Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Executive Summary

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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

December 1979

This document is
PUBLICLY RELEASABLE

Barry Steinhilber
Authorizing Official

Date: 8-30-89

DRAFT

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

D R A F T

EXECUTIVE SUMMARY

TABLE OF CONTENTS

	<u>Page</u>
PREFACE	iii
Securing Energy Supply and Preventing the Proliferation of Nuclear Explosives Are Essential to National and International Security	iii
Many Organizations Contributed to the NASAP Study	v
 SECTION I: BACKGROUND	 1
U.S. Nonproliferation Policy Seeks To Restrain the Spread of Nuclear Weapons	1
The NASAP Study Is One Response to Proliferation Concerns	2
This Program Assessed Alternative Nuclear Systems To Find Those with the Lowest Proliferation Risk	3
 SECTION II: WHAT THE NASAP STUDIES FOUND	 4
Current and Future Nuclear Power Systems Can Be Made More Proliferation-Resistant	5
As Long As Doubts About Security of Fuel Supply Remain, More Resource-Efficient (and Potentially Less Proliferation-Resistant) Systems Will Be Attractive to Some Nations	6
Under Some Scenarios, Domestic Uranium Supply/Demand Imbalances Are Possible Beyond the Year 2010	11
The Worldwide Uranium Supply/Demand Balance Is Even Less Certain than the Domestic Picture	11
Other Nuclear Resources Are Less of a Problem than Uranium	12
Doubts About Fuel Supply Can Be Alleviated in Several Ways	12
Resource Extension Options Include Improvements to Once-Through Cycles, Advanced Converters, Recycle, and Breeder Reactors	13

D R A F T

TABLE OF CONTENTS - Continued

	<u>Page</u>
The Most Promising Resource Extension Options Are Light-Water Reactor Improvements (Including Reduced Enrichment Tails Assay) and Continued Development of the Plutonium-Fueled Breeder Reactors	18
Uranium-Supply Initiatives Include Measures To Reduce Uncertainty in the Estimated Size of the Resource Base, To Exploit It Efficiently and To Ensure Equitable Access	20
An International Nonproliferation Regime Will Require Institutional Measures and Technical Approaches	22
SECTION III: IMPLICATIONS FOR RESEARCH AND DEVELOPMENT	27
The Federal Share Would Have To Increase	27
More Immediate Solutions Should Have Priority, But Not to the Exclusion of Long-Range Alternatives	27

LIST OF FIGURES

Figure

1	Comparison of U_3O_8 Supply Capability and Demand, Using the Current Light-Water Reactor on the Once-Through Fuel Cycle ..	9
2	Comparison of Foreign WOCA U_3O_8 Annual Supply Capability and Demands for Current Light-Water and Heavy-Water Reactors	10

LIST OF TABLES

Table

1	Organizations Preparing Studies for NASAP	vi
---	---	----

D R A F T

EXECUTIVE SUMMARY

PREFACE

Securing Energy Supply and Preventing the Proliferation of Nuclear Explosives Are Essential to National and International Security

It is widely acknowledged that the real and perceived risks of nuclear proliferation constitute one of the most serious threats to international peace and stability. While there are other routes to nuclear weapons, the Nonproliferation Alternative Systems Assessment Program's (NASAP's) central concern is that as nuclear power systems and supporting civilian research and development activities become more widespread or as more advanced systems develop, their abuse, whether overt or covert, may provide a more attractive route to a nuclear weapons capability, whether national or subnational, than other routes. It is important, therefore, to ensure that nuclear power programs and systems, as they evolve here and abroad, do not present an attractive route, or make significant contributions, to a nuclear weapons capability.

The contribution that nuclear power programs can make to nuclear weapons programs depends upon the presence of sensitive materials and facilities in any of the processes associated with nuclear electrical power. Sensitive material is weapons-usable material; examples are highly enriched uranium or plutonium. Sensitive facilities are those that can produce, or can be easily modified to produce, weapons-usable material; examples are enrichment or reprocessing plants for reactor fuel. The proliferation risks arise because of the technical similarities between nuclear-power and nuclear-weapons materials and facilities, and the opportunities for abuse that those similarities provide.

Admittedly, constructing sensitive facilities with the intention of abusing them may not be the most efficient route to acquire weapons-usable materials. However, if such facilities already exist, the additional resources and time required to abuse a civilian program by diverting sensitive materials may be much less than those required to develop an independent military program and could allow little opportunity for a timely warning to, or an effective response by, the international community. Furthermore, the expertise acquired in these facilities can be drawn upon later for a dedicated weapons program. To this extent, the existence and potential abuse of sensitive facilities to obtain weapons-usable materials represent proliferation risks.

D R A F T

While today's most widely used system does not readily lend itself to the proliferation of nuclear-weapons (or nuclear-explosives) capabilities, it may nonetheless facilitate the acquisition of the materials, facilities and expertise necessary to develop nuclear weapons. This system involves mining and milling uranium ore, enriching uranium to a concentration of about 3 to 5 percent in the fissile U-235 isotope, fabricating the enriched uranium into reactor fuel elements, using this fuel in the light-water reactor in a "once-through" mode, that is, using it to generate power and then discharging the spent fuel into interim storage (also called "stow-away"), without deciding whether to put it into long-term storage or to dispose of it permanently. It should be noted that spent fuel from interim storage could later be used in a closed fuel cycle--that is, reprocessed to recover uranium and plutonium for re-use ("recycle") in nuclear power reactors.

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 proportion (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 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 designed to improve the nonproliferation regime. In short, economic, environmental, political and technical factors affect national decisions about the acceptability, role, and timing of the development and deployment of various nuclear power fuel cycles.

D R A F T

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 made 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.

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 without jeopardizing the development of nuclear energy.

Many Organizations Contributed to the NASAP Study

In support of its goal of finding more proliferation-resistant systems, NASAP has conducted over 50 interrelated studies, and has spent more than \$23.5 million during its nearly three years. In addition to the studies directly funded by NASAP, considerable technical data and analyses were obtained from ongoing research being conducted by various organizations within the Department of Energy. Also, the work of the International Nuclear Fuel Cycle Evaluation (INFCE) was drawn upon. 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 technical studies prepared for NASAP were performed by 7 national laboratories, 13 independent research organizations, 10 companies from the nuclear industry, and 5 universities. Industry leaders, trade associations, and representatives of special interest groups were consulted for their views. A list of the organizations that performed studies directly for NASAP is contained in Table 1.

Throughout the course of NASAP, intermediate findings and results were reviewed by the Department of Energy, other Federal agencies, and independent consultants. Contractor reports and early drafts of the NASAP final report were circulated for review and comment. In addition, more than 50 recognized experts in the areas of nuclear technology, foreign policy, and nuclear-weapons proliferation participated in a series of major conferences to review NASAP's progress and direction.

DRAFT

Table 1. Organizations Preparing Studies for NASAP

<u>PROLIFERATION RESISTANCE</u>	<u>RESOURCES AND FUEL CYCLE FACILITIES</u>	<u>COMMERCIAL POTENTIAL</u>	<u>ECONOMICS AND SYSTEMS ANALYSIS</u>	<u>SAFETY AND ENVIRONMENTAL CONSIDERATIONS FOR LICENSING</u>	<u>INTERNATIONAL PERSPECTIVES</u>	<u>ADVANCED CONCEPTS</u>	<u>TECHNICAL DATA FOR REACTORS AND FUEL CYCLES</u>
<ul style="list-style-type: none"> • Battelle Pacific Northwest Laboratory • Brookhaven National Laboratory • Hudson Institute • Lawrence Livermore Laboratory • Massachusetts Institute of Technology • Pan Heuristics • RAND Corporation • Science Applications, Inc. • System Planning Corporation 	<ul style="list-style-type: none"> • Hanford Engineering Development Laboratory • S. M. Stoller Corporation 	<ul style="list-style-type: none"> • Decision Focus, Inc. • George Washington University • Arthur D. Little, Inc. • S. M. Stoller Corporation • Westinghouse Electric Corporation 	<ul style="list-style-type: none"> • Burns and Roe, Inc. • Hanford Engineering Development Laboratory 	<ul style="list-style-type: none"> • Argonne National Laboratory • Babcock & Wilcox • Battelle Pacific Northwest Laboratory • General Electric Co. • NUS Corporation • Oak Ridge National Laboratory 	<ul style="list-style-type: none"> • Atlantic Council of the United States • Booz-Allen and Hamilton, Inc. • Brookings Institution • Georgetown University • Harvard University • Hudson Institute • International Energy Associates Ltd. • Institute for Energy Analysis-Oak Ridge Associated Universities • Nuclear Assurance Corporation • Pan Heuristics • RAND Corporation 	<ul style="list-style-type: none"> • Burns and Roe Industrial Services Corporation • Oak Ridge National Laboratory 	<ul style="list-style-type: none"> • Argonne National Laboratory • Brookhaven National Laboratory • Burns and Roe Industrial Services Corporation • Combustion Engineering, Inc. • General Electric Co. • Hanford Engineering Development Laboratory • Los Alamos Scientific Laboratory • Massachusetts Institute of Technology • Oak Ridge National Laboratory • Pennsylvania State University • Pickard, Lowe, Garrick and Associates • Southern Science Applications, Inc. • University of Washington

D R A F T

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:

Albert Carnesale	- Harvard University
Thomas Cochran	- Natural Resources Defense Council
Gordon Corey	- Commonwealth Edison
W. Kenneth Davis	- Bechtel Corporation
Lincoln Gordon	- Resources for the Future
Frederick Hoffman	- RAND Corporation
John Kearney	- Edison Electric Institute
Myron Kratzer	- International Energy Associates, Ltd.
Joseph Nye	- Harvard University (formerly Department of State)
George Rathjens	- Massachusetts Institute of Technology
Henry Rowen	- Stanford University
Chauncey Starr	- Electric Power Research Institute
Jessica Tuchman-Mathews	- Washington Post (formerly National Security Council)
Albert Wohlstetter	- University of Chicago

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 contributing analyses and technical guidance to the project within the Department of Energy were the Offices of the Assistant Secretaries for Energy Technology, Resource Applications, Defense Programs, Environment, International Affairs, and the Office of Energy Research.

The NASAP final report is composed of nine separately bound volumes and this Executive Summary. The most important findings and recommendations from NASAP are reported in this Executive Summary. The Program Summary (Volume I) contains the results of each of the following individual assessment areas: proliferation resistance, resources, commercial potential, economics, safety and environmental considerations for licensing, and international perspectives, which are contained in Volumes II through VII. An assessment of long-term advanced nuclear systems comprises Volume VIII, and technical descriptions of the reactors and fuel-cycle systems analyzed are contained in Volume IX.

D R A F T

EXECUTIVE SUMMARY

SECTION I: BACKGROUND

U.S. Nonproliferation Policy Seeks To Restrain the Spread of Nuclear Weapons.

While concern about the relationship between civilian nuclear power and research programs and the proliferation of nuclear weapons is not new, international attention to this problem has increased in recent years. There are a number of reasons for this heightened concern, including in particular the Indian nuclear explosion of 1974, which involved material and facilities supplied for peaceful purposes. In this new atmosphere, the United States has introduced important adjustments in its nonproliferation policy, while continuing to stress the importance of previous efforts in this area such as the Treaty on the Non-Proliferation of Nuclear Weapons (commonly known as the Non-Proliferation Treaty) and the International Atomic Energy Agency (IAEA) safeguards system. These policy adjustments in large part reflect the fact that an increasing number of nations either already possess or plan to acquire nuclear fuel-cycle facilities that produce or can be used to produce weapons-usable plutonium or uranium. While recognizing that political and security incentives remain central to the problem of proliferation, U.S. policy now gives increased emphasis to the risks of proliferation through the fuel cycle, and the concomitant need for restraint in moves toward a nuclear economy that would involve ready access to weapons-usable materials and the facilities to produce them. On April 7, 1977, President Carter issued a Nuclear Power Policy Statement that contained several initiatives designed to bring U.S. nuclear policy into line with this new emphasis.

This policy deferred commercial reprocessing, delayed commercializing the fast breeder reactor, and restructured the fast-breeder program to give greater priority to alternative designs and accelerated research into alternative fuel cycles.

The U.S. reiterated its policy of restraint in the export of sensitive nuclear technology and materials, a policy which culminated in the Nuclear Non-Proliferation Act of 1978. The U.S. has been 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. Finally, in recognition of the need for an international

D R A F T

cooperative effort to address nuclear proliferation, the U.S. has joined 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."

The NASAP Study Is One Response to Proliferation Concerns

The Nonproliferation Alternative Systems Assessment Program (NASAP), 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 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 inhibit, impede, or prevent the diversion of associated fuel-cycle materials or facilities from civilian to military uses.

The primary focus of NASAP, to assess the proliferation risks associated with civilian nuclear power systems, could not be undertaken without considering other factors of nuclear power systems that influence national decisions on the acquisition or expansion of nuclear power programs: the demand for nuclear energy; the supply of uranium; the economics, resource-use efficiency, safety, environmental and other aspects that dictate commercial acceptability; and the plans, programs, and needs of other nations.

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

- The study was limited to assessing the technical and institutional features of civilian nuclear power systems, the reactors and their associated fuel cycles. 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. Nevertheless, differences among the various systems regarding safety and environmental implications were discussed.

D R A F T

- Several other important nuclear power issues were outside the scope of the NASAP study: waste-management, use of the Allied General Nuclear Services reprocessing facility, and breeder-reactor funding, although they are affected by the NASAP recommendations.

It is important to recognize that the NASAP studies were completed before the accident at the Three Mile Island nuclear power plant in Pennsylvania. Thus, the NASAP report does not reflect the impact of events resulting from the investigation of the accident.

This Program Assessed Alternative Nuclear Systems To Find Those with the Lowest Proliferation Risk

Assessing the proliferation resistance of nuclear power systems, a new and complex problem, was central to the NASAP effort. 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 enriched to high concentrations in the isotopes U-235 (more than about 20 percent) or U-233 (more than about 12 percent) and plutonium are considered to be weapons-usable materials, whether in oxide or metallic form. The activities examined include the possible removal of materials from the fuel cycle, necessary preparation activities such as the construction of a new and possibly dedicated facility for conversion of these materials into 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.

Assessment of the proliferation resistance of various fuel cycles involved the simultaneous evaluation of many variables, most of which proved to be unquantifiable, and an awareness of the evolutionary nature of nuclear power programs. The NASAP proliferation assessment was not purely technical in nature, nor was it possible to develop a meaningful "index" of proliferation resistance of individual systems. Despite these difficulties, it was possible to analyze alternative nuclear systems and fuel cycles in terms of:

Resources required -- the technological base, personnel, and financial resources needed for proliferation activities in light of their inherent difficulties.

D R A F T

Time required -- the approximate times needed to carry out proliferation activities, including preparation, removal, and conversion.

Risks of detection -- the chances, timeliness, and consequences of detection of proliferation activities, including preparation, removal, and conversion.

Estimates of these factors led to qualitative findings and conclusions about the proliferation resistance of alternative fuel cycles and to an identification of technical and institutional measures that, developed over time, might be employed to reduce their proliferation vulnerabilities.

SECTION II: WHAT THE NASAP STUDIES FOUND

This section of the Executive Summary covers the results of NASAP assessments of alternative nuclear power systems. First, it examines today's 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 section 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 be used to meet the future demand for nuclear energy. The implications of deployment of nuclear options for proliferation resistance, the prospects for commercialization in each case, the potential for imbalances in the estimated requirements for uranium resources and the available supply of uranium have been examined. Next, ways that future fuel supplies might be assured to users whose alternative might otherwise be the adoption of less proliferation-resistant technology have also been examined. Finally, some of the institutional and technical measures that might reduce proliferation risks have been reviewed.

The concluding section summarizes the implications that the NASAP assessment results have for research and development.

D R A F T

Current and Future Nuclear Power Systems Can Be Made More Proliferation-Resistant

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

1. All nuclear 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 directly 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 highly enriched uranium or pure plutonium.
2. 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 to closed fuel cycles involving reprocessing), and some would result from institutional arrangements (e.g., the limited deployment of existing international enrichment services).

No nuclear fuel cycle which could be commercially deployed in the next few decades would offer more proliferation resistance than that associated with a light-water reactor once-through fuel cycle, in which spent fuel is safeguarded in interim storage facilities and enrichment services are provided by the existing suppliers.

Under any realistic deployment schedule for the foreseeable future, the amount of plutonium and the rate of its increase would not be likely to differ very much no matter which fuel cycle was adopted. However, fuel cycles differ greatly in the form in which plutonium appears. 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 fuel cycles, major fast-breeder programs are expected to remain confined for several decades to a few nations. The spread of breeder reactor research and development activities, however, continues to be an area of concern.

3. Technical and institutional proliferation-resistance features can help. With the progressive introduction of such features, the proliferation-resistance differences among fuel cycles might be much smaller by the

D R A F T

time they eventually came into widespread use. Such measures for the near term, when few recycle or fast breeder systems will be commercialized, and those for different fuel-cycle development choices, can be summarized as follows: 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); development of effective safeguards, now in the conceptual stage, for enrichment facilities, which should themselves be designed to facilitate safeguards; continued reliance on existing suppliers of enrichment services, including ventures under international or multinational auspices rather than undertaking new research and development in the absence of a clear demonstration of need; and adherence to export controls and the present suppliers' guidelines.

Additional measures are: cooperative arrangements to ensure adequate spent-fuel storage and to provide for interim storage; 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 when the need is clear. Finally, it is important to limit the use of materials in research reactors to enrichment levels which minimize the presence of weapons-usable materials.

4. The vulnerability to threats by subnational groups varies among 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.

As Long As Doubts About Security of Fuel Supply Remain, More Resource-Efficient (and Potentially Less Proliferation-Resistant) Systems Will Be Attractive to Some Nations

The ability of uranium and other resource and material supplies to support demand for nuclear power is an important consideration in future planning, both domestically and internationally. Unfortunately, both supply and demand projections are highly uncertain, and will be increasingly so as the planning horizon is extended in time.

D R A F T

Predicting this demand, either for the U.S. or for foreign countries, is inexact at best, because demand for nuclear power will depend on individual countries' attainment of their broad economic and industrial expectations, their dependence on and the availability of alternative sources of fuel supply, as well as on their specific plans for nuclear power growth. Likewise, the assurance of uranium supply is subject to uncertainties, especially with regard to the adequacy of uranium resources, their productivity and to the terms and conditions of trade.

One Problem is the Uncertainty in Forecasts of Future Demand for Nuclear-Generated Power -- The uncertainty of nuclear energy forecasts is evidenced by how often, and how dramatically, they are adjusted. Over the past two or three years, the outlook for nuclear power, both in the U.S. and abroad, has changed significantly. For the U.S., the latest (1979) forecast is for 235 to 300 gigawatts (GW)¹ of nuclear electrical generating capacity in the year 2000, a Median of 260 GW. The 1979 Median is less than one-third of the prediction four years earlier. Recent projections for the world outside the centrally planned economic areas show a similar decrease, although many believe these lower estimates are still too high. The reasons for these changes include differences in the expected contribution of alternative technologies, lower electrical growth projections, and in future industrial and economic expectations in light of recent past events with world oil supplies. To deal with these uncertainties, NASAP used a range of forecasts of domestic nuclear growth based upon 1978 and 1979 Department of Energy analyses. For countries outside centrally planned-economy areas, nuclear growth foreign estimates prepared for INFCE and 1979 Department of Energy analyses were used.

Another Problem Involves Predicting the Adequacy of Future Supplies -- There has been a considerable diversity of opinion on the question of the future availability of uranium from domestic sources. The views range from prediction of adequacy of supply well into the next century² to warnings of shortages well before the end of this century³.

¹One gigawatt is equal to 1 million kilowatts (10^9 watts).

²Nuclear Power Issues and Choices, Ford Foundation/The Mitre Corporation, Ballinger Publishing Company, 1977.

³Problems of U.S. Uranium Resources and Supply to the Year 2000, report of Uranium Resource Subpanel to CONAES Committee, National Academy of Sciences, 1978.

D R A F T

There are three principal reasons for this uncertainty over the future availability of uranium:

1. Lack of differentiation between estimated resources "in the ground" and predictable supplies.
2. Differences in the degree, if any, to which practical constraints and uncertainty factors are taken into account.
3. Different and constantly changing perceptions of future uranium demand.

The projected potential for supplying uranium from low-grade, domestic resources shows less than 10 percent of total production from these resources before 2000, mainly by-product uranium from phosphoric acid production. Two projections were developed: one based upon a conservative rate of production from phosphates and shales, the other based upon more optimistic assumptions.

The Department of Energy's estimate of maximum domestic supply capabilities of high-grade and low-grade resources are shown in Figure 1, ranging from 90,000 short tons of U_3O_8 in 2000 to 125,000 short tons of U_3O_8 in 2025. The estimates of annual supply from high-grade resources only, influenced by expectations of the demand corresponding to the 1978 Median nuclear growth, ranges from 50,000 short tons of U_3O_8 in 2000 to 70,000 short tons of U_3O_8 in 2025. The maximum possible annual production from high-grade resources after 2000 was estimated to be 85,000 short tons of U_3O_8 as indicated in Figure 1. The lower projections give a range of annual supply capability of from 50,000 to 65,000 short tons of U_3O_8 in 2000 and from 70,000 to 90,000 short tons of U_3O_8 in 2025.

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 U_3O_8 supply for countries outside the centrally planned-economy areas. Figure 2 shows the range of supply projections which result from combining the high-grade and low-grade projections from work by the Joint Working Group of the Nuclear Energy Agency and the IAEA as well as estimates made by the Department of Energy, Office of Uranium Resource Assessment Operations.

Figure 1. Comparison of U_3O_8 Supply Capability and Demand Using the Current Light-Water Reactor on the Once-Through Fuel Cycle

DRAFT

Figure 2. Comparison of WOCA Annual U_3O_8 Supply Production Capability and Demand for Current Light-Water and Heavy-Water Reactors

D R A F T

Under Some Scenarios, Domestic Uranium Supply/Demand Imbalances Are Possible Beyond the Year 2010

When the uranium that would be required to meet the NASAP range of domestic 1978 and 1979 nuclear-growth forecasts is shown in Figure 1 (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). When compared with domestic uranium supply capability, the possibility of supply and demand imbalances is indicated.

If a nuclear growth to about 300 GW in the year 2000 occurs and growth continues at a rate of 12 GW per year thereafter, a uranium supply/demand imbalance might occur between 2010 and 2025 unless there were maximum development of high-grade resources and large-scale development of low-grade uranium resources, particularly the Chattanooga shales. This development would need to begin by 2000 and might be limited by environmental impacts and technical problems. The lower range of nuclear growth as currently forecast would not be constrained by uranium supply to any great extent. However, because uranium is a commodity in international commerce, both imported and exported by the U.S., some domestic shortfalls might be made up from foreign resources, while excess production could be sold overseas.

The Worldwide Uranium Supply/Demand Balance Is Even less Certain than the Domestic Picture

When the uranium that would be required to meet the range of nuclear-growth forecasts for the world outside the centrally planned-economy areas (WOCA) (assuming the continued use of reactors on the once-through cycle) is compared with world uranium supply capability, scenarios can be found in which supply and demand imbalances could occur. For example, as shown in Figure 2, a low supply capability could result in an imbalance before 2000, although if the 1979 growth trend persists, such an imbalance is unlikely to occur much before 2010.

On the other hand, supply may be adequate beyond 2025 if there is an aggressive worldwide development of resources the extent and existence of which are subject to considerable uncertainty. Nations with small uranium resource bases may wish to reduce their dependence on imports of uranium.

D R A F T

Other Nuclear Resources Are Less of a Problem than Uranium

The U.S. requirements for enrichment services will continue to increase with time. Through the early 1990's, existing and planned U.S. capacity of about 29 million separative work units would be adequate to meet the projected domestic demand; similarly, existing and planned world capacity would also be adequate to meet projected worldwide demand. To meet requirements at the end of the century and beyond, however, enrichment capacity may have to be expanded.

The supply/demand balance for other resources, such as thorium and heavy water, appears to pose no problem under any of the domestic and worldwide nuclear-growth projections.

Doubts About Fuel Supply Can Be Alleviated in Several Ways

A number of approaches are available to provide security of supply. Some would afford greater proliferation resistance and economic benefits than others. The approaches fall into three categories:

- Resource extenders: nuclear systems and technologies that use 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 future for nuclear power 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

D R A F T

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 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).

Resource Extension Options Include Improvements to Once-Through Cycles, Advanced Converters, Recycle, and Breeder Reactors

Measures to extend resources do exist for the United States. NASAP investigated a broad range of resource extension options, which included the following.

Improvements to Once-Through Fuel Utilization -- The fuel efficiency of light-water reactors might be improved by as much as 30 percent through fuel redesign, reoptimization of fuel-management practices, and plant design changes. Significantly, some of these gains in fuel-utilization efficiency can be applied to existing reactors (retrofitted) and new reactors coming on line now and in the future. Thus, a large overall system improvement would be possible. Also, enrichment plants can extract more of the fissionable isotope U-235 from the natural uranium feed, but this approach could require additional enrichment capacity. To avoid increasing proliferation risks, the increased capacity could be either at existing sites or under multinational or international auspices. Advanced converter reactors, such as high-temperature gas-cooled reactors and heavy-water reactors, have lower uranium requirements when operated in a once-through mode, but their impact on the uranium needs for the total worldwide nuclear power network would be constrained by the pace at which such reactors could be commercially deployed in significant numbers. Each of these improvements has been assessed, and is discussed below.

By 1990, a 15 percent improvement in the uranium utilization of light-water reactors on a once-through cycle may be achievable by extending fuel burnup, making operational changes, and improving fuel management. An additional 5 to 10 percent improvement might be realized by the year 2000. Further increases, up to a total of 30 percent or more, are less certain technically, would take longer to develop and implement commercially, and in some cases, would require plant-design changes which could be applied only to new plants. Improving fuel utilization in the once-through light-water reactor fuel cycle would

D R A F T

reduce the incentive for plutonium recycle and, therefore, would contribute to nonproliferation goals. In addition, the proliferation resistance of the once-through light-water reactor fuel cycle is increased directly by reducing the amount of plutonium contained in spent fuel discharged annually, and indirectly by reducing the pressure on existing spent-fuel storage capacity. Since these fuel-use improvements are modifications to existing light-water reactor technology and can reduce fuel-cycle costs, there are a priori good prospects that some of them will be commercially acceptable.

Separating More of the U-235 from Natural Uranium -- The requirements for newly mined uranium for use in light-water reactors on a once-through cycle can be reduced by operating enrichment plants at lower tails assay, thereby extracting more of the fissionable isotope U-235. The current commercial enrichment technologies, gaseous diffusion and gas centrifuge, cannot, at today's uranium prices, enrich uranium economically at tails assays lower than the present 0.20 percent U-235. However, improved centrifuges and advanced isotope separation enrichment processes, such as laser or plasma separation, might provide enrichment services at lower cost than current technology, on a tails assay from 0.1 to as low as 0.05 percent U-235 for the most advanced techniques, thereby reducing uranium requirements by as much as 20 percent. However, operating at these low tails assays increases the requirements for enrichment capacity by about 80 percent. The institutional mechanisms by which new technologies and increased enrichment capacity, if required, would be put in place must be carefully planned and subjected to strict safeguards, if proliferation resistance is not to be reduced. Technically, gas-centrifuge enrichment plants can be modified more easily than gaseous-diffusion plants to produce highly enriched uranium and, therefore, are a greater proliferation risk. Advanced isotope separation technologies are at an early stage of development, so that assessment of their proliferation potential is not possible in the same detail as with other technologies. The current assessment is that adaptation of plants using this technology to produce highly enriched uranium would be difficult; but this result must be subject to continued expert scrutiny. Institutionally, additional enrichment capacity could be provided at existing sites or under multinational or international auspices.

Instituting the retrofittable fuel-utilization improvements along with reduced tails assays could produce resource savings of about 40 percent. Near-term concerns over uranium availability and spent-fuel storage would be reduced, but the longer-term concerns over these issues and over security of supply would remain.

Advanced Converter Reactors -- Another approach to resource savings may be to employ advanced converter reactors, such as the high-temperature

D R A F T

gas-cooled reactor or the heavy-water reactor. Such systems use uranium more efficiently, even on the once-through cycle, than does the light-water reactor. The current designs of these reactors operating on a once-through fuel cycle can use about 25 to 40 percent less uranium over their operating lifetime than the present light-water reactor fuel design.

On a once-through fuel cycle, heavy-water reactors are somewhat less proliferation resistant than light-water reactors. In particular, heavy-water reactors, which use on-line refueling, require different techniques and are more difficult to safeguard than reactors using batch refueling; in addition, the heavy water can be used with natural uranium (presently unsafeguarded in some countries) in a plutonium production reactor. The proliferation resistance of the high-temperature gas-cooled reactor using low-enriched uranium is comparable to that of the light-water reactor, but use of low-enriched uranium reduces its economic advantage somewhat; and some (but not all) of its fuel-cycle options with low uranium requirements must use highly enriched uranium, which is directly usable in weapons. With the exception of those options, it appears that there are no nonproliferation reasons for preferring or not preferring any of these alternatives to the light-water reactor.

Although demonstration high-temperature gas-cooled reactors are operating in the U.S. and the Federal Republic of Germany, this reactor is not yet a commercial system. Neither is the heavy-water reactor commercial in the U.S., although the Canadian heavy-water reactor in particular has achieved some market penetration in other countries. Thus, these systems would require additional research, development, and demonstration programs before they could be commercially deployed in this country. The same is true to a lesser extent overseas. Given current domestic nuclear power circumstances, such programs clearly would depend upon Government financing, particularly as these systems offer no significant economic advantage to utilities over light-water reactors.

Even with Government financing, such deployment would not occur in the United States before the year 2000, and introduction then into a régime with hundreds of operating light-water reactors would have little effect on the total system's annual uranium requirements much before the second quarter of the next century.

Recycle of Plutonium in Thermal Reactors -- While plutonium recycle in light-water reactors (also known as thermal recycle) cannot provide total independence from U_3O_8 supply constraints, it can reduce requirements by 35 to 40 percent over the lifetime of a reactor system. Recycle could increase, however, the risk of proliferation because plutonium-bearing materials

D R A F T

or separated plutonium may be stored and transported in forms readily usable in weapons. Measures to reduce the vulnerabilities of plutonium recycle include modifying the materials to make them more difficult to convert to weapons-usable form and instituting more comprehensive safeguards and physical security measures to improve the ability to detect diversion. Sensitive facilities such as reprocessing plants could be placed under international or multinational auspices, or located in nuclear-weapons states. Finally, effective plutonium management schemes and systems would be essential if plutonium were to be recycled.

Plutonium recycle has been deferred in the U.S. If desired, it could be made available by about 1990. This time would be needed to complete work on the remaining unresolved technical problems and institutional issues.

Breeder Reactors -- The fast-breeder reactor has a completely different resource-utilization potential than does either a light-water reactor or an advanced converter reactor operating in a recycle mode, since fast-breeder reactors can eventually provide a practically inexhaustible supply of energy by using stockpiled depleted uranium from enrichment plants, and the plutonium and uranium in available supplies of spent fuel. However, fast breeders require fuel reprocessing, to produce the needed plutonium, and the handling and transportation of very substantial quantities of plutonium. Thus, while deploying the fast breeders would represent a new dimension in efficient resource utilization, it could also represent a new dimension in proliferation risk. Measures to reduce proliferation vulnerabilities would be similar to those for plutonium recycle.

In many respects, the proliferation resistance of breeder systems is similar to that of recycle systems; however, there would be differences due to the greater flows of plutonium at higher concentrations in the breeder cycle. Fast-breeder mixed-oxide fuels would have plutonium concentrations of 15 to 25 percent, considered to be weapons-usable, whereas mixed-oxide fuels for recycle would contain only 4 to 6 percent plutonium, not considered to be weapons-usable. Further proliferation implications of fast breeder systems are related to the fact that they could not be deployed commercially on a major scale for at least two decades and possibly much longer. The international institutional framework within which such nuclear power systems will be operated could be clarified during the period of development. However, research and development activities, largely motivated by anticipated fast-breeder needs, are already of concern. In other words, the proliferation vulnerabilities of fast breeder systems will appear long before actual reactor deployment and must be accommodated in current efforts to establish a satisfactory nonproliferation regime.

D R A F T

The long-term commercial potential for the fast-breeder systems, especially the liquid-metal fast breeder reactor, is good. Their commercial attractiveness would be substantially enhanced as cost competitiveness improved with rising uranium prices. However, compared with the current once-through light-water reactor, deployment of advanced converter reactors and plutonium recycle may involve a high initial risk from the standpoints of financing, operational reliability, and institutional (public acceptance and licensing) concerns.

Resource-efficient alternatives to the plutonium-fueled fast breeder reactor, using isotopically diluted fuels that are not weapons usable, were assessed to determine whether they offered any improvement in proliferation resistance. While some of these advanced conceptual systems appear to promise somewhat greater proliferation resistance than the fast breeder reactor, they have long (40- to 50-year) development times, so that the context of proliferation concerns and the world nuclear regime will have changed before they can be deployed. Because these alternative systems have technical problems, have had minimal research and development support, and have not been demonstrated, commercial deployment is highly uncertain and, if achievable, would be more time consuming and costly (over \$10 billion) than the liquid-metal fast breeder. Thus, these advanced concepts do not appear to be credible alternatives to the liquid-metal fast breeder reactor for any country that believes it must rapidly develop a hedge against possible shortages, real or artificial, in uranium fuel supply. The fast mixed-spectrum reactor, however, has features of sufficient interest for it to merit further examination. While it appears to offer proliferation-resistance advantages over the liquid-metal fast breeder reactor, it has vulnerabilities, too. It would use the heat transport system and plant technology of either the liquid-metal or gas-cooled breeder reactor but would eliminate reprocessing. Moreover, the fuel development program could be of benefit also to the existing liquid-metal fast breeder reactor program.

Another breeder reactor assessed was the light-water version, as a proxy for the general category of water-cooled breeders. Such reactors use the basic plant technology of pressurized water reactors but with a uranium/thorium fuel design. In order to breed, they must have fuel highly enriched in U-233; reprocessing and recycling of the fuel are also required. A light-water breeder reactor has about the same proliferation risk as an advanced converter reactor or light-water reactor, recycling fuel. Resource utilization is somewhat less efficient than with the fast breeder reactor. While the light-water breeder reactor has the basic advantage of building upon light-water reactor technology (and component reliability), this has not stimulated private-sector interest to date, and any development would require substantial Government funding.

D R A F T

The Most Promising Resource Extension Options Are Light-Water Reactor Improvements (Including Reduced Enrichment Tails Assay) and Continued Development of the Plutonium-Fueled Breeder Reactors.

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 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

D R A F T

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

D R A F T

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.

Uranium-Supply Initiatives Include Measures To Reduce Uncertainty in the Estimated Size of the Resource Base, To Exploit It Efficiently, and To Ensure Equitable Access

While improving the uranium utilization of once-through systems could reduce the pressure to adopt more 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. The United States and other nuclear-energy users can encourage and assist other nations both directly and through international organizations, to locate, estimate and exploit their uranium resources. 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.

D R A F T

Research and development aimed at improving extraction and milling techniques can also 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; but they will not satisfy the primary concerns about access to uranium felt by nations that do not have adequate domestic uranium resources. A number of potential approaches for assuring supplies have been considered in the NASAP study, including:

- **Bilateral fuel-supply assurances:** agreements between fuel-supplier and recipient nations covering terms, conditions, warranties, and other aspects of trade.
- **Secondary fuel-supply assurances:** 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, (natural and enriched) under the bank's physical control.
- **Market-oriented initiatives** including commodity agreements and inter-governmental consultative systems.

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 but would require specific actions: developing and implementing a comprehensive technical program to use more efficiently the uranium resource base, including making available improvements to light-water

D R A F T

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 Nuclear Energy Agency, 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 inter-governmental 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.

An International Nonproliferation Regime Will Require Institutional Measures and Technical Approaches

Depending on their make-up, manner of operation, and location, international institutional arrangements have the potential to address both nonproliferation concerns and the long-term viability of nuclear power. 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 various possible arrangements shaped the following major observations:

- New enrichment capacity should be under effective multinational or international auspices. Consideration should 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 enrichment 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-fuel values.

D R A F T

- 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 to be provided by a few large facilities using more proliferation-resistant technologies, if safeguards were to be strengthened at all bulk-handling facilities, and if services were to be supplied based on schedules driven by fast breeder and advanced reactor research and development needs where there exist 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 U.S. should develop advanced safeguards techniques, especially for bulk-handling facilities and transport systems for spent and plutonium fuels. This 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 cooperation 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

D R A F T

a nuclear weapons capability. Therefore, disincentives such as sanctions should also be investigated.

Sanctions and the threat of sanctions represent an important element of nonproliferation efforts. 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. Nevertheless, it is essential that there be a visible international consensus that wide-ranging sanctions appropriate to the particular circumstances be invoked if there were a breach of nonproliferation obligations. Developing internationally agreed-upon guidelines for an implementation procedure would be useful.

Technical modifications have been suggested as one means of reducing the proliferation risks associated with certain aspects of the nuclear fuel cycle, particularly that part of the fuel cycle containing plutonium. Such measures could be combined with the institutional arrangements discussed above. Several modifications have been identified that could be applied to plutonium recycle in light-water reactors, and subsequently in the fast breeder reactor. Generally, these modifications have been designed to increase the proliferation-resistance of reprocessing and the use of plutonium fuels. The technical modifications investigated include:

1. Coprocessing and coprecipitation of uranium and plutonium in the reprocessing plant so that plutonium would never be produced alone but would always be diluted with uranium.
2. Coprocessing and coprecipitation with partial decontamination of fission products. Some fission products would remain with the mixture of uranium and plutonium, creating a radiation barrier throughout the fuel cycle.
3. Addition of radioactive isotopes to fresh mixed uranium/plutonium-oxide fuels creating a radiation barrier throughout the fuel cycle.
4. Pre-irradiation of fabricated mixed-oxide fuel, creating a radiation barrier by irradiating fuel in a special facility.
5. Active countermeasures (use-denial) within the fuel-cycle facilities by which barriers to abuse of materials and facilities could be remotely controlled to shutdown or disable processes or equipment.

D R A F T

6. Passive countermeasures within fuel cycle facilities whereby the facilities are designed to make abuse more difficult, time consuming, or detectable.

The six 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, 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 does not provide effective protection against misuse.

Based on the NASAP analysis, none of the above technical initiatives appear to mitigate the concern that a national operator might take over a reprocessing 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 advantages with regard to subnational threats, although their appropriateness in this context would depend on environmental, economic, and safeguards disadvantages. Key findings are:

- In countries where reprocessing or fabrication facilities were deployed, the effect of coprocessing on proliferation resistance would be limited for two reasons. First, separated plutonium oxide could

D R A F T

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. 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.
- Coprocessing and coprecipitation of uranium and plutonium was found to be the least intrusive and least costly measure to implement. The cost impact would be less than a 0.15 mill/kWh¹ increment to the power-generation costs and would occur primarily within the reprocessing plant during coprecipitation.

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

D R A F T

- The measures designed to have highly radioactive fuel throughout the fuel cycle (coprocessing with partial decontamination, deliberate addition of radioactive isotopes, e.g., Co-60 spiking) would lead to incremental costs 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, from 0.9 to 1.5 mills/kWh was estimated.
- The research-and-development costs of implementing these measures (with the possible exception of coprocessing) would be substantial. Preliminary estimates have been made only for the gamma-spiking concepts. These estimates are in excess of \$275 to \$430 million.

SECTION III: IMPLICATIONS FOR RESEARCH AND DEVELOPMENT

The Federal Share Would Have To Increase

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. 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.

D R A F T

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.

More Immediate Solutions Should Have Priority, But Not to the Exclusion of Long-Range Alternatives

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.

D R A F T

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.

Thus, the NASAP recommendation is to continue liquid-metal fast-breeder development. 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.

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 facilities and materials which, although not of the same magnitude

D R A F T

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. This objective is 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. 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

D R A F T

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 on-going 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 Table 2.

D R A F T

TABLE 2. RESEARCH AND DEVELOPMENT PROGRAM RECOMMENDATIONS

<u>Program</u>	<u>Target</u>
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 nonretrofitable 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	Complete proof of breeding demonstration in Shippingport Atomic Power Station by 1985.
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	Continued improvement in
o Interim spent-fuel storage	surveillance, containment,
o Spent-fuel disposal repository	and material accountancy.
o Reprocessing plants	
o Plutonium storage	
o Mixed-oxide fabrication plants	
o Transportation	