor fueled with uranium and plutonium. This system is also of interest because of its technical feasibility, commercial potential, economics, and resource use.

The light-water breeder reactor has the proliferation vulnerabilities of recycle systems, but uses pressurized-water reactor technology. Since the light-water breeder reactor would evolve from the current nuclear technology and, depending on the light-water breeder option chosen, some of the fuel technology could be applied to existing light-water reactors, the benefits in resource savings from this technology could be large. However, the thorium fuel cycle would need to be commercially demonstrated and deployed, and the light-water breeder reactor concepts that would be the most resource-efficient over the long term may not be the most commercially desirable options from an economic point of view. The fast mixed-spectrum reactor is also attractive because of its potentially improved proliferation resistance (using the once-through fuel cycle) and because of its potential benefit to the existing liquid-metal fast breeder reactor program.

Resource-extension options do exist for the U.S. By themselves, however, they would not be sufficient to relieve proliferation and worldwide resource-availability concerns. Other nations lack indigenous uranium resources and the technical and economic resources to implement large research and development programs. Some of them perceive recycle and fast breeder systems as necessary to ensure long-term supplies for nuclear energy and regard early implementation to be required. For these reasons, resource extension options must be supplemented by measures that ensure access to supplies and improve the international nonproliferation regime.

In any case, continued use of nuclear power will require an expansion of IAEA capabilities to keep pace with the expanded demand on the international safeguards system as the number, kinds, and scope of nuclear activities increase and as stockpiles of various fuels under national control also increase. In addition, a number of primarily technical measures for improving the proliferation resistance of recycle and breeder systems over the longer term have been examined, and the following is a summary of those assessments.

1. Technologically more advanced and comprehensive safeguards and physical security systems will be required to handle plutonium-bearing materials, particularly in bulk. These may include plutonium management systems such as inventory reduction as well as improved instrumentation for accounting and containment and surveillance. However, such systems are likely to be costly to both the operator and the IAEA, and may require a politically significant degree of instrusiveness in national facilities. They may also involve measures that conflict with one another. For instance, the deliberate introduction of radiation barriers might enhance some containment and surveillance systems while curtailing the effectiveness of inspection. This result adversely affects all accounting systems and may render some inoperative. Technological and safeguard decisions will involve sophisticated trade-offs in resolving such problems.

2. Intensive research and development efforts, particularly by the U.S., over several years have been directed toward developing potential solutions to these problems, and there is expectation that improvements in accounting, containment and surveillance systems can be made to ensure technically effective safeguards, although no large-scale demonstration has been attempted.

3. Realization of a plutonium-based fuel cycle in which the nation concerned restricts itself to the deployment of the reactor alone and relies upon reprocessing or fabrication services supplied from a few large facilities would be significantly less vulnerable to the risk of proliferation. However, the form of the plutonium and the conditions under which it is returned to the country are important.

   - An arrangement to minimize or avoid bulk materials, either plutonium metal, plutonium oxide, or mixed oxides of uranium or plutonium, in storage or transit would be a significant improvement.

   - The addition of a radiation barrier may increase somewhat the time and additional out-of-system facilities required to produce weapons-usable material so that an international response can be developed.

- Placing these few large facilities under some form of international or multinational arrangement could also be helpful in reducing proliferation risks.

4. In the case where all the nuclear facilities are deployed within a nation, none of the technical alternatives, including radiation barriers, can be very effective in preventing abuse, particularly with regard to overt diversion. Engineering features to reduce accessibility to plutonium and to facilitate safeguards may be helpful in reducing the risks of covert diversion. In addition, agreeing to minimize or avoid significant quantities of undiluted plutonium in any form in any part of the fuel cycle could provide an indication that a country stood in violation should undiluted plutonium be found.

5. Resistance to subnational theft can be improved by the introduction of appropriate combinations of colocation of sensitive facilities, co-conversion, coprocessing, pre-irradiation, spiking, or partial processing, and engineering features to reduce accessibility to plutonium.

6. The appropriateness of radiation barriers against a subnational group will depend largely on their effect on safeguards and physical protection, and economic and environmental considerations.

7. The improvements contemplated in international safeguards, including improved plutonium management schemes, will also make subnational theft more difficult.

Many of these measures, however, will require time to resolve significant technical and institutional issues before they may be judged to be practicable.

Among these issues are the technical and institutional uncertainties surrounding the thorium cycle. The proliferation-resistance attributes of thorium-based fuel cycles may be summarized as follows:

- Fresh reactor fuel containing only denatured U-233 and thorium has an isotopic barrier and at this time is considered more proliferation resistant than fuel containing plutonium, but somewhat less resistant than low-enriched uranium. Moreover, it is accompanied by a radiation barrier associated with U-232, which may provide deterrence against the subnational threat. The isotopic barrier may decrease in future decades if enrichment capabilities become more widely available.

- Thorium-based fuel cycles requiring reprocessing and recycle have a level of proliferation resistance which is generally similar to that of closed fuel cycles.

- Thorium-based fuel cycles which require highly enriched U-233 or U-235 introduce additional proliferation vulnerabilities associated with the enrichment, storage, transportation, and fabrication of such materials.

- With particular institutional arrangements, such as restricting sensitive portions of the fuel cycle to multinationally controlled centers, the proliferation resistance of thorium-based fuel cycles could be substantially improved.

Finally, one approach to the problem of abuse of civilian nuclear activities centers on the development of radically different reactor designs. Several speculative advanced reactor concepts (for example, the gaseous-core reactor or the fast mixed-spectrum reactor) which would appear to have nonproliferation advantages have been examined, but none seems to be without proliferation vulnerabilities. Each of these systems requires resolution of significant technical, safety, and economic uncertainties. Such systems cannot be fully developed for many decades; by then, the context for proliferation concerns and the world nuclear energy regime will have changed. Nevertheless, some of these systems appear to have enough nonproliferation advantages to warrant further investigation, depending on considerations of technical feasibility, economics, and safety.

The improvements discussed above, for the near term and for the long term, can be conveniently summarized into six basic norms for a strengthened international regime designed to minimize the worldwide distribution of weapons-usable materials while taking account of energy security needs:

1. Institutions to ensure the availability of the benefits of nuclear energy.

2. Full-scope safeguards and a timely international system of warning and response.

3. Use of diversion-resistant technologies and forms of materials.

4. Avoidance of unnecessary sensitive facilities and materials.

5. Effective export control systems.

6. Joint or international control of necessary sensitive facilities and materials.

2.2.2 Uranium Supply Improvements

While improving the uranium utilization of once-through systems could reduce the pressure to adopt more resource-efficient but less proliferation-resistant systems, this pressure might be reduced still further if the world had a clearer picture of how extensive its uranium resources really are. More than this, however, measures to enhance the assurance of fuel supplies must address both the adequacy of uranium resources and the continued accessibility to uranium.

Today, one estimate of world uranium resources may be three times higher than another. Planning in the face of such uncertainty about the sufficiency of future supplies is extremely difficult. Since 1974, the United States has conducted the National Uranium Resource Evaluation (NURE). NURE is a systematic effort to develop the data needed to identify geological features that suggest the presence of uranium; these data are the basis for estimating resources. While NURE has focused primarily on lower-cost resources, higher-cost resources in the range of $50 to $100 forward cost per pound U_3O_8 are also being investigated. Only a very few countries have comparable programs, so that no reliable estimates of world uranium resources can be said to exist. The United States and other energy users can encourage and assist other nations both directly and through international organizations, to locate, estimate and exploit their uranium resources. Many countries have not been offered the kinds of incentives that could prompt their cooperation. A successful worldwide exploration and resource-evaluation program could have the double benefit of increasing the supplies of uranium while diversifying the uranium supplier community, thereby increasing the security of supply.

Research and development aimed at improving extraction and milling techniques can be accelerated, with particular emphasis on the exploitation of low-grade deposits and the production of salable by-products. Although the above approaches would be unlikely to eliminate uranium supply constraints entirely, they could extend the period of assured supplies, providing valuable time to develop and deploy resource-efficient nuclear power technologies in a more proliferation-resistant regime. At a minimum, such approaches would improve the planning process considerably by reducing the uncertainty of supply estimates.

Coupled with measures for extending resources, improved resource evaluations can go a long way toward eliminating supply/demand imbalances. A number of potential approaches for assuring supplies have been considered in the NASAP study, including:

- Bilateral fuel-supply measures: agreements between fuel supplier and recipient nations covering terms, conditions, warranties, and other aspects of trade.

- Secondary fuel-supply measures: stockpiles of fuel-cycle material (usually uranium, fabricated fuel rods or enriched fuel) maintained by suppliers or consumers or possibly under multinational control to ensure access to and availability of fuel; an international nuclear fuel bank that would allow member nations, suffering supply interruptions unrelated to their nonproliferation undertakings to draw upon a limited inventory of uranium under the bank's physical control.

- Market-oriented measures including commodity agreements and intergovernmental consultative systems.

Of overall concern will be the development of any of these approaches in a manner consistent with U.S. policy as embodied in the Nuclear Non-Proliferation Act of 1978, which established strict conditions that must be met before any export of nuclear materials could be approved; these would presumably apply to any export pursuant to any of the potential approaches listed above. There are consumers who now obtain nuclear fuel (natural uranium or enrichment services) from other suppliers under somewhat less strict conditions.

Section 104 of the Nuclear Non-Proliferation Act authorizes the President to seek international agreement to establish an international nuclear fuel authority with functions similar to, but somewhat broader than, the nuclear fuel bank. The same section also directs the President to submit a proposal for the creation of an interim stockpile of enriched uranium. Access of non-nuclear-weapons states to both an international nuclear fuel authority and the stockpile would be limited, however, to those states that "accept IAEA safeguards on all their peaceful nuclear activities (also referred to as full-scope safeguards), do not manufacture or otherwise acquire any nuclear explosive device, do not establish any new enrichment or reprocessing facilities under their de facto or de jure control, and place any such existing facilities under effective international auspices and inspection."

In addition to improvements to bilateral fuel-supply mechanisms, various measures to deal with short-term interruptions of nuclear fuel supplies were considered. Included were bilateral and multilateral cross-guarantees, stockpiles, and an international nuclear fuel bank.

Simply on grounds of feasibility, the creation of a system of multinational agreements such as guarantees and pooling arrangements appears to deserve priority. However, such a system might lack the credibility of guarantees backed by dedicated stockpiles and, even more, the credibility of a fuel bank in which suppliers and consumers would share control. Under these circumstances, a system of multinational agreements could be a useful link in a chain of fuel-assurance arrangements and could be initiated in conjunction with a system of guarantees backed by dedicated stockpiles and an international nuclear fuel bank.

An important issue, however, is whether any of these measures to deal with short-term interruptions address problems perceived by consumers. Consumers appear concerned more because the existing uranium supply may not be made available for political reasons than about the sufficiency of uranium resources. There is the question of whether, as a matter of some nations' policies, uranium will actually be mined. There are also great concerns related to ensuring that supply contracts, once entered into, will not be interrupted or have additional nonproliferation terms and conditions unilaterally or retroactively applied.

In addition, there are two possible adverse developments that may appear over the longer run. First, there is a danger that a natural uranium cartel, which would be a manifestation of market imperfections, could cause unpredictable price fluctuations. Second, there is a danger that the lack of an international consensus on developing nuclear power without increasing the risks of proliferation might lead a small group of suppliers to apply stricter nonproliferation requirements on trade than do others. Such a situation could indirectly encourage the spread of sensitive technologies.

Approaches to the problem of stabilizing the market for natural uranium which were assessed include commodity agreements and a system of intergovernmental consultations.

A commodity agreement would have little chance of success unless it were to establish a buffer stock that could be built up or drawn down to counter undesired price fluctuations. Such an operation would have to be financed by participating governments, and the cost would increase if the target price range were to lag too far behind changing market conditions. It is doubtful that governments with different interests would permit the management of the buffer stock to make timely changes in the target price range or provide the money needed for the prolonged defense of a price range that was under heavy market pressure.

A feasible approach to the problem of stabilizing the uranium market appears to be the establishment of a system of intergovernmental consultations including both suppliers and consumers. Periodic meetings could be held for the purpose of discussing a wide range of policy issues, such as world supply and demand, country reprocessing plans and other issues germane to the world uranium market. Solutions to impending problems could be discussed, but the meetings would have no authority to direct particular remedial measures. Whether so informal an approach would be sufficient is at best uncertain. If experience were to show that it was not, the international climate might become conducive to a more structured effort. It is conceivable that in the long term a concept as broad as that of an international nuclear fuel authority could evolve which would control all nuclear supply services.

In the final analysis, it appears that reliance on a single fuel-assurance arrangement under a single institutional control may not be acceptable to consumer nations. Instead a variety of measures--a fuel-assurance regime--would be necessary to strengthen consumer reliance on nuclear fuel markets. Whether, from a consumer perspective, these measures could deal adequately with the political aspects of the problem of availability, as opposed to adequacy, of supply is not clear. In fact, with regard to the existing situation, the most pressing need is to reestablish confidence in the current supply system, which, correctly or incorrectly, has been perceived by some consumers to be unreliable. In particular, many see the need for governmental actions to ensure consistency in the application of export and import controls; to develop mechanisms, such as prior consultation, to manage changes in nonproliferation policy and to guarantee continuity of supply during such changes. Common approaches need to be developed in the near term which could encompass a three-tiered scheme for fuel assurances:

- Bilateral fuel assurances--continue to strengthen existing bilateral arrangements
- Secondary supply assurances--encourage unilateral measures such as supplier stockpiles and multilateral measures such as cross-guarantees and pooling arrangements
- International fuel assurances--encourage the development of a fuel bank with the authority to stockpile and distribute natural and low-enriched uranium to countries which suffer supply interruptions unrelated to their nonproliferation undertaking.

In the long term, the feasibility of any fuel-assurance regime will depend on the extent of economically recoverable uranium resources. At the present time, there is much uncertainty on the extent of uranium resources. To provide better information for nations planning nuclear programs, unilateral efforts (NURE program) and international initiatives to define the extent and location of uranium reserves should be continued. Furthermore, efforts are needed to stabilize future uranium markets. In this regard, a system of intergovernmental communications to discuss resource projections and coordinate production activities appears feasible.

Implementation of these fuel-assurance alternatives implies specific actions: developing and implementing a comprehensive technical program to use more efficiently the uranium resource base, including making available improvements to light-water reactors; continuing to reduce the uncertainty of the extent and producibility of the domestic resource base; developing a strategy--encompassing foreign governments, the IAEA, the NEA/IAEA, and financial and exploratory enterprises--to expand the information base on international uranium reserves; stockpiling natural and low-enriched uranium for emergency allocation; developing with other nations multinational agreements covering emergency allocation procedures and pooling arrangements for nuclear fuels; promoting the concept of a fuel bank; and developing a system of intergovernmental communications designed to ensure that the development and implementation of fuel-supply policies facilitate orderly fuel markets and prevent any commercial manipulation of uranium markets.

2.2.3 Institutional Measures and Alternatives

Developing and assessing measures to reduce proliferation risks require the articulation of principles to be used for establishing (1) the range of measures and alternatives to be considered, (2) the assessment of the measures and alternatives in terms of proliferation resistance and other considerations, and (3) the selection of candidate measures for further consideration.

To establish the range of measures and alternatives to be considered, NASAP has set its scope to reflect the breadth of the various nonproliferation vulnerabilities of present and prospective deployments of the civilian fuel-cycle systems in an international context. The scope of these activities is itself broad; at a minimum, measures for dealing with assurance of supply, enrichment and spent-fuel management for once-through fuel cycles, and reprocessing, plutonium management, and fast breeder reactor development for closed fuel cycles must be considered. At the same time, however, NASAP's scope is not so broad as to encompass all the issues, nuclear and nonnuclear, bearing on nonproliferation. This important limitation needs to be recognized when viewing NASAP analyses. Nevertheless, these assessments have value in suggesting guidance for improving the institutional regime controlling civilian nuclear activities.

Developing and assessing nonproliferation measures and alternatives requires consideration of policies and attitudes affecting nonproliferation controls and constraints, and those affecting energy security and assistance. Consideration must be given not only to nuclear development and nonproliferation concerns, but also to the differing interests of suppliers and consumers, and of nations with nuclear programs in various stages of development. However, it is important to note that the development and assessment of measures and alternatives use a generic approach which depends on the characterization of general rather than specific national interests.

The principles for developing and selecting these measures must be consistent with two basic aspects of the strategy for achieving nonproliferation objectives--namely, to reduce incentives for nations to acquire nuclear weapons and to limit the development of nuclear weapons capabilities. These principles are:

- Any strategy should recognize, utilize, and build on the bases provided by the Non-Proliferation Treaty and the IAEA safeguards program.
- The development of a strategy does not require the resolution of all the issues at once.
- Any strategy should be flexible enough to take into account the legitimate technology development, economic, and programmatic interests of suppliers and recipients.
- Nuclear power systems should be designed to avoid contributing to nuclear weapons development.
- Nuclear power systems, as they evolve, should not significantly enhance the development of a dedicated nuclear weapons program for any nation.
- Access to sensitive materials and facilities should be carefully controlled in order to maximize barriers to proliferation.

Results of the Assessments

The results of the assessments of institutional measures and alternatives can be grouped by near-term considerations to improve the current nonproliferation regime and by long-term considerations to the same purpose. More important, these major observations have implications for U.S. programs. Together, these observations and their implications can suggest possible guidelines for developing a U.S. nonproliferation strategy.

NASAP considered multinational and international arrangements to accommodate enrichment and reprocessing services as well as spent-fuel storage and disposal services. The need for, characterization of, and implications of U.S. participation in one or more of various possible arrangements shaped the following major observations:

- New enrichment capacity should be under effective multinational or international auspices. Consideration should now be given to inviting participation in planned U.S. enrichment facilities by foreign nations meeting nonproliferation norms. Moreover, planned expansion of domestic capacity should continue, as should the programs to develop more proliferation-resistant technology and to develop advanced technology to provide more economical services.

- Improved institutional arrangements for spent-fuel storage and disposal services should be pursued. These could include participation in regional storage facilities under international control as well as domestic activities. The U.S. should take the steps necessary to solve the environmental and institutional problems associated with spent-fuel storage and disposal and to carry out its offer to accept foreign fuel for domestic storage. Research and development for storage and disposal techniques should be accelerated. In any case, the arrangements which are needed for providing spent-fuel storage can leave open for the future the decision regarding ultimate disposal, whether directly as waste or following reprocessing to recover the fissile values.

- The U.S. should continue to urge others to refrain from developing reprocessing capability until it is clearly needed. However, where reprocessing occurs, there would be less proliferation risk if services were provided by a few large facilities using more resistant technologies; if safeguards were strengthened at all bulk-handling facilities; and if services were supplied based on schedules driven by fast breeder and advanced reactor research and development needs, where there existed both economic and technical justifications.

- The U.S. should seek to ensure that any international plutonium-management regime operate under effective and credible nonproliferation norms. Considerations should include criteria for siting of depositories, release (e.g., intended use, timing, and form of materials) and control, and physical security.

The assessment of international deployment plans emphasizes the need for a number of technical improvements which should be developed and demonstrated domestically so that they would be available to be implemented both domestically and internationally, as appropriate. These proposed improvements would include such considerations as:

- Research, development, and demonstration on technical initiatives such as coprocessing and on advanced fast-breeder fuel-cycle technologies such as pyrometallurgy.

- Developing advanced safeguards techniques, especially for bulk-handling facilities and transport systems for spent and plutonium fuels. This recommendation implies strengthening the role of the IAEA and would be a fundamental element of any nonproliferation strategy.

Furthermore, the U.S. should continue to stress full-scope safeguards and work to strengthen the safeguards and physical protection systems by developing advanced safeguards techniques for at-reactor operations, particularly spent-fuel storage and spent-fuel transport. Finally, in order to discourage the spread of sensitive research and development activities, the U.S. should consider offering to cooperate with other nations in making available the use of large research reactors, critical facilities, and fast-breeder research and development facilities when the need is clear, and under appropriate controls and conditions.

U.S. policy should continue to be directed toward establishing a nonproliferation regime which would take account of the need for security of energy supply. Critical elements of such an approach would include enhancing the U.S. image as a reliable source of nuclear-energy assistance to parties to the Non-Proliferation Treaty and to others who accept full-scope safeguards, expanding and using more efficiently the U_3O_8 resource base, assuring reliable fuel supplies, providing alternatives to national reprocessing, addressing environmental problems of spent-fuel storage and disposal, strengthening safeguards and inspection activities, and ultimately placing reprocessing under international auspices and control. Nonetheless, these steps cannot ensure that a non-nuclear-weapons state may not move closer to a nuclear weapons capability. Therefore, disincentives such as sanctions should also be investigated.

Sanctions and the threat of sanctions also represent an important element of nonproliferation efforts. Since the threat of terminating nuclear energy cooperation may not always be an effective deterrent, possible sanctions outside the nuclear area also need consideration. The existing system to verify activities outside the norms of nuclear conduct and to impose sanctions relies heavily on multinational and international mechanisms. On the one hand, it is unrealistic to expect a broad multinational consensus on the future automatic imposition of specific sanctions to be applied if a nation were to engage in proscribed activities. On the other hand, it is essential that there be a visible international consensus that wide-ranging sanctions appropriate to the circumstances be invoked if there were a breach of non-proliferation obligations. To deal effectively with specific cases when they arise, those concerned must be prepared to consult on developing specific courses of action. Developing internationally agreed-upon guidelines for this procedure would be useful.

Finally, the discussion of sanctions emphasizes a critical aspect of foreign nonproliferation policy. At the current time, the utilization of nuclear power to meet growing energy requirements is hampered by differences in national policies and planning assumptions. This situation does not serve well the interests of supplier or consumer nations. Moreover, it does not lead to an improved nonproliferation regime. Accordingly, an international consensus on the issue of nonproliferation and nuclear-energy development is desirable. In this regard, INFCE is a valuable step toward continued development of such a consensus, in a forum recognizing simultaneously the benefits of nuclear power and the risks that abuse of its sensitive nuclear materials and facilities makes possible. The U.S. should seek to maintain this momentum.

Some Guidelines for a U.S. Nonproliferation Strategy

Taking Account of National Interests -- Nations' perceptions of the need for and effectiveness and acceptability of nonproliferation measures vary widely. Thus, while a generic approach used to determine the effectiveness and acceptability of nonproliferation measures may depend on the characterization of general national interests, it is important to point out that, in the final analysis, the policies and needs of the specific nations will influence the success or failure of the initiative. That is, an effective nonproliferation strategy may have to provide for country-specific implementation. Thus, any measure or alternative should consider the multidimensional aspects of factors influencing nonproliferation concerns, the varying degrees of existing fuel-cycle deployments, and the range of country-specific pressures.

Furthermore, the assessment of some alternatives suggests that there may be substantial obstacles to their acceptability to other countries and to the availability of measures to realize them. Nonetheless, the discussion of their implications suggests points relevant to the design of feasible measures and alternatives for an international nonproliferation regime.

It appears that two tasks confront the U.S. in working to foster a world nuclear power regime less vulnerable to proliferation. First, it is necessary to limit the damage that may be done by the proliferation vulnerabilities in the existing regime. Carrying out this damage-limiting task might entail holding the line against the spread of spent-fuel reprocessing activities. The second task is to begin now to move toward a longer-term policy framework for the future use of nuclear energy, a framework containing fewer proliferation vulnerabilities. Such a framework would serve as a means of incorporating into a safer set of possible outcomes the expanding nuclear activities of many nations that today have programs in various stages of development.

Especially difficult in fulfilling these two tasks will be ensuring that near-term accommodations are consistent with pursuit of the longer-term framework. For example, rather than simply "grandfathering-in" activities such as existing enrichment research and development or existing commercial spent-fuel reprocessing, it may be necessary to think in terms of arrangements whereby shifts away from U.S. preferences would be compensated for by changes elsewhere. Even if such consistency were unobtainable in all cases, it need not be dropped as a guiding principle to help avoid unnecessary compromise. Nonetheless, the possible difficulties in ensuring such consistency between near-term accommodation and long-term framework building suggest that any ultimate framework will be a mixture, rather than a more conceptually elegant and interlocking set, of possible alternatives to control all civilian nuclear activities.

An Evolutionary Approach -- Previous conclusions suggest that the implementation of any nonproliferation strategy should employ an evolutionary approach, which is necessarily an incremental approach. Rather than firmly choosing now to pursue the internationalization principle, U.S. efforts to foster a more acceptable long-term nuclear energy regime might be most useful if they were to adopt an incremental approach. Particular stress might be placed on first steps that could lead in several directions. For example, support for a multinational facility for spent-fuel storage would not fully commit the U.S. to the internationalizing approach elsewhere; it could be a useful learning mechanism and, if attractive, could be combined with various other measures to reduce overall proliferation risk. In any case, more attention needs to be paid to identifying possible building blocks for longer-term change by utilizing the assessment of alternative institutional arrangements.

Concomitantly with the decision to adopt an incremental approach, it would also be important to identify critical decision points that are likely to occur over the next 10 to 50 years. For a given set of decisions in the early 1980's, it would be desirable to know which steps would leave open alternative courses of action and at what time decisions would need to be made. In summary, an effective nonproliferation strategy must take account of the dynamic problem--what is out there now and what will be there by the time an institutional arrangement takes effect. Static solutions, whether technical or institutional, would be of short-lived utility.

The enormous uncertainties which exist make compelling an approach that is evolutionary in nature and incremental in development as the uncertainties are reduced. The flexibility of such an approach enables it to address the significant developments likely to occur in technology, resources, market demand, and public attitudes. Not least among these are the recent decline in nuclear energy projections and substantial discoveries of uranium in Australia, and current vacillations in national perceptions of the nonproliferation issue. For instance, although reactions to the detonation of a nuclear device by a newly capable nation may be hard to predict, such an event would be unlikely to leave international attitudes unaffected.

For these reasons and others, an evolutionary and incremental sequential approach to the nonproliferation problem is essential. It begins with a pause in the development and implementation of less proliferation-resistant systems.

2.2.4 Technical Measures

A major nonproliferation issue associated with the reprocessing of spent fuel is the manner in which the reprocessing would occur, under what conditions, and when (and whether) and in what form the separated fissile fuels would be returned to users.

Technical modifications have been suggested as a partial means of reducing the proliferation risks associated with certain aspects of the nuclear fuel cycle, particularly that part of the fuel cycle containing plutonium. Several modifications have been identified that could be applied to plutonium recycle in light-water reactors and subsequently in the fast breeder fuel cycle. Generally, these modifications have been designed to increase the proliferation-resistance aspects of reprocessing and the use of plutonium fuels.

The framework used to assess technical modifications involved a cost-effectiveness assessment. The costs that were considered are:

- Research, development, and demonstration costs--The costs necessary to bring the technological status of the modification to a commercially acceptable state.
- Economic and environmental costs--The incremental unit power costs associated with the capital, operating, and maintenance costs of the technical modification. For those modifications involving added radioactivity, the incremental environmental costs were included in the economic costs and represented the increased capital, operating, or maintenance costs required to keep radiological impacts on facility personnel and the environment within current standards.

The nonproliferation benefits derived from the technical modifications were developed as a function of the increased difficulty, costs, time required, or detectability associated with dedicated facility preparation or commercial facility modification, and material diversion and conversion. In addition, benefits or drawbacks to safeguards were assessed as the impact of the technical modification on existing and planned safeguards techniques and procedures.

The Technical Modifications Assessed

The technical modifications investigated include:

1. Coprocessing and coprecipitation of uranium and plutonium in the reprocessing plant. This measure is a modification to the reference PUREX reprocessing technology, in which plutonium would never be produced alone but would always be diluted by a portion of the recovered uranium. It has the primary advantage that there would be no separated plutonium anywhere in the fuel cycle. Its concentration in uranium would never be greater than 20 to 25 percent by weight.

2. Coprocessing and coprecipitation with partial decontamination of fission products. This measure is a modification of coprocessing in which some of the fission products would remain with the recovered uranium and plutonium, creating a radiation barrier throughout the fuel cycle. Thus, all intermediate products and the fabricated fuel would be highly radioactive. Any diverted material would require remote handling and shielded recovery facilities before weapon fabrication could be attempted. The practical fission products for this purpose (Ru-106 and Ce-144) would have half-lives of about one year. Thus, this measure would be effective for fuel storage for less than about five years.

3. Addition of radioactive isotopes to fresh mixed-oxide uranium/plutonium fuels. This measure would rely on the introduction of a source of gamma radiation (such as Co-60) to the coprocessed uranium/plutonium nitrate product at the reprocessing plant. The radiation level would be sufficiently high that separation of the plutonium from the uranium would require a shielded processing facility. An adequate dose level has been estimated to be in the range 100 rem per hour at 1 meter. As a result, the uranium/plutonium fuel would be radioactive throughout the fuel cycle. This concept would require remotely operated, remotely maintained conversion and fabrication facilities.

4. Pre-irradiation of fabricated mixed-oxide fuel. This measure would rely on a radiation barrier in fresh mixed-oxide fuels by irradiating

fabricated fuel in a specially constructed neutron irradiation facility. The facility could be a reactor designed for rapid on-line refueling that would provide a small but significant burnup to the fresh-fuel elements. At such low burnup the fuel would be radioactive enough that it would require, in effect, a dedicated, shielded, and remotely operated chemical separation facility to recover the plutonium. This initiative would require colocation of reprocessing, fabrication, and irradiation facilities, and would imply that no fuel fabrication had been done outside such secure fuel-cycle facilities.

5. Active countermeasures (use-denial) within the fuel-cycle facilities. These concepts have been proposed as methods that could be employed by international inspection organizations to interfere with the seizure by the host country of a multinational nuclear fuel center. Active concepts include automatically or remotely controlled systems designed to create barriers to material diversion at fuel-cycle facilities by denying access to critical areas, shutting down or disabling equipment, or disabling control circuitry.

6. Passive countermeasures within fuel cycle facilities. Passive resistance countermeasures are engineering concepts, facility design features, and operational procedures intended to make material diversion or facility modifications more detectable, more difficult, and more time-consuming. These measures may range from design features which restrict access to sensitive areas and equipment to self-locking door mechanisms.

Summary Assessment

These technical modifications were assessed individually and subsequently compared with each other as they might be applied to the light-water reactor with recycle of plutonium and to the fast breeder reactor fuel cycle. The comparative analysis represents the assessments of both the associated research, development, and demonstration and the economic and safeguards costs, and the proliferation-resistance effectiveness that would accrue to each technical modification.

It has also been suggested that special nuclear materials can be "downgraded" to inhibit their use in nuclear weapons by enhancing the emission rate of alpha particles, gamma rays, neutrons, or heat. Judgments about the use of special nuclear materials would depend on detailed knowledge of nuclear weapons design and testing. Producing such details would conflict with U.S. nonproliferation policies; certain conclusions can, however, be drawn:

- U-233 is, in principle, as weapons-usable as U-235 or plutonium.
- Increasing the emission rate of neutrons in U-233, U-235, or plutonium would not preclude their use in nuclear weapons. This conclusion also applies to the presence of Pu-238.
- The presence of U-232 in U-233 would not provide effective protection against misuse.

Research, Development, and Demonstration, Economic, and Environmental Costs -- The major identified cost impacts for most of these modifications would lie primarily in the areas of fuel reprocessing, fuel fabrication, and fuel transportation. Smaller, but nonetheless significant, costs would occur in other portions of the fuel cycle, in incremental capital, operation, and maintenance costs at the reactor. Costs shown below are for the light-water reactor fuel cycles. Costs for fast breeder reactor cycles would generally be higher.

Coprocessing and coprecipitation of uranium and plutonium were found to be the least intrusive and least costly initiative to implement. The cost impact would be less than a 0.15 mill/kWh[1] increment to the power-generation costs and would occur primarily within the reprocessing plant during coprecipitation. The environmental impact would be small.

The measures designed to have highly radioactive fuel throughout the fuel cycle (coprocessing with partial decontamination, deliberate addition of radioactive isotopes, i.e., Co-60 spiking and Pu-238 heat spiking)--all

[1] A cost increment of 1 mill/kWh represents a cost to the consumer of $6.1 million per year from each power plant of 1,000 MW generating capacity operating at a 70 percent-capacity factor. Average nuclear power costs in 1978 were about 15 mills/kWh.

would lead to remotely operated, remotely maintained design concepts in reprocessing and refabrication. In addition, substantial costs would be incurred both at the reactor and in fresh-fuel transportation. A total cost increment can be expected in the range of 0.3 to 0.6 mill/kWh, of which approximately 0.15 mill/kWh can be ascribed to transportation and reactor modification and handling.

It appears that pre-irradiation of fresh fuel in an especially constructed reactor would be the most costly concept to implement. The irradiation facility would be the primary cost item, and no cost increments were ascribed to the reprocessing or fuel-fabrication facilities. A cost increment of 0.9 to 1.5 mills/kWh was estimated.

The proliferation-resistance benefits obtained by increasing radiation levels throughout the fuel cycle would have to be balanced against the potential for increased population exposures and environmental costs.

The incremental costs of the proliferation-resistance engineering concepts are largely unknown. In a preliminary estimate, the costs of implementing an active resistance concept (assuming that the necessary control instrumentation exists) appear to be comparable to those of the spiking concepts. The higher potential costs from increased plant outage as a result of accidental system malfunction were not considered. The passive concepts would be largely facility-dependent, and no cost evaluations have been made. Lowest cost implementation would occur if these concepts were designed as part of the physical protection and safeguards in a new plant. The costs of modifying an existing facility could likely be prohibitive.

The research and development costs of implementing these initiatives (with the possible exception of coprocessing) would be substantial. Preliminary estimates have been made only for the gamma-spiking concepts. These estimates range from $275 million to more than $430 million.

Nonproliferation Benefits and Drawbacks -- The fissile-fuel material of primary concern in both recycle and fast breeder reactors is plutonium. Isotopic dilution cannot render this material unusable for weapons in the way that diluting U-235 with U-238 does in once-through reactor systems. However, for the plutonium that would be available via reprocessing, technical measures would center on chemical dilution and the provision of a radiation barrier by radioactive contamination.

The benefits to be gained from technical modifications would vary in terms of what the perceived threat was (e.g., national versus subnational proliferation) and the context in which the proliferation occurred (e.g., Did national reprocessing facilities exist? Did the proliferation involve an overt national takeover of such a facility? Did the proliferation involve the covert diversion of materials to be processed later in a dedicated facility?).

When taken in the abstract, dilution with uranium by coprocessing and coprecipitation would significantly increase the amount of material that must be removed from the fuel cycle and would require the chemical separation of plutonium from uranium. Radioactive contamination effected by either spiking, partial decontamination, or pre-irradiation would afford a protective radiation barrier to plutonium-bearing materials, including the fresh fuel. The radiation fields can be substantial and, although not as high as those from spent fuel, can require special handling and remote radioactive chemical reprocessing to recover weapons-usable material. However, as a result of the relatively shorter isotopic half-lives involved, both the partial decontamination and pre-irradiation measures would provide lower long-term protection than spiking. Radiation levels on the order of 10 to 100 rem per hour at 1 meter have been judged sufficient to force a nation seeking to produce tens of weapons to conduct reprocessing in a hot facility. This protection would correspond to that of spent fuel 100 to 150 years after discharge from a reactor.

As a means of increasing resistance to national proliferation, the retention of a chemical dilution barrier would not be relevant in contexts where only reactors (and not reprocessing and fabrication facilities) were deployed in a given country because recycle fuels are comprised of mixtures of uranium and plutonium oxides in any case. In countries where reprocessing or fabrication facilities were deployed, the effect on proliferation resistance of coprocessing would be limited for two reasons. First, separated plutonium oxide could probably be readily obtained by simple changes in process-control variables or by batch recycle of normal product material. Second, out-of-system facilities for separating plutonium oxide from mixed plutonium/uranium-oxide fuel and converting it to plutonium metal would require only slightly more time and resources for design, construction, testing, and operation than those for converting plutonium oxide alone.

The addition or retention of a radiation barrier in recycle materials would offer somewhat greater potential for increasing proliferation resistance than would coprocessing. This potential would be primarily associated with the fact that more elaborate out-of-system facilities would be required to recover plutonium from diverted materials. Such facilities would have to provide for shielding and remote operation, and would take up to twice as long for design, construction, and testing, as would facilities processing nonradioactive material. These additional resources would enhance the opportunities for detection and increase the potential warning time before removal of material. The actual operating time for recovery of a given quantity of fissile material would likely be only slightly longer than that for nonradioactive material, however.

In situations in which all fuel-cycle facilities were deployed in a country, the radiation-barrier concept would suffer, although perhaps to a lesser degree, from the same weakness as would coprocessing--namely, that clean, separated plutonium compounds could readily be obtained by changing process variables or by batch recycle. These changes would eliminate or substantially reduce the requirements for out-of-system facilities. Thus, the radiation barrier would provide only marginal improvements to the system, particularly in the event of an overt national proliferation attempt. Moreover, although radiation might facilitate containment and surveillance, it would be highly detrimental to material accounting as a protection against covert diversion. In fact, most of the methods and procedures which have been or are being developed through years of intensive research, development, and demonstration would be rendered ineffective. The radiation barrier would, on the other hand, represent a substantial impediment to a subnational threat, although its appropriateness in this context would depend on environmental, economic, and safeguards disadvantages.

It is conceivable that reprocessing and fabrication plants could be combined into an integral facility and designed with engineering features that would make access to plutonium and process modification very difficult, or perhaps highly visible to safeguards inspectors. The potential effectiveness of such features would be highly dependent upon specific plant design details, however, and cannot be evaluated at a conceptual level. An integral reprocessing/fabrication facility would eliminate a transportation link and possibly improve prospects for effective safeguards against covert diversion (or overt diversion in the case of subnational threats). The resistance engineering concepts might find their best means of implementation as they complemented other measures and the safeguards and inspection processes.

A radically different, but possibly supplemental, approach to improving the proliferation resistance of plutonium-based systems would be based on the concept of "use-denial" by means of active operational control features incorporated into fuel-cycle facilities and transport vehicles. This concept would have obvious advantages in protecting against seizure by subnational groups. It would have equally obvious problems from the viewpoint of acceptability to facility operators and would offer little protection against overt takeover by the operators themselves.

In summary, none of the above technical initiatives appear to mitigate the concern that a national operator might take over the facility and, within a very short time, have weapons-usable material available. On the other hand, some would be inexpensive to implement (e.g., coprocessing) and would offer some benefits in a national context. Still others (e.g., spiking) would have significant advantages with regard to subnational threats.

2.2.5 Implications for Research and Development

The current status of nuclear power in this country and abroad is characterized by a great deal of uncertainty. Utilities are unsure about future electricity demand, manufacturers are faced with deferrals and cancellation of orders, and financial institutions see higher risks in nuclear-related investments than previously estimated. In addition, there are doubts associated with the Federal and State laws and regulatory decisions that govern utility rates, health and safety requirements, and environmental impacts. Waste disposal remains an unresolved issue, and the recent accident at the Three Mile Island Plant has increased concern over the public acceptance of nuclear power and the extent of possible safety and licensing changes for both existing and new plants.

In this environment, the private sector is unlikely to be an important investor in new nuclear technology when its overriding concern is to assure that the existing light-water reactor technology remain viable. The Federal Government will have to provide the financial resources for any nuclear research, development, and demonstration programs on new systems; but Government resources are not limitless. It is, therefore, imperative that in structuring the nuclear research, development, and demonstration program, the

Government set strict priorities and be in a position to make changes in the program as needed.

Based on the electrical growth projections used in NASAP, there appears to be adequate time to conduct the necessary research, development, and demonstration on any new nuclear technology. At least 20 to 30 years would be required to conduct the necessary steps and deploy a new system. This time could be shortened for light-water reactor improvements, for example, or could be longer if more conservative planning assumptions were utilized.

Highest priority should be given to programs which would improve the resource utilization of the present nuclear system. Of prime importance are improvements in the fuel utilization of light-water reactors on the once-through cycle. The near-term options of high fuel burnup and changes in fuel management are being pursued jointly by industry, utilities and the Government and should continue to receive all necessary Government support. These projects should be targeted for the earliest possible commercial implementation, at least by 1990. Other possible improvements in light-water reactors, those long-term improvements involving design changes, should be investigated to determine their technical and economic feasibility. Since these would be longer-term, higher-risk projects, the Federal Government will have to take the lead in evaluating proposed concepts and, along with industry, will identify the research, development, and demonstration needs.

Also of high priority is the continuation of programs to develop less highly enriched uranium fuel for the large number of research reactors deployed worldwide. The ultimate objective should be the reduction of U-235 enrichment to less than 20 percent.

While reductions in enrichment plant tails assay might occur over a period of time if uranium costs were to increase faster than enrichment costs, these reductions would likely be modest, because of economic constraints on current enrichment technology. On the other hand, the advanced isotope separation processes may offer the potential of economically extracting U-235 from tails down to very low assays on the order of 0.05 percent. Three processes are currently under development. Two, the molecular process and the atomic-vapor process, have been based on the use of lasers; the third, the plasma-separation, would use ion cyclotron resonance. The Federal Government is supporting research into these three processes, and a private company is developing a proprietary process. These Government programs should continue and should receive the level of financial support necessary to have demonstrated the technical and economic feasibility of the processes by the early 1990's.

Support should also be provided to expanded uranium exploration and to development of improved mining and milling techniques, with emphasis on low-grade ores and by-product recovery.

The liquid-metal-cooled fast breeder reactor is the major, new nuclear-power system under development in the industrialized nations because it is seen as an option that can alleviate doubts about resource availability and security of supply. The United States is endowed with an abundance of resources, including uranium and coal, but there are many restrictions on their production and use. Judicious use of both these resources may prove adequate to meet this nation's electrical energy demands and to support the role of nuclear power in the U.S. energy mix for some decades without use of the breeder. However, the uncertainties in future energy supply and demand are so many and so large that it would be extremely difficult to determine when a shift to new technology might be desirable. For example, this study suggests that the breeder reactor may be commercially viable as early as about 2010, depending on nuclear growth and conditions of uranium supply and price in the U.S.

High nuclear growth and high-priced supplies of uranium would favor earlier commercialization, while low nuclear growth and plentiful and inexpensive uranium would favor later market entry. However, the assessment also suggests that it would take until 2010 or later, even with a vigorous research, development, and demonstration program, for widespread commercial installation of the breeder in U.S. utility systems to begin. Any research, development, and demonstration program aimed at minimizing financial risk would take until that time to complete. Breeder introduction dates beyond 2010 are plausible also. Postponing decisions to construct major facilities could result in breeder introduction in 2020 or beyond.

Foreign commitment to more aggressive demonstration of the commercial-sized liquid-metal fast breeder reactors indicates earlier deployment internationally. The French breeder program, for example, has a planned mid-1980's power operation date for the large Super Phenix breeder plant.

Thus, the NASAP recommendation is to continue liquid-metal fast-breeder development. This would serve two objectives: to put the U.S. in a position to influence the development of more proliferation-resistant breeder technology in other countries, and to make breeder technology available domestically when it is needed. This should not be construed as an irrevocable decision to deploy the breeder commercially; obviously, the program should be reviewed as more and better information becomes available about future energy demands, uranium resources, and fast-breeder economics. Such reviews should in fact be timed to provide the basis for making the major investment decisions to implement the many research, development and demonstration steps. The gas-cooled fast reactor, proposed as a back-up breeder, would not be available until after the liquid-metal-cooled fast breeder reactor; in view of its uncertain commercial prospects, and the finite amount of Federal research and development funds available, the development priority for the gas-cooled fast reactor must be secondary to the liquid-metal fast-breeder.

More important, planning for breeders must take into account that although commercial deployment of the fast breeder reactor is several decades away, both here and abroad, proliferation risks associated with fast breeders are not. Research, development, and demonstration programs require the use of sensitive facilties and materials which, although not of the same magnitude as those of a commercial-breeder economy, represent significant proliferation vulnerabilities. Thus, the several national fast-breeder programs must be made as proliferation-resistant as possible.

In order to influence the liquid-metal fast breeder reactor programs of other countries, not only must the U.S. be a member of the fast-breeder development community, but it also needs to exercise leadership in developing the technical measures which would reduce the proliferation risk of fast breeder reactors. In particular, how to design reprocessing and recycle plants to facilitate international safeguards and improve proliferation resistance, and more proliferation-resistant processes, such as coprocessing, should continue to be investigated to understand their proliferation-resistance effects better, as well as to establish their technical and economic trade-offs. Research and development efforts directed at the safeguards and physical security systems for facilities handling plutonium-bearing bulk material should continue. These efforts should be directed at surveillance and containment, as well as material accountancy. The safeguarding of enrichment plants also deserves major attention.

The light-water breeder reactor does not appear to offer any significant advantages of proliferation resistance, economics, or resource utilization over the liquid-metal fast breeder reactor; it is, however, based on the light-water-reactor technology in use today. Because it would evolve from current technology, and some of its fuel technology could be applied to existing light-water reactors, the benefits in resource savings from this technological advance could be large. The present Department of Energy research and development program has the objective of confirming that breeding can be achieved in existing and future light-water reactor systems using the thorium/U-233 fuel system, and of developing and disseminating technical information to assist in evaluating the light-water breeder reactor concept for commercial-scale application. These objectives are being achieved by operating a light-water breeder core in the Shippingport Atomic Power Station over a period of several years, after which a detailed fuel examination and determination of breeding performance will be made. In addition, technology development--including additional irradiation testing--is continuing. This program should continue in order to meet this objective, and its future course should be decided after considering these results, along with industry interest in future development of the light-water breeder concept.

The advanced converter reactors, that is, the heavy-water reactor and the high-temperature gas-cooled reactor on a once-through cycle, do not offer significant economic improvements over improved light-water reactors on a once-through cycle. The proliferation resistance of the high-temperature gas-cooled reactor would be similar to that of the light-water reactor while the heavy-water reactor would be less proliferation resistant. While more efficient uranium utilization can be achieved in these reactors when fuel is recycled, similar efficiency can be attained by light-water reactors, for example, through extensive fuel improvements and other modifications, or by using light-water breeder fuel technology to achieve a high conversion ratio. There is no commercial interest in the heavy-water reactor in the U.S., and it does not appear that any Government-supported work on this system would be justified. There is some commercial interest in the high-temperature gas-cooled reactor. This reactor technology might have application in the industrial process-heat market and, with dry cooling, could have market application in water-poor regions. Other countries--namely, the Federal Republic of Germany and Japan--have research and development programs on this technology for process-heat applications. The research and development program on the high-temperature gas-cooled reactor should continue.

Of the advanced concepts, the fast mixed-spectrum reactor can benefit to some extent from the ongoing fast breeder reactor program due to their technical similarities. Further, the institutional controls needed to minimize proliferation risk with the fast mixed-spectrum reactor are similar to those required for the once-through light-water reactor system and, hence, these controls would be in place. For these reasons, the fast mixed-spectrum reactor merits limited research and development support.

Recommendations for research and development are summarized in the following table.

TABLE 15. RESEARCH AND DEVELOPMENT PROGRAM RECOMMENDATIONS

Program	Target
Light-Water Reactor Fuel-Utilization Improvements:	
o High burnup, operational, and fuel management changes	Commercial implementation by 1990.
o Additional high burnup and other fuel design changes	Commercial implementation by 2000.
o Longer-term nonretrofittable improvements	Identify initial attractive candidates by mid-1980; commercial capability after 2000.
Reduced Enrichment of Research Reactor Fuel	Demonstrate 20-45% enriched fuel by 1982; demonstrate <20% enriched fuel by 1984.
Liquid-Metal Fast Breeder Reactor	Continue development so that it could be commercially available if and when needed (possibly 2010-2020).
Advanced Isotope Separation	Demonstrate technical and economic performance of a process by 1990-1995.
Light-Water Breeder Reactor	Continue development and complete proof of breeding demonstration in Shippingport Atomic Power Station by 1985 or 1986.
Proliferation-Resistance Engineering of Reprocessing	Demonstrate in breeder program pilot fuel-cycle facilities.
High-Temperature Gas-Cooled Reactor	Assess unique markets, such as for process heat and usability at water-poor sites.
Fast Mixed-Spectrum Reactor	Investigate high-burnup fuel technology.
National Uranium Resource Evaluation	Complete program by 1985. Continue research and development in discovery and extraction methods.
Technology Support for IAEA Safeguards on:	
o Enrichment plants o Interim spent-fuel storage o Spent-fuel disposal repository o Reprocessing plants o Plutonium storage o Mixed-oxide fabrication plants o Transportation	Continued improvement in surveillance, containment, and material accountancy.

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APPENDIX

PROJECTED DOMESTIC NUCLEAR GENERATING CAPACITY

PROJECTED DOMESTIC NUCLEAR GENERATING CAPACITY

BACKGROUND

The Nonproliferation Alternative Systems Assessment Program (NASAP) analyses were based primarily on the nuclear growth forecasts provided in the 1977 Annual Report of the Energy Information Administration of the Department of Energy, with projections through 2025 provided by the Office of Policy and Evaluation. However, during the final preparation of the NASAP report in the summer of 1979, the Energy Information Administration (EIA) published its "Annual Report to Congress - 1978," which included new projections of nuclear generating capacity. In October 1979 and January 1980, the Energy Information Administration released a revised set of projections; new projections from the Office of Policy and Evaluation were published in January 1980, in the Secretary of Energy's Report to Congress. The projections reported differ from those reported previously, with the current EIA report showing lower total primary energy consumption, increased reliance on coal, and less reliance on nuclear power.

The 1979 High forecasts approximate the arithmetic mean of the 1978 High and Low forecasts, while the 1979 Low forecast is slightly lower than the 1978 Low forecast. The 1980 forecasts lie below the 1978 Low forecast, but do not go beyond the year 2000. The NASAP assessments were based primarily on the arithmetic mean of the 1978 forecast, with sensitivity studies covering the wider range. The 1978 forecast range was used because it extends to the year 2025 and represents both limited nuclear growth as suggested by recent trends and faster growth which could occur if utilities were to resume ordering nuclear plants in the 1980's.

Implicit in these projections are the underlying assumptions of technical, political and societal continuity. That is, there are no major changes in present governmental policies, no unforeseen technological breakthroughs, and no major social traumas such as war or environmental catastrophe. Changes in methods of energy production and conservation are limited to those now envisioned. Also, no new regulatory constraints will be enacted that would restrict the use of an energy source, and the public concerns with nuclear power are resolved so that it remains a viable long-term option.

In the following sections more detailed descriptions of the forecasting methods are presented. These forecasts are then compared with other recent forecasts.

1978 Forecasts

Projected domestic nuclear generating capacities in the United States for the years between 1980 and 2025 are shown in Table A-1. These projections are based on the Project Independence Evaluation Systems (PIES) forecasting methods, which cover the period 1977 to 2000, and another method for the period 2000 to 2025 which depends on projections of U.S. population, labor force, and total electrical power generation.

TABLE A-1. 1978 ESTIMATES OF INSTALLED DOMESTIC NUCLEAR POWER GENERATING CAPACITY

Year	Nuclear Generating Capacity (GW) High	Low
1980	66	62
1985	122	100
1990	192	157
1995	275	200
2000	395	255
2005	480	275
2010	590	295
2015	690	305
2020	800	315
2025	910	320

Source: Department of Energy (Energy Information Administration, Office of Policy and Evaluation, May 1978)

Projections for 1980 to 2000 -- Energy supply/demand projections for the years 1980 to 2000 were developed by EIA,[1] with the aid of the PIES, which is an iterating macroeconomic model that assesses the energy supply-demand balance for each of the ten Federal regions of the United States. It uses a linear programming algorithm to determine the minimum cost combination of energy supplies required to meet projected levels of regional energy demand. Depending on the scenario considered, possible supply constraints and assumptions in the model may include: declining production rates for oil and

[1] "Projections of Energy Supply and Demand and Their Impacts," Energy Information Administration, Annual Report to Congress, Volume II-1977, DOE/EIA 0036/2 (1978).

gas; transportation limitations for coal supplies; and realistic construction lead times, retirement rates, and fuel availability for electric generating capacity.

For nuclear power, limits on the rate of construction in the near term (before 1990) are determined through an assessment of the construction "pipeline," including units under construction, and in many regions, units currently on order. Typically, corrections are made to schedules for units with unrealistically short construction lead time estimates, or for units for which the utility is known to have problems with its capital formation/expenditure schedule.

The projections for 1980, 1985, and 1990 are in reasonable agreement with published industry lists of nuclear power plants currently in operation, under construction, and on order. The projections through the year 1990 will thus reflect the commonly recognized 10 to 12 year lead time between the utility order and commercial operation. Beyond 1990 the High growth projection assumes that trouble-free completion of present commitments can be achieved, while the Low growth projection assumes substantially longer construction lead times and a delay of schedules for units on order, consistent with utility reactions to reduced demand growth.

For the High projection through 1990, EIA reported an average annual growth rate in national electricity consumption of 4.5 percent. Under this projection, nuclear power represents about 19 percent of all generating capacity and provides nearly 29 percent of the nation's electrical energy. In the Low case, the average annual growth rate in electric consumption is 3.9 percent, and nuclear power represents about 18 percent of all generating capacity while providing 26 percent of the nation's electrical energy. In all projections, an average capacity factor of 65 percent is assumed for the nuclear generating system. This represents the ratio of power produced to that possible with full utilization of installed capacity. A 5 percent increase in capacity factor would lead to installation of 5 percent less capacity.

On the basis of the detailed PIES projections through the year 1990, the U.S. energy and electricity forecasts are extended through the year 2000. Essentially, total energy demand is extrapolated on the basis of the average growth rates projected in the High and Low cases between the years 1985 and 1990. Electricity growth rates, extrapolated on the basis of the declining growth rates experienced before the year 1990, are 3.7 percent per year in the High projection after 1990 and 2.0 percent per year in the Low projection.

To forecast nuclear power beyond 1990, EIA employed different techniques than those used before that year--the "pipeline" analysis is no longer valid because the time frame involved is beyond the utility planning horizon. While the forecasts become more speculative in nature, it is possible that nuclear power will become more responsive to the demand for base-load power. The EIA projections to the year 2000, 395 GW in the High case and 255 GW in the Low, reflect the broad range of uncertainty that characterizes the long term. In the High projection, nuclear power represents about 28 percent of all generating capacity and provides 41 percent of the nation's electrical energy, while in the Low projection it represents about 25 percent of all generating capacity and provides 34 percent of the nation's electrical energy.

Projections for 2000 to 2025 -- Projections for the years 2000 to 2025 were developed by the Department of Energy Office of Policy and Evaluation with assistance from the EIA. Since projections more than 20 years into the future are highly speculative, a less detailed model was adopted for projections beyond the year 2000 as compared to the 1977 to 2000 model. This model took the PIES projection for the year 2000 as a base and then tied subsequent projections of nuclear power generating capacities to total electrical power generation projections. The general context of the energy projections was defined by assumptions of growth of the U.S. population and labor force consistent with U.S. Census Bureau[1] Series II figures. Declining rates of growth of the labor force lead to projections of economic growth for different scenarios which are in the generally accepted range of 3.5 percent to 0.1 percent. These, in turn, lead to decreasing growth rates for primary energy requirements and electrical energy demand.

For the High trend case, the growth rate of the demand for electrical power was assumed to be 3.7 percent for the year 2000 decreasing to 1.5 percent by 2025. Nuclear power was assumed to be responsible for 41 percent of the electrical energy generated in 2000, and its contribution increased linearly to 50 percent by 2025. For the Low trend case, the growth rate of the demand for electrical power was assumed to be 2 percent in 2000 decreasing to zero by 2025. The percentage of electrical energy generated by nuclear power was assumed to remain constant at 34 percent throughout.

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[2] "Projections of the Population of the United States, 1977 to 2050," July 1977.

1979 Forecasts

The newer EIA nuclear growth forecasts for the mid-term (1985, 1990, and 1995) were based on the Midrange Energy Marketing Model System, the successor computer model to PIES. This model simulates the complex interactions of energy producers, energy converters, and energy consumers, including important regional detail, through 1995. Projections beyond 1995 were based on the Long-Term Energy Analysis Program (LEAP) prepared by the EIA. The 1979 Estimates of U.S. Nuclear Generating Capacity are shown in Table A-2.

TABLE A-2. 1979 ESTIMATES OF U.S. NUCLEAR GENERATING CAPACITY (GW)[3]

Year	High	Mid-Range	Low
1985	118	114	102
1990	171	152	142
1995	225	208	186
2000	300	260	235
2010	450	-	-
2020	675	-	-

Detailed projections were made through 1995, with extensions of the High and Low growth scenarios to 2000. Starting from the mid-range estimate in 2000, the projections were extended to 2020, based on an approximate doubling of the annual nuclear deployment rate. This post-2000 projection would be representative of a High nuclear growth trend.

In this forecast, compared with an annual rate of 6.4 percent increase in electricity demand from 1962 to 1977, a reduced growth of 3.9 percent per year from 1977 to 2000 and 2.3 percent per year after 2000 is seen. The primary assumptions for these projections were an annual economic growth rate of 3.2 percent between 1980 and 1995, dropping to 2.4 percent thereafter, and a population growth rate decreasing to 0.5 percent by 2020.

[3] Energy Information Administration, Annual Report to Congress, Volume III - 1978, DOE/EIA 0173/3 (1979).

1980 Forecasts

Although the 1979 forecasts were published in mid-1979, most of the analysis behind these forecasts was completed by February of that year. As a result of the Three Mile Island accident and other regulatory and market factors, the EIA updated their projections in October of 1979 through the year 1995. These projections were published in January of 1980. Reflecting the most recent trends, these new forecasts reduced the 1979 forecasts for the year 1995 by about 30 GW.

The EIA forecasts represent a very detailed analysis of U.S. utility plans for new nuclear generating capacity. The Low estimate includes all the reactors operating, actively under construction, and authorized for construction. The Mid case includes, in addition, plants that are in construction permit review, plants that have been ordered, and a few plants that have not been ordered. The High case assumes a more active resumption of orders in the 1980's.

In the Secretary's Annual Report to Congress in January 1980, it was projected that U.S. generating capacity would rise to 150 to 200 GW by 2000. As with the EIA Low and Mid cases, this allows for few or no new plant orders. However, that report also shows a projection of about 260 to 380 reactors by the year 2000. Implied in that projection is a resumption of new plant orders within the next few years. The 1980 forecasts are presented in Table A-3.

It should be noted that for neither of these more recent projections were estimates made for the period beyond 2000, reflecting the uncertainty for that period. However, soon after this report has been published, new EIA projections will have become available. Scheduled for publication in July 1980, the EIA Annual Report to Congress -- 1979, will confirm the forecast in the Secretary's Report, about 160 to 200 GW of nuclear generating capacity in the year 2000. In a more comprehensive evaluation of the long term, the EIA report will also forecast between 290 and 460 GW of nuclear generating capacity by the year 2020.

TABLE A-3. 1980 ESTIMATES OF U.S. NUCLEAR GENERATING CAPACITY (GW)

Year	High	Mid	Low
1985[a]	113	106	95
1990[a]	155	140	129
1995[a]	196	179	156
2000[b]	200	--	150

[a] Commercial Nuclear and Uranium Market Forecasts for the United States and the World Outside of Communist Areas, DOE/EIA-0184/24, January 1980.

[b] U.S. Department of Energy, Secretary's Annual Report to Congress, DOE/S-0010(80), January 1980.

Comparison with Other Forecasts

The foregoing projections of domestic nuclear generating capacity (Tables A-1, A-2, and A-3) are best evaluated in the context of the estimates of primary energy use and electrical energy consumption upon which they are based. Figure A-1 illustrates the consistent set of energy projections used for NASAP: Total Primary Energy Use, Total Energy Use for Production of Electricity, Electrical Energy Generated, and Nuclear Electrical Energy Generated. High and Low projections are shown for each, and the comparable installed nuclear generating capacity is also shown. As shown in Table A-4, the forecasts are in the general range of other recent estimates. Depending on the purpose of the estimates and the scenarios considered, some industry projections show greater growth, while conservation-oriented studies show lower growth. The projections used for NASAP lie between these extremes. More detailed discussions of some of these long-term forecasts are presented in Chapter 2 of the 1978 forecast and Chapter 5 of the 1979 forecast.

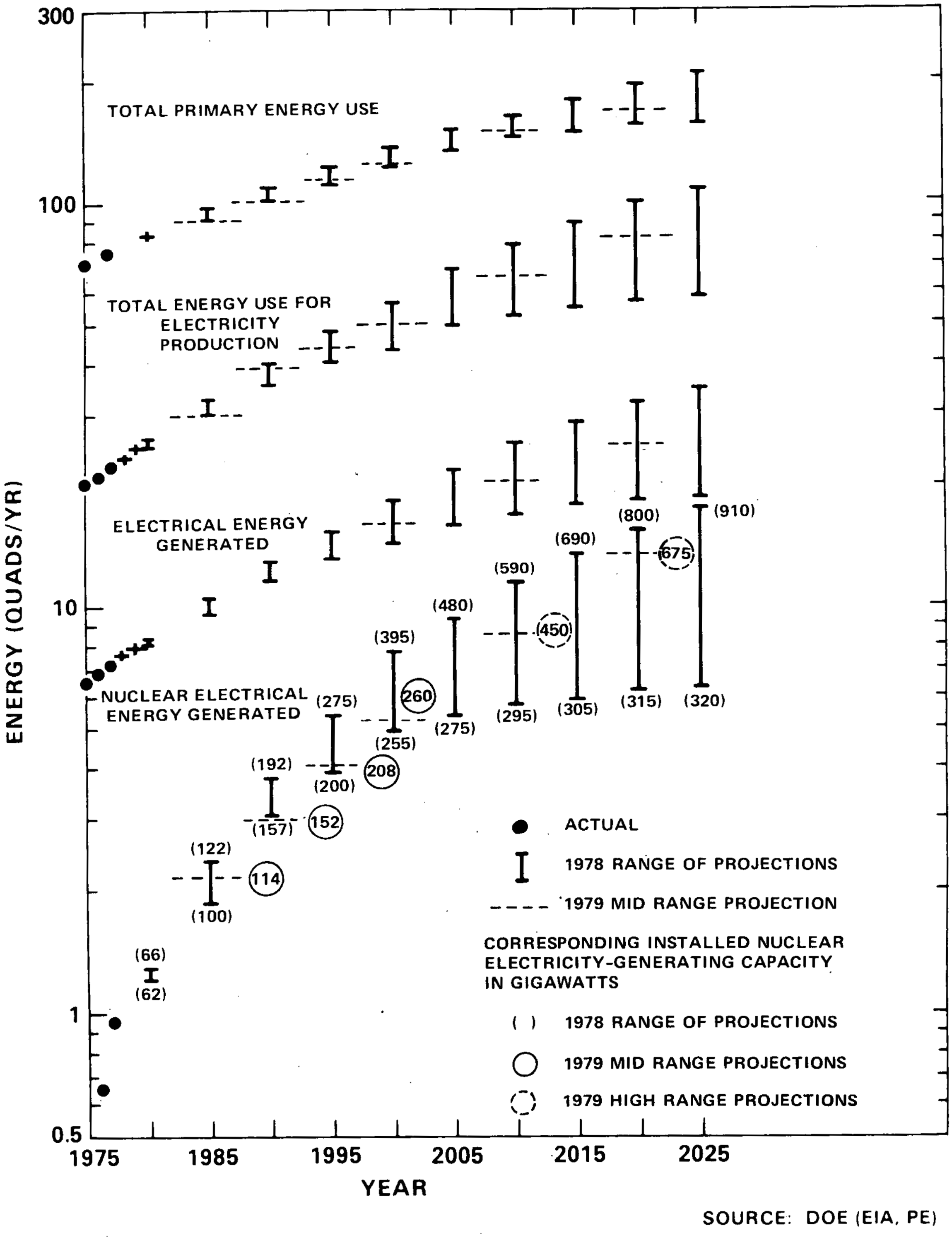

Fig. A-1. PROJECTIONS FOR TOTAL ENERGY, ELECTRICAL ENERGY, AND NUCLEAR ENERGY GENERATION, 1980-2025
(With Corresponding Nuclear Generating Capacity)

TABLE A-4. COMPARISONS OF RECENT PROJECTIONS OF TOTAL ENERGY AND ELECTRICITY CONSUMPTION AND OF INSTALLED NUCLEAR ELECTRICAL GENERATING CAPACITY

Forecast	Total Energy (10^{15} Btu/year)			Electricity Consumption (10^{15} Btu/year)			Installed Nuclear Electrical Generating Capacity (GW)		
	1985	1990	2000	1985	1990	2000	1985	1990	2000
Department of Energy (1978)	91.0-93.9	100.5-106.2	122.3-135.6	10.1-10.5	11.8-12.9	14.4-18.5	100-122	157-192	255-395
Department of Energy (1979)	86.2-93.7	94.4-110.2	117-129	-9.41-	10.7-12.3	-15.8-	102-118	142-171	235-300
EPRI Overview 1978[1]	94.9	108.4	117-138.6-158	10.6	12.3-14.7 -18.4	17.7-23.9 -31.1	--	197-280	350-675
WAES '77[2]	92.2-94.4	--	115.1-132.1	8.16-11.8	--	14.27-17.69	127-166[6]	--	380-620
Simpson[3]	--	--	--	--	--	--	--	158-190-204	230-320-420
EPRI[4]	88-102	94-125	108-180	9.9-12.9	11.3-18.5	13.8-28.0	--	--	--
Westinghouse[5]	91.7	101.2	115.2	9.2	11.2	15.2	111	173	323
CONAES[7]	--	--	63-137 (in 2010)	--	--	--	--	--	--
B&W[8]	--	--	--	--	--	--	123	165	245

(1) Electric Power Research Institute, Research and Development Program Plan, Report PS-830-SR, July 1978.

(2) Energy Supply-Demand Integration to the Year-2000 - Global and National Studies, Third Technical Report of the Workshop on Alternative Energy Strategies (WAES), Cambridge, Massachusetts: MIT Press, 1977.

(3) Simpson, J. W., "Dismal Outlook for U.S. Reactor Suppliers," Nuclear Engineering International, December 1978, p. 39.

(4) Electric Power Research Institute, Fuel and Energy Price Forecasts, Report EPRI EA-433, Menlo Park, California: 1977.

(5) Overview on Trends in the Electric Utility Industry, Westinghouse Electric Corporation, Report MRA 79-01, Vol. 1, January 1979.

(6) Energy-Global Prospects 1985-2000, Report of the Workshop on Alternative Energy Strategies (WAES), New York, New York: McGraw-Hill, 1977, p. 203.

(7) "U.S. Energy Demand: Some Low Energy Futures," Science, April 14, 1978: The Report of the Demand and Conservation Panel of CONAES, National Research Panel, 1978, pp. 142-152.

(8) Babcock & Wilcox Co., Long-Range Utility Forecast for the Power Generation Group, March 1979.

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