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BY THE COMPTROLLER GENERAL

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# Report To The Congress

OF THE UNITED STATES

# Nuclear Reactor Options To Reduce The Risk Of Proliferation And To Succeed Current Light Water Reactor Technology

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Nearly all commercial nuclear reactors in the United States are light water reactors. Until recently, the "heir apparent" to the light water reactor was the liquid metal fast breeder reactor. Primarily because of proliferation concerns, the liquid metal fast breeder reactor program has been deemphasized.

In response to a request from the Vice Chairman of the Joint Economic Committee and widespread interest by other Members of the Congress, GAO compared a number of alternative reactor technologies, a number of modifications to reprocessing technology, and the thorium fuel cycle. TNT00700

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GAO found that there is no proliferation-proof reactor technology, nor is there any technology which is clearly superior when compared in terms of resource utilization, licensability, environmental acceptability, cost, commercialization schedule, proliferation resistance, safeguardability, and economics. Therefore, GAO believes that the Congress should not preclude the liquid metal fast breeder reactor option, at least at this time.

UNITED STATES GENERAL ACCOUNTING OFFICE

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COMPTROLLER GENERAL OF THE UNITED STATES
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To the President of the Senate and the
Speaker of the House of Representatives

This report provides a comparison of a number of advanced nuclear fission technologies not only from the perspective of proliferation risk, but also from other perspectives such as the environment, licensability, safeguardability, and resource utilization.

Copies of this report are being sent to the Director of the Office of Management and Budget, the Secretary of Energy, and interested members and committees of the Congress.

Elmer B. Staats
Comptroller General
of the United States

COMPTROLLER GENERAL'S REPORT TO THE CONGRESS

# NUCLEAR REACTOR OPTIONS TO REDUCE THE RISK OF PROLIFERATION AND TO SUCCEED CURRENT LIGHT WATER REACTOR TECHNOLOGY

## D I G E S T

Rec to Cong.

Until a decision is made on which nuclear technology should become the successor to current light water reactor technology the Congress should continue to maintain research and development efforts relating to the liquid metal fast breeder concept so as to not preclude at this time the option of building a liquid metal fast breeder demonstration reactor.

All but two commercial nuclear reactors in the United States are light water reactors. A light water reactor uses only about 2 percent of the energy potential contained in its uranium fuel. Until recently, the "heir apparent" to the light water reactor was the liquid metal fast breeder reactor.

The breeder reactor is expected to extract at least 30 times more energy from uranium than light water reactors and produce more fuel than it uses. It represents a substantial advancement in fuel use efficiency and its breeding capabilities render it a virtually inexhaustible resource for generating electricity.

The discharged or spent fuel from both the light water reactor and the liquid metal fast breeder reactor can be reprocessed to extract plutonium and other elements. The extracted plutonium can then be used again as nuclear fuel. The problem is that plutonium can also be used to make nuclear weapons.

Since the 1950s, there has been considerable concern that nations with nuclear powerplants, but without nuclear weapons, might attempt to reprocess spent nuclear fuel to acquire plutonium for nuclear weapons. To

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reduce the risk of nuclear weapons proliferation from reactor systems which involve plutonium reprocessing, the President proposed in April 1977 that the United States (1) indefinitely defer commercial reprocessing and recycling of plutonium as well as the commercial introduction of the liquid metal fast breeder reactor, (2) reduce funding for the liquid metal fast breeder reactor research and development program and redirect efforts towards evaluating alternative nuclear concepts and fuel cycles, and (3) cancel construction of the Clinch River Breeder Reactor--the Nation's first liquid metal fast breeder reactor demonstration powerplant. Since April 1977 most of the President's proposals have been carried out as part of current energy policy.

In response to a request from the Vice Chairman of the Joint Economic Committee, GAO reviewed (1) technical methods to reduce the risk of nuclear proliferation from spent fuel reprocessing, including making use of the thorium fuel cycle, (2) institutional methods to reduce the risk of nuclear proliferation, and (3) status and obstacles associated with developing various alternative nuclear fission concepts.

## TECHNICAL METHODS OF REDUCING THE RISK OF PROLIFERATION FROM REPROCESSING NUCLEAR FUEL

To determine if current nuclear reactors can be made "proliferation-proof," GAO reviewed four proposed technical alterations to current nuclear power systems.

--Coprocessing - a form of reprocessing whereby plutonium, which could otherwise be extracted for use in weapons, is never completely separated from the spent reactor fuel. The highly radioactive spent fuel would make handling extremely difficult.

--Spiking - a process in which extracted plutonium is deliberately contaminated with dangerous levels of radiation to make handling difficult.

--Colocation - a concept whereby all parts of the fuel cycle providing access to plutonium are placed at a single, centralized location.

--The Civex process - an alternative to current reprocessing techniques which involves such features as coprocessing and spiking.

None of these technical methods is proliferation-proof. GAO found that none of the proposed technical alternatives to current nuclear power system methods presents insurmountable obstacles to a nation or subnational terrorist group intent on diverting nuclear material to make weapons. In addition, none of the technical methods has been developed beyond the experimental state. Each would, however, make the diversion of weapons material more difficult, thereby lowering the risk of nuclear proliferation. (See pp. 7 to 10.)

Another possible method for reducing the risk of nuclear weapons proliferation is to phase out the uranium fuel cycle and adopt the thorium fuel cycle. GAO found that, in some respects, the thorium fuel cycle is superior to the uranium cycle. However, the thorium fuel cycle is not proliferation proof as it produces a form of uranium which is a weapons material as well as some plutonium. Also, the thorium fuel cycle has not been demonstrated and major economic and development questions must be answered. (See pp. 10 to 14.)

## INSTITUTIONAL METHODS TO REDUCE THE RISK OF NUCLEAR PROLIFERATION

In addition to altering the current technology or adopting a new nuclear fuel cycle, institutional methods are available for reducing the risk of nuclear proliferation. Institutional methods attempt to discourage countries from acquiring nuclear weapons.

Through the 1950s and 1960s and into the early 1970s, an institutional framework has existed. This framework includes the International Atomic Energy Agency, the Treaty on the Nonproliferation of Nuclear Weapons, and agreements between suppliers and users of nuclear materials. However, the explosion of a nuclear device by India and the emergence of terrorist activities coupled with the widespread knowledge of nuclear technology has led to a general belief that a strengthening of institutional methods is required.

Several actions, such as a tightening of controls over spent fuel by suppliers of nuclear materials and facilities, have been taken and the United States is implementing the Nuclear Non-Proliferation Act of 1978 (Public Law 95-242, March 10, 1978). This act is aimed at decreasing the worldwide risk of proliferation. Institutional actions, however, like technical alterations cannot totally eliminate the risk of nuclear proliferation. The United States cannot unilaterally provide assurances against weapons proliferation. However, if nuclear energy is going to remain an important source of energy and a viable energy alternative to be pursued in the future, the United States has little choice but to push for the worldwide adoption of additional institutional measures which would decrease the potential for proliferation of nuclear weapons including those which would facilitate colocation and international management of nuclear facilities. (See pp. 16 to 20.)

## EVALUATION OF ADVANCED NUCLEAR FISSION TECHNOLOGIES

Current U.S. nuclear energy policy emphasizes finding a fission technology to succeed current light water reactor technology. Because present nuclear power systems cannot be made proliferation-proof, the pursuit of a superior nuclear technology would seem a logical course of action.

An evaluation of advanced nuclear fission technologies, however, should not be restricted solely to proliferation concerns. Proliferation is an important factor, but in making decisions concerning the next generation of nuclear power, consideration should also be given to other evaluation factors such as resource utilization, licensability, environmental acceptability, cost and commercialization schedule, safeguardability, and economics. In that context, GAO, with the aid of a contractor, reviewed a number of the major advanced nuclear technologies currently being studied by the Department of Energy--the spectral shift control reactor, the heavy water reactor, the high temperature gas reactor, the gas-cooled breeder reactor, the light water breeder reactor, the molten salt breeder reactor, the accelerator breeder reactor, the fission-fusion breeder reactor, and the gaseous core reactor.

These candidate technologies vary greatly in their state of development and in their desirability under each of the criteria. In addition, some are already, or are very close to being, commercially available in the United States. Others are only conceptual and some are not yet defined or analyzed in sufficient detail to permit meaningful comparison. GAO found that no one technology was clearly superior to all other systems. A decision on which nuclear technology is best to pursue depends on the relative weight assigned to each of the evaluation factors. In addition, none of the advanced technologies which GAO reviewed can be considered proliferation-proof although they vary in their relative level of proliferation risk. (See pp. 21 to 41.)

Major studies of advanced nuclear fission technologies are now being conducted under the auspices of the Nonproliferation Alternative Systems Assessment Program and the International Nuclear Fuel Cycle Evaluation Program. The results of both studies should be available during calendar year 1979 and should prove helpful in making a decision concerning which second generation nuclear fission technology to pursue.

MATTERS FOR CONSIDERATION BY THE CONGRESS

Nuclear fission research and development, with the objective of developing a technology superior to that used in current generation light water reactors is an important part of the Nation's energy program. Most of the technologies being explored will take many years to develop to the point of commercialization and all will be expensive. In addition, none of the alternatives is clearly the most desirable when viewed in light of the criteria listed in this report.

For more than 25 years, the Congress has supported development of the liquid metal fast breeder reactor. In April 1977 the President proposed reduced funding for the liquid metal fast breeder reactor program and cancellation of the Clinch River Breeder Reactor project. Despite the President's proposal, the Congress has supported continuation of the liquid metal fast breeder reactor program and has provided funding to maintain the option of building the Clinch River Breeder Reactor. It is quite likely that the issues surrounding the Clinch River Breeder Reactor will again be considered during the 96th Congress. Such consideration requires an evaluation of the liquid metal fast breeder reactor program measured against the alternatives to this reactor concept. GAO believes the results of the studies currently being conducted under the Nonproliferation Alternative Systems Assessment Program and the International Nuclear Fuel Cycle Evaluation, together with this report, should prove useful in making such an evaluation.

In developing this report, GAO had the benefit of comments by a varied group of distinguished experts knowledgeable about nuclear issues. In addition, copies of a draft of this report were reviewed by the Department of Energy, the Nuclear Regulatory Commission, and the Department of State. Where appropriate, changes were made to the report to reflect the agencies' comments.

# Contents



## ABBREVIATIONS

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| DOE | Department of Energy |
| GAO | General Accounting Office |

# CHAPTER 1

## INTRODUCTION

As of February 1, 1978, 66 of the 68 commercial nuclear powerplants in the United States used light water reactors to generate steam for electricity production. 1/ Light water reactors use only about 2 percent of the potential energy available in the uranium fuel. Although there is not universal agreement, many nuclear proponents have claimed that if nuclear power is to be a viable energy option in the future, advanced nuclear reactors will have to be developed which either use uranium fuel more efficiently or use a non-uranium nuclear fuel.

For over two decades the United States and other countries have attempted to develop reactors to improve the fuel utilization offered by existing light water reactors. Foremost among these reactors has been the liquid metal fast breeder reactor. Under the two previous administrations, development of the liquid metal fast breeder reactor was this country's highest energy priority and its most expensive energy research and development program. By producing plutonium which could be reprocessed 2/ and recycled 3/ as additional fuel, this reactor would extract 30 to 60 times more energy from uranium than light water reactors. Plutonium, however, is a radioactive substance which remains radioactive for thousands of years and can be used to make nuclear explosives. Plutonium requires care in handling and poses long-term storage or disposal problems unless it is used as a nuclear fuel.

In April 1977, after a reevaluation of the proliferation risks of commercial fuel reprocessing, the President took steps to (1) defer indefinitely commercial reprocessing and recycling of plutonium, as well as the commercial introduction of the liquid metal fast breeder reactor; (2) reduce funding

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1/The remaining two reactors are a high temperature gas reactor and a graphite moderated, light water cooled reactor built both for the production of weapons material and the production of electricity from byproduct steam.

2/Reprocessing is the processing of used reactor fuel to recover the unused fissionable material.

3/Recycling is the reuse of fissionable material after it has been recovered by chemical processing from spent or depleted reactor fuel and then refabricated into new fuel elements.

for the liquid metal fast breeder reactor research, development, and demonstration program and redirect funds toward the evaluation of alternative breeders, 1/ advanced converter reactors, 2/ and other fuel cycles; and (3) cancel construction of the Clinch River Breeder Reactor--the Nation's first liquid metal fast breeder reactor demonstration powerplant. These actions were taken primarily in the hope they would help reduce the risk of nuclear weapons proliferation 3/ associated with reactor systems which involve reprocessing plutonium.

## PERSPECTIVE ON PROLIFERATION

Implicit in the President's nuclear power initiatives is the assumption that the potential for diversion of weapons materials from a commercial nuclear power system is at least as probable as other routes. While the remaining chapters to this report discuss proliferation exclusively as related to the diversion of material from a commercial nuclear power system, a nation or group planning to develop nuclear weapons has several basic additional options for obtaining weapons materials. It could (1) construct and operate dedicated production facilities, (2) divert the material from research reactors, or (3) steal or purchase the material. Some nuclear experts have contended that a nation could also use nuclear research accelerators to produce plutonium; however, this is conceptual at this time and currently not a practical alternative.

### Dedicated production facilities

Two basic routes are available to a nation desiring to build dedicated production facilities to obtain weapons material. It could construct and operate

--a plutonium production reactor and a reprocessing plant to separate the plutonium from the spent fuel or

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1/A breeder reactor produces more fissionable material than it consumes. The new fissionable material is created by capturing neutrons in fertile material.

2/A converter reactor produces some fissionable material, but less than it consumes.

3/Nuclear weapons proliferation is the acquisition of nuclear weapons by nonnuclear weapons nations.

--an enrichment plant to produce highly-enriched uranium from natural uranium.

Plutonium production facilities

A country wanting a small weapons program might need only a small plutonium production reactor and reprocessing plant. One of the most recent studies on this subject, 1/ estimated that a reactor producing enough plutonium for only one or two explosions annually could be built and operated in about 3 years by a small number of experienced, competent professional engineers at a cost of $15 to $30 million. In the same study, the Office of Technology Assessment estimated that a small reprocessing plant to separate the plutonium from the spent fuel could be built for less than $25 million.

Many developing countries with a modest technical infrastructure now have the capability to build and operate small plutonium production and reprocessing facilities. Only countries with a high level of industrialization and a considerable nuclear base would find large plutonium production facilities attractive for an ambitious weapons program.

Enrichment facilities

Once a nation has enrichment 2/ capacity, it can produce highly enriched uranium--a weapons material. Several enrichment methods--such as gaseous diffusion, Becker nozzle, gas centrifuge, and other advanced methods--might be considered by a nation desiring a nuclear weapons capability.

The enrichment method currently used in the United States is gaseous diffusion. It was developed during World War II and has remained essentially the only source of enriched uranium. There are seven known gaseous diffusion plants in the world, and all are located in countries with well-developed nuclear weapons capabilities. Gaseous diffusion plants are so

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1/"Nuclear Proliferation and Safeguards," Office of Technology Assessment, June 30, 1977.

2/A process where the percentage of a given isotope has been artificially increased so that it is higher than that naturally found. Enriched uranium contains more of the fissionable isotope uranium-235 than found in natural uranium.

expensive and technologically complex that their construction and operation is feasible only for a few of the most developed countries. An alternative enrichment method, the Becker nozzle process, is also very expensive and technologically complex. A nozzle enrichment facility is being sold to Brazil by West Germany, and a variation of it is being developed in the Union of South Africa.

Centrifuge enrichment was researched during World War II but abandoned. The technique reemerged and has now reached an advanced state of development, both in this country and abroad. It may be the cheapest of the present methods and has the additional advantage of modular operation; that is, small groups of centrifuges can operate as soon as they are built and tested without awaiting the completion of a large facility.

The cost of a small centrifuge enrichment plant is not known, but can be speculated based on estimates made by countries now planning large commercial plants. For a nation desiring only a small weapons program (one or two explosive devices a year) the Office of Technology Assessment's study has estimated the capital costs at $2 to $5 million. This estimate does not include research and development costs. Such costs would have to be included because centrifuge enrichment is a sophisticated technology which is closely protected by the few nations that have it.

Four advanced enrichment techniques are being investigated that may allow enriched uranium to be produced more cheaply and easily. Three of the processes involve laser isotope separation, and two of these are being developed under the auspices of the Department of Energy (DOE) at Government-sponsored laboratories. The other laser isotope separation process is under investigation by a private firm in the United States. Research is also underway in several other countries on these processes. The fourth advanced enrichment technique, the Dawson process, is under development by DOE through a private contractor and involves separation by ion cyclotron resonance. All processes are in the research or early development stage but have promise of extending uranium resources through advancing enrichment efficiency, and have potential for lowering the cost of enrichment. Each process builds on a high technology base and also has the potential for producing weapons-grade materials. The proliferation questions for these advanced technologies are under study and the results are expected to be available by the end of 1979.

Research reactors

There are more than 300 research reactors operating around the world. However, very few of these have the capability of producing enough useful material for a nuclear weapon. The Office of Technology Assessment's study estimated there are 18 countries with research reactors having the potential of producing enough plutonium for one or more weapons by 1984 and/or requiring enough highly enriched uranium as fuel which, if diverted, could produce one or more weapons. The Westinghouse Electric Corporation has estimated there are nine nonnuclear weapons countries which now have the potential for producing sufficient plutonium for one or more nuclear weapons from research reactors.

A nation diverting plutonium from a research reactor would need a reprocessing plant similar to that associated with a plutonium production reactor. India is the only nation known to have used material from a research reactor for a nuclear explosive device.

Purchase or theft

There is no evidence that any nation has used the route of purchase or theft to acquire materials for a nuclear weapons capability. It appears the least likely of all the routes. However, this route might extend the proliferation problem to less technologically developed nations and terrorists or other subnational groups since it bypasses the need for the expensive and demanding technologies required by other routes.

If weapons materials were to become routinely traded in international commerce, then the purchase or theft route would become more attractive. Such materials might be acquired through an illegal nuclear "black market" or bought or traded from a friendly nation secretly in what is termed a "gray market."

SCOPE OF REVIEW

The President's April 1977 initiatives prompted the late Senator Hubert H. Humphrey, Vice Chairman, Joint Economic Committee, to request GAO to assess the issues surrounding the possible adoption of proliferation resistant nuclear technologies to succeed reactors based on current light water reactor technology. This report was prepared in response to that request and discusses the various technical and institutional means to reduce the risk of nuclear weapons proliferation from the commercial reprocessing of fuel from the uranium fuel cycle and the advantages and disadvantages of the thorium fuel cycle (chs. 2 and 3). This report also identifies criteria--including proliferation resistance--which we believe to be critical to the selection of an advanced reactor technology and discusses advanced reactor technologies as they relate to those criteria (ch. 4).

In developing this report, we had the benefit of comments by a varied group of distinguished experts knowledgeable about nuclear issues. In addition, we obtained information from the following organizations:

--The Atomic Industrial Forum.

--The Arms Control and Disarmament Agency.

--Battelle Columbus Laboratories.

--The Department of Energy.

--The Department of State.

--Ebasco Services Incorporated.

--The Electric Power Research Institute.

--The General Electric Company.

--General Atomic Company.

--The Nuclear Regulatory Commission.

--The Office of Technology Assessment.

--Westinghouse Corporation.

In addition, copies of a draft of this report were reviewed by DOE, the Nuclear Regulatory Commission, and the Department of State. Where appropriate, changes were made to this report to reflect the agencies' comments.

# CHAPTER 2

## TECHNICAL APPROACHES TO REDUCE THE RISK OF NUCLEAR PROLIFERATION

Many groups are now advocating various approaches to improve the proliferation resistance of the current uranium fuel cycle. Many of these technical approaches involve alterations to current nuclear fuel reprocessing technology which are designed to make it more difficult, time consuming, and costly to divert weapons material. In addition, there is support for phasing out the current uranium fuel cycle in favor of the thorium fuel cycle. This is based on the belief that, from a proliferation resistance perspective, the thorium cycle may be superior to the uranium cycle.

### TECHNICAL PROPOSALS TO MAKE THE URANIUM FUEL CYCLE MORE PROLIFERATION RESISTANT

The predominant technique for reprocessing spent nuclear fuel is the Purex process. One product of the Purex process is plutonium, which can be recycled as fuel in a nuclear powerplant or as material for nuclear weapons. It is generally believed that in nations without nuclear weapons the Purex process would provide relatively easy access to weapons material, thus constituting a high proliferation risk. To improve the proliferation resistance of the Purex process, coprocessing, spiking, colocation, and the Civex process have been proposed.

#### Coprocessing

Coprocessing refers to a form of reprocessing, whereby plutonium and unused uranium are never completely separated from the spent reactor fuel. Plutonium and unused uranium are kept in combination so that low concentrations of plutonium are maintained, and further chemical processing would be required to separate them.

The additional step to separate the coprocessed material to get plutonium is not, however, technologically difficult. Marginal adjustments to operating conditions could enable a coprocessing facility to produce pure plutonium. Consequently, coprocessing alone is not a major step towards reducing the risk of proliferation by nations. It has potential for helping to prevent the diversion of pure plutonium by terrorists. Coprocessed material diverted by terrorists would have to be chemically processed to make a nuclear bomb, which may be beyond their capabilities.

Coprocessing appears to be feasible. However, it has yet to be verified in pilot and experimental plants to the extent necessary to justify early design of large facilities.

Spiking

Although plutonium is used to make nuclear weapons and is radioactive, in general, its radiation is easily stopped by a minimal amount of shielding. Plutonium, therefore, can be safely handled if only crude shielding is provided. Spiking refers to a process which contaminates plutonium fuels with dangerous levels of radiation which cannot easily be stopped. All plutonium, prior to leaving a reprocessing plant, would be contaminated in order to make diversion and reprocessing to obtain weapons materials a difficult, time consuming, dangerous, and expensive activity.

Spiking has been proposed in a number of ways, including

--partially contaminating plutonium with fission waste products from the spent fuel by not completely separating them,

--mixing highly radioactive material with plutonium at the reprocessing plant before delivery to a fuel fabrication plant,

--briefly irradiating the assembled, recycled nuclear fuel to induce an acceptable residual level of radioactivity, and/or

--implanting a high energy radiation source in the plutonium fuel before it is shipped to the powerplant.

Spiking would significantly reduce the possibility of diversion of plutonium by terrorists intent on fabricating a nuclear weapon because of the radiation hazard of any attempted separation of the spiked material from the plutonium. It cannot, however, be considered a fully effective deterrent to proliferation by a nation because the spiked material could be separated in a heavily shielded facility.

Colocation

Colocation is an approach involving the placement of nuclear activities together in a centralized facility. It reduces the risk of proliferation and terrorism because the parts of the fuel cycle providing access to plutonium are in a centralized heavily safeguarded complex and transportation of weapons material between activities is eliminated. For example, uranium enrichment, fuel reprocessing (or coprocessing), and fuel fabrication facilities could be located in a safeguarded complex. The complex could be controlled by an international group such as the International Atomic Energy Agency to insure that the host nation would not divert weapons material, or could be located in an existing nuclear weapons state where diversion of weapons material by the host nation would not add to nuclear proliferation. The nuclear powerplants and transportation to and from nuclear powerplants would be the only vulnerable portions of the fuel cycle which are not colocated.

It is theoretically possible to have most of the vulnerable parts of the nuclear fuel cycle colocated. Whether it it is politically practical remains to be answered. There are major unresolved questions on the number or mix of colocated facilities, their ownership, and siting. If a colocated fuel cycle complex is internationally controlled or managed by a nuclear weapons nation, proliferation risk is decreased. However, colocation does not absolutely prevent proliferation since nuclear technology would still be generally available, and a nonnuclear weapons nation would still have direct access to nuclear powerplants and the associated spent fuel from which weapons material could be extracted.

<u>The Civex process</u>

On February 27, 1978, representatives of the Electric Power Research Institute, the research arm of the U.S. electric utility industry, proposed that an alternative to the Purex reprocessing technique, called the Civex process, be developed. They claimed that this new process is "as far as technology can go in protecting the back-end of the nuclear fuel cycle against illicit diversion of fissile material." According to its proponents, the Civex process would incorporate features such as coprocessing and spiking to assure that "at no time and in no place is there pure, weapons-usable plutonium" available. These two features result in a highly diluted fuel that is so radioactive that it cannot be diverted except at the risk of disability and death.

According to its proponents, it would take 4 to 5 months to achieve a national diversion of weapons material from a Civex plant because the components of the Civex plant would have to be restructured or altered to obtain such material. The process also presents a formidable obstacle to nuclear terrorists so that the threat of a successful terrorist diversion would be virtually nonexistent. This would be a significant improvement over the Purex process.

According to the Institute, the Civex process is at least 10 years away from commercial availability. All of its features have been proven in laboratories, but the various process steps have never been operated together in one plant. A demonstration facility would be required, of course, before the process is ever introduced commercially.

Unfortunately, the Civex process will not completely solve the problem of nuclear proliferation. As stated above, while many of its features will make the plutonium fuel cycle more proliferation resistant, a nation could still obtain weapons materials by altering or reconstructing components of the process to produce weapons materials.

## THE THORIUM FUEL CYCLE

The thorium fuel cycle is often described as an alternative to the uranium fuel cycle. The thorium fuel cycle initially involves using enriched uranium or plutonium to change thorium into uranium-233 which can be recycled as a nuclear fuel or used to change more thorium into uranium-233. When in a pure state, uranium-233 is comparable to plutonium in its explosive capabilities.

The nuclear community has long recognized thorium as an untapped source of nuclear energy. Thorium exists in readily available deposits throughout the world and there has been some experience with thorium in the United States. Thorium has been tested in three commercial nuclear powerplants--Indian Point, Peach Bottom, and Elk River. The U.S. Atomic Energy Commission has produced uranium-233 at its Hanford and Savannah River facilities and conducted early development programs at the Argonne and Oak Ridge National Laboratories. However, a large market does not exist for thorium-based fuels.

Proponents of the thorium fuel cycle claim that it provides certain resource and nonproliferation advantages over the current fuel cycle. Although we found some merit to these claims, we also found a number of disadvantages and potential impediments. The following section presents the advantages and disadvantages of the thorium fuel cycle in comparison to the uranium fuel cycle on the basis of industrial requirements and proliferation resistance.

### Industrial requirements

Changing from the uranium to the thorium fuel cycle would require extensive modifications to the current industrial base--new mines and mills, new reprocessing plants, and new fuel fabrication plants. There would also be a need to develop related reactor operating and safety data and licensing criteria. There is no major movement by the nuclear industry towards developing this new industrial base.

Mining and milling

If there were substantial demand for thorium it could be obtained with a minimum of problems. Although thorium exists in large quantities, very little thorium is currently mined in the United States. However, firms in the uranium mining and milling business as well as those in other types of mining could shift to mining and milling thorium. No new technology would be needed for thorium mining and milling. Exploration and mining methods would be similar to those used for uranium, and the impacts of milling and refining the ore should be similar to those of the uranium industry. Radon, a radioactive gas which is released from thorium during production, is expected to be released in quantities greater than that released in uranium production. The risk of radiation exposure would, therefore, be greater. There would also be additional concern for the control of thorium tailings (waste materials resulting from the extraction of thorium from thorium ore--this is also a problem in the uranium fuel cycle).

Enrichment

To use uranium in light water reactors, the concentration of uranium-235 in natural uranium must be increased to about 2 to 4 percent. The most developed and widely used method of such enrichment is the gaseous diffusion process. 1/ Although thorium itself does not require enrichment, most thorium-based reactors require a substantial amount of enriched uranium for their initial fuel cycles. For maximum resource efficiency, uranium enriched to about 93 percent should be used with thorium. Highly enriched uranium is a weapons material, and is radioactive, but can be handled with only minimal radiation protection. These properties make highly enriched uranium an attractive material to work with in manufacturing an explosive device.

Presently the Government provides all enrichment services. By the early 1990s, existing enrichment capacity will not meet projected demand 2/ and additional capacity is planned using

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1/The gaseous diffusion process is an enrichment method based on the different diffusion rates of different weight isotopes through a porous membrane. In uranium enrichment a membrane is used to separate fissionable uranium-235 from uranium-238.

2/"Uranium Enrichment Policies and Operations: Status and Future Need," U.S. General Accounting Office, EMD-77-64, Nov. 18, 1977, p. 19.

the centrifuge enrichment technology. 1/ Presently envisioned expansion of enrichment capacity will cost several billion dollars (this expenditure would be partially recouped during operation). Conversion to a thorium fuel cycle would further add to the demand for enrichment services resulting in the need for even more capacity and, of course, additional cost.

Fuel fabrication

Using thorium in modified light water reactors would require a fuel fabrication process similar to that currently used for uranium. Design changes to the current fabrication process would be minimal and existing uranium facilities could be converted to thorium or a new facility could be constructed in about 5 years. Fabricating thorium fuels for other reactor systems (for example, the light water breeder reactor) would require a different process.

Some research and development in fabricating thorium fuels has been done but because of limited demand, thorium fuel is not now manufactured by any firms on a commercial scale. General Atomic Company produced some thorium fuel for high temperature gas cooled reactors, but the facility that was used for this program closed when the utilities' contracts to purchase these reactors were terminated.

Reprocessing

The efficient reprocessing of spent thorium fuel is essential to a successful, economic, and commercially acceptable thorium reactor. In a reactor using the thorium fuel cycle, thorium is converted to uranium-233. In order to realize the largest conservation and fuel utilization benefits of the thorium fuel cycle, uranium-233, with its excellent thermal fission characteristics, must be reprocessed and reused.

There currently is no commercial fuel reprocessing industry in operation for any nuclear fuel. The technology for reprocessing uranium and plutonium is known. One facility was operated at West Valley, New York, from 1966 to 1972, but shut down when the applicant withdrew its request to enlarge the plant and decided to abandon that business venture. Another plant at Barnwell, South Carolina, is nearly ready to

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1/Centrifuge enrichment involves spinning gaseous uranium until the heavier and lighter isotopes (uranium-238 and -235, respectively) separate.

operate, however, the administration's current policy does not allow the licensing of any reprocessing plants.

Commercial reprocessing for thorium-based fuels has not been demonstrated, but would be more complex than uranium reprocessing because the process will produce byproducts which are highly radioactive and will require heavy shielding and remote operations.

### Recycled fuel fabrication

Because reprocessing of thorium-based fuels is a prerequisite to a commercially acceptable reactor, it follows that fabrication of the reprocessed fuel in assemblies is also required. There are no facilities for the fabrication of fuel assemblies from recycled thorium-based fuel. Some systems are currently being developed by the Oak Ridge National Laboratory. Whatever fabrication process is developed, operation must be remotely handled and more heavily shielded than in the uranium-plutonium fuel cycle because of uranium-232. 1/ To avoid the shielding requirement, the spent fuel could be stored. After about 4 years, the radioactivity would start to decrease and fabrication could be accomplished more easily. Shielded storage facilities, however, would be required.

### Licensing base

A preliminary review conducted by a Nuclear Regulatory Commission ad hoc task force at the request of GAO stated that they do not expect any significant new licensing problems from the thorium fuel cycle. However, detailed safety and environmental analyses would have to be performed. Some potential licensing issues are known; specifically, the need for shielded-remote reprocessing, refabrication, and waste handling facilities because of uranium-232 contamination; and the increased level of radon gases in mining, milling, reprocessing, and fuel fabrication operations.

## Proliferation issues

For weapons purposes, uranium-233 is comparable to plutonium in its weapons capability when in a pure state. However, uranium-233 can be mixed or denatured with natural uranium to make it unsuitable for weapons use. To separate the uranium-233

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1/Uranium-232 is a byproduct of the thorium fuel cycle which is highly radioactive and must be heavily shielded.

and natural uranium to acquire uranium-233 in a concentration suitable for weapons use would require technology similar to that needed to enrich uranium for light water reactors. This separation capability now exists in only a few countries. Consequently, denatured uranium-233 has clear proliferation resistance advantages over plutonium as a recycled nuclear fuel. Denatured uranium-233 fuel also provides a greater deterrent to diversion than either highly enriched uranium or plutonium fuel because it emits high level radiation. Therefore, any attempts to separate natural uranium and uranium-233 would entail a significant radiation hazard unless heavily shielded.

Despite some apparant proliferation resistance advantages, denatured uranium-233 fuel cannot be considered "proliferation-proof" for two major reasons:

--The denatured uranium-233 fuel will produce plutonium in the spent reactor fuel. This is because the denaturant--natural uranium--is partially converted to plutonium during reactor operations. The more natural uranium mixed with uranium-233 to make it unsuitable for weapons, the more plutonium produced. Hence, while denatured uranium-233 lessens the availability of a weapons material at the front end of the fuel cycle, such material would be available in the spent fuel at the back end of the fuel cycle.

--Advancements in developing simpler, less expensive enrichment technologies could enable many more nations to separate natural uranium from uranium-233 in the future.

The addition of natural uranium to uranium-233 is believed to degrade the performance (economics and efficent fuel use) of any reactor that would otherwise be using undenatured uranium-233 fuel. What the optimal mix of natural uranium to uranium-233 should be for various types of reactors to minimize proliferation risk and maximize reactor performance is a question that cannot be answered at this time without further study.

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Although various technical alterations are being explored, none currently offers the potential for rendering the uranium fuel cycle proliferation-proof. Each of the proposed alterations, even when considered in various combinations, have weaknesses that could allow a national diversion of weapons materials to occur. The thorium fuel cycle has been proposed by some as an alternative to the uranium fuel cycle and its inherent proliferation risks. The thorium cycle, however, has its own unique proliferation risks and most of the supporting fuel cycle technology has yet to be demonstrated.

Thus, a substantial amount of attention has been focused on the use of other nontechnical methods of lowering the risk of nuclear proliferation associated with the current uranium fuel cycle. Some of these other methods are discussed in the following chapter.

# CHAPTER 3

## INSTITUTIONAL METHODS FOR LOWERING THE RISK OF NUCLEAR PROLIFERATION

Other methods to reduce the risk of nuclear proliferation from a commercial power system fall into the "institutional" category. Institutional methods include treaties, agreements, and organizations with the objective of discouraging nations from acquiring nuclear weapons from the reprocessing of spent nuclear fuel.

Institutional nonproliferation efforts have existed since the 1950s. From the 1950s through the early 1970s certain basic institutional controls existed. The mid-1970s brought the realization that the basic institutional framework was insufficient and that new international efforts were needed.

### THE BASIC INSTITUTIONAL NONPROLIFERATION FRAMEWORK

The primary institutional nonproliferation framework was developed during the 1950s and 1960s. This was a period of international consensus that peaceful nuclear development could take place with an acceptable risk of proliferation under a system of international safeguards designed to detect, and thereby deter, any violations of peaceful nuclear undertakings. This was moderately successful in that only one nuclear weapons nation has emerged in the last 15 years despite widespread technical capability.

This institutional framework primarily consisted of three mechanisms: the International Atomic Energy Agency, the Treaty on the Non-Proliferation of Nuclear Weapons, and suppliers' agreements.

#### International Atomic Energy Agency

The International Atomic Energy Agency was founded in 1957 under the auspices of the United Nations. The Agency consists of over 100 member-nations and has the objective of promoting peaceful uses of nuclear energy without contributing to military uses of nuclear energy. To accomplish that objective, the Agency is authorized to establish and administer safeguards on nuclear materials, services, facilities, and information--with the consent of the host nation.

The Agency conducts on-site inspections of nuclear activities to verify compliance with the principle of peaceful uses of nuclear materials. The inspections include accounting and bookkeeping for nuclear materials and physical surveillance of activities where material could be diverted.

Practically, the Agency's most beneficial service is detecting a diversion and issuing a warning to the member-nations and to the United Nations that such a diversion has occurred. If the Agency originally supplied the material, it could, of course, also recall the material. The Agency has little other recourse in the event a violation is detected.

EURATOM, the European Atomic Energy Community, performs a similar function for the member-nations of the European Economic Community.

## The Treaty on the Non-Proliferation of Nuclear Weapons

The Treaty on the Non-Proliferation of Nuclear Weapons was opened for signature on July 1, 1968, and was implemented on March 5, 1970. Over 100 countries have ratified the Treaty. The Treaty grants nonnuclear weapons countries the right to develop nuclear energy for peaceful purposes but prohibits those countries from acquiring and/or manufacturing nuclear weapons. The Treaty also subjects all peaceful nuclear facilities to International Atomic Energy Agency safeguards. Nuclear weapons countries are required to (1) refrain from helping nonnuclear weapons countries to acquire or develop nuclear weapons and (2) provide nonnuclear weapons countries with nuclear materials and technology.

## Supplier's agreements

A nation which supplies nuclear material or facilities to another nation often requires that certain safeguards and accountability be maintained, and, in some cases, requires that spent fuel be returned to the supplier nation. Previously, these agreements were on a case-by-case basis. In recent years, there have been efforts to standardize some of these agreements.

Since April 1975, the United States, Soviet Union, France, Great Britain, Japan, West Germany, Canada, and eight other countries have held periodic meetings with the goal of tightening nonproliferation policies. On January 11, 1978, the countries announced a set of guidelines designed to block the spread of nuclear weapons. The rules cover the international transfer of nuclear technology, reactors, enrichment plants, reprocessing plants, enriched uranium, and other sensitive nuclear materials.

In order to purchase any of the materials listed above, an importing nation must agree to:

--Provide "formal governmental assurances" that the material or facilities will not be used to produce any nuclear explosive device whether for a weapon or for "peaceful" purposes.

--Place the material or facilities under "effective physical protection" to prevent theft or sabotage. The levels of protection required, depending on the sensitivity of the item, have been agreed upon by the supplier nations.

--Accept International Atomic Energy Agency inspection of the imported materials or facilities and any similar items produced internally using the same design.

--Not retransfer supplies without requiring the same rules which applied to the original sale and, in some cases, without the permission of the original supplier.

Each of the nations agreed that sanctions would be considered against a nation violating the guidelines, and while the considerations are taking place, further supplies to the violator would be banned.

The rules do not constitute a formal international agreement; however, each of the 15 nations agreed to abide by the rules and unanimous consent is required for any changes.

## NEED FOR AN IMPROVED INSTITUTIONAL FRAMEWORK

Since the establishment of the basic nonproliferation framework described above, a number of factors have spurred interest in tightening international controls over nuclear proliferation. The event which renewed interest in nonproliferation more than any other event was the 1974 nuclear explosion by India. That was the first time a country exploded a nuclear device containing material obtained from a research reactor in which the basic reactor technology was obtained for peaceful purposes from another country (Canada). Some of the heavy water for the reactor was obtained indirectly from the United States. Apparently the supplier's agreement, in this case, did not provide adequate safeguards. India contended that the device was exploded for peaceful purposes and, therefore, was not in violation of the agreement. Canada has stated that the agreement was violated.

India is a member of the International Atomic Energy Agency but has not ratified the Treaty on the Non-Proliferation of Nuclear Weapons. The Indian explosion pointed out that a nonnuclear weapons nation could obtain nuclear weapons irrespective of the terms of a supplier's agreement.

The Indian explosion was not the only factor, however, which has triggered interest in tightening controls. Terrorism has become a frequent occurrence. International safeguards are primarily directed against a nation misusing nuclear materials. Protection against terrorist activities, however, is essentially the responsibility of individual nations, and there is considerable uncertainty at this time concerning the adequacy of the various protective measures being employed by some nations.

In addition, the West Germans have agreed to sell a complete nuclear fuel cycle to Brazil and the French had agreed to sell nuclear fuel reprocessing facilities to Korea and Pakistan. (The Pakistan agreement since has been modified to a coprocessing facility and the Korean agreement has been cancelled.) The export of these technologies to a growing number of nonnuclear weapons countries causes concern for continuing maintenance of safeguards and the continued use of the technologies for peaceful purposes.

In summary, the recent renewal of interest in reducing the risk of proliferation has resulted from a series of events which caused international recognition that nuclear technologies, especially enrichment and reprocessing technologies and the plutonium breeders, cannot be adequately safeguarded within the current framework of agreements and treaties. However, the widespread implementation of a plutonium-based nuclear economy is not yet at hand and, given international cooperation, there is still sufficient time for remedial action.

## U.S. INITIATIVES TO IMPROVE THE INTERNATIONAL NONPROLIFERATION FRAMEWORK

In part, the events previously described led the United States to first reevaluate the proliferation of commercial fuel reprocessing, and later, defer indefinitely commercial fuel reprocessing and the liquid metal fast breeder reactor program in the United States. In addition, the Congress enacted the Nuclear Non-Proliferation Act of 1978 (Public Law 95-242, March 10, 1978)--the most recent effort directed toward helping develop nuclear energy for power, not weapons.

The act establishes a broad range of incentives and controls to help reduce the risk of other nations using nuclear power facilities and materials as a means for obtaining nuclear weapons.

The act requires the United States to (1) provide a reliable supply of nuclear fuel to nations which adhere to United States nonproliferation policies; (2) negotiate international sanctions or procedures to be followed in the event of a diversion, theft, or sabotage of nuclear materials; (3) support a strengthened and more effective International Atomic Energy Agency and safeguards system; and (4) establish new requirements for the export of nuclear equipment and material and require tougher safeguards and assurances related to the use of those exports.

To encourage international implementation of nonproliferation policies, the act also requires the President to seek agreement for all nations to commit themselves to (1) transfer no nuclear materials, equipment, or sensitive technology to another nation unless the recipient nation commits itself to undertake the actions prescribed in the act; (2) perform no reprocessing, enrichment, fabrication, or stockpiling of nuclear materials except in a limited number of facilities under international auspices and inspection; and (3) establish and maintain adequate physical security measures. In addition, the act authorizes DOE to initiate an international study of spent fuel storage from a proliferation perspective and to provide for storage of foreign spent fuel in the United States. 1/

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Recent institutional actions have tightened international controls over nuclear proliferation, and the United States has enacted legislation aimed at reducing the worldwide risk of nuclear proliferation. However, institutional means--like technical alterations to the nuclear fuel cycle--have only the capability of reducing the risk. In addition, one nation cannot unilaterally affect the worldwide proliferation environment.

Because of the shortcomings of technical alterations to the nuclear fuel cycle and institutional nonproliferation methods, much work has been focused on developing a nuclear fission technology with more favorable proliferation characteristics. The following chapter discusses some of the major technologies being considered.

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1/The act requires GAO to complete a study and report to the Congress on the act's implementation and impact by Mar. 10, 1981.

# CHAPTER 4

## EVALUATION OF ADVANCED NUCLEAR FISSION TECHNOLOGIES

Because of proliferation issues, the United States' choice of the second generation nuclear technology is uncertain. This leaves the next generation of nuclear power unresolved, to be filled by any one of a number of fission technologies.

While the focus of this chapter is on nuclear fission technologies substantially different from current light water reactor technology, it should be noted that DOE is conducting a program to improve light water reactors currently in use. The objective of the program (funded with $12 million during fiscal year 1979) is to improve the efficiency of existing light water reactors using new, backfittable technology. Such technical improvements are expected to reduce a light water reactor's need for uranium by about 30 percent and to be available for commercialization by the end of this century. If successful, such a program would somewhat delay, but not preclude, the need for a new, second generation nuclear fission technology.

### THE TECHNOLOGIES

This chapter discusses 10 nuclear fission technologies including 3 nonbreeder reactor concepts: the spectral shift control reactor, the heavy water reactor, and the high temperature gas reactor. The other seven are breeder reactor concepts: the gas-cooled fast reactor, the liquid metal fast breeder reactor, the light water breeder reactor, the molten salt breeder reactor, the accelerator breeder, the fission-fusion breeder, and the gaseous core reactor.

#### Nonbreeder concepts

##### Spectral shift control reactor

The spectral shift control reactor is a variation of the light water reactor. A combination of heavy and light water 1/ replaces the light water coolant and moderator used in a light water reactor. The amount of heavy water is greatest at the

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1/Heavy water is water containing more than the normal number of heavy hydrogen atoms (deuterium). Light water is ordinary water.

start of operation and is reduced as the nuclear fuel burns. There has been little interest in this concept since the early 1960s when a small spectral shift control reactor was demonstrated in Belgium. The primary reason for its lack of development is that it has been overshadowed in most countries by the liquid metal fast breeder reactor.

Heavy water reactor

The heavy water reactor is cooled and moderated by heavy water. It is fueled with natural uranium and enrichment is not required. Heavy water reactors have been advocated by various groups and countries since the 1940s. Nevertheless, only the Canadians and the West Germans have actively pursued development of the heavy water reactor concept for commercial power. The heavy water reactor is at a comparable state of commercialization in Canada as the light water reactor is in the United States, and heavy water reactors have been exported to several foreign countries. However, there are no commercial heavy water power reactors in the United States.

High temperature gas reactor

The high temperature gas reactor is a helium-cooled, graphite moderated reactor, presently fueled with highly enriched uranium. It has been under development for about 20 years, primarily by the General Atomic Company. It is the latest phase in the development of gas-cooled thermal reactors which was started in England with the MAGNOX gas-cooled reactors. The high temperature gas reactor concept has not received as much support from the Federal Government as the light water reactor or the liquid metal fast breeder reactor.

The first high temperature gas reactor in the United States--the small 40-megawatt Peach Bottom Nuclear Powerplant in Pennsylvania--was placed in commercial operation in June 1967. It was shut down in 1974 after 7 years of successful operation because it was uneconomical to operate such a small plant. It was also believed that dismantling and examining plant components could provide knowledge useful for designing reactors of this type.

The second high temperature gas reactor in the United States is the Fort St. Vrain Nuclear Generating Station near Denver, Colorado. The plant is currently operating at 70 percent of full power. Full power operation has been delayed by about 5 years due to various problems related to both the nuclear and nonnuclear components.

In the early 1970s the General Atomic Company had as many as 10 contracts for commercial-sized high temperature gas reactors. The impact on business conditions due to the economic recession of the early 1970s and reduced demand for electricity in the United States in the post-oil embargo period resulted in all of these contracts being cancelled.

Variations of the high temperature gas reactor have been explored by other countries. In the Federal Republic of Germany, a small high temperature experimental reactor began operating in 1967. Called a "pebble bed" reactor, it differs from other high temperature gas reactors mainly in that it contains spherical fuel elements which are continuously recycled during operation. As spent fuel pebbles are removed, they are replaced by new pebbles. This reactor is still in operation and has achieved encouraging operating and experimental results. In 1972 West Germany began constructing a large pebble bed reactor.

## Breeder concepts

### Gas-cooled fast reactor

The gas-cooled fast reactor has been studied in the United States since the early 1960s, but no such reactor has yet been built because, until recently, emphasis has been on the liquid metal fast breeder reactor. It is called a gas-cooled reactor because helium gas is used as the cooling agent. The General Atomic Company, which is developing the high temperature gas reactor in this country, has developed a gas-cooled fast reactor concept that embodies many of the high temperature gas reactor's principles. An alternate design is being studied by an association of European manufacturers and Government agencies.

### Liquid metal fast breeder reactor

The most widely developed breeder concept is the liquid metal fast breeder reactor. Until the President's April 1977 proposal, the liquid metal fast breeder reactor, which uses liquid sodium as its coolant, was the highest priority research and development effort in the United States with a number of industrial organizations strongly supporting its development. The Clinch River Breeder Reactor was to be a demonstration of this concept. England, France, Japan, and the Soviet Union have operating demonstration or prototype reactor plants and, together with West Germany, have strong liquid metal fast breeder reactor programs. France and the Soviet Union have large commercial-scale liquid metal fast breeder reactors under construction.

## Light water breeder reactor

The light water breeder reactor is basically a modified light water reactor with a core designed to maximize the conversion of fertile material to fissile material. It may produce just enough fuel to be self-sustaining (when incorporated with fuel reprocessing). The light water breeder reactor concept is being developed by DOE's Division of Naval Reactors. To date, the primary program effort has been the installation of a light water breeder reactor core with a designed power level of about 240 megawatts (thermal), in the Shippingport Atomic Power Station.

## Molten salt breeder reactor

The molten salt breeder reactor is a very different concept. A chemicl substance, technically known as a "salt" serves not only as the primary coolant, but as a carrier for the fuel as well. Fuels in most other reactors are solid materials and are separate from the coolant. In the molten salt breeder reactor, the fissile and the fertile materials are circulated together as a liquid through the reactor. The molten salt breeder reactor was studied as early as 1947 in the United States as a candidate for powering nuclear aircraft. A very small experimental reactor was built and operated at Oak Ridge, Tennessee, in the late 1950s as part of AEC's Aircraft Nuclear Propulsion program. In the late 1960s, a molten salt reactor experiment was built and operated. No other reactors employing the molten salt concept have been built.

## Accelerator breeder

The accelerator 1/ breeder is only a concept at this time. Major resources would be needed to bring this concept to fruition. The accelerator breeder involves using an accelerator to produce neutrons and allowing those neutrons to collide with other atoms in a target. Reactions taking place in the target would produce additional neutrons which would be used to breed fuel in a surrounding blanket (a shield of fertile material surrounding a reactor core).

One variation of this concept, called "direct reenrichment," would use this reactor to raise the fissile content of spent fuel taken from conventional reactors so that the spent fuel could be reused as fuel without reprocessing.

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1/An accelerator is a device for increasing the velocity and energy of subatomic particles.

Theoretically, of all the breeder systems, the external neutron source systems--the accelerator and fission-fusion breeders (discussed below)--would have the highest rates of fissile fuel production. Such systems would operate more efficiently using uranium-238 to create plutonium than using thorium to create uranium-233. Because each such breeder could provide fuel for a relatively large number of other reactors, it follows that in comparison to conventional breeder reactors, a smaller number of them would be needed to produce an equivalent quantity of fuel.

### Fission-fusion breeder

In fission, a heavy atom is split to form two new lighter atoms and release energy. In nuclear fusion, two atoms are joined to form one heavier atom which results in the release of neutrons and energy. A fission-fusion breeder would use neutrons escaping from a fusion reactor core to bombard heavy atoms in a blanket thereby creating a fission reaction. This reactor would release additional neutrons which would cause breeding reactions in subsequent blanket layers. Nuclear fusion has not yet been demonstrated to be technically feasible, although research is underway in the United States and other countries.

### Gaseous core reactor

The gaseous core reactor concept is the least developed of all alternative reactors under consideration. As its name implies, it would use uranium fuel in the form of gas, as opposed to the solid or liquid fuels of the other concepts. It has not been determined whether it could ever be a large central station power system or that it would be a breeder.

## TECHNOLOGIES EVALUATED USING DECISION FACTORS

Although proliferation resistance is an important criterion, a decision concerning the next generation of nuclear power should not be determined by a single factor. Consideration should also be given to a broad range of social, political, economic, environmental, and technical factors. Accordingly, we compared the 10 reactor concepts to the following 7 criteria: resource utilization, licensability, environmental acceptability, cost and schedule to commercialize, proliferation resistance, safeguardability, and economics. Consideration of these criteria should provide a framework for determining which concepts should receive future support. Some of the information for this section was obtained from a report prepared for GAO by the NUS Corporation and by a preliminary report prepared by a Nuclear Regulatory Commission ad hoc task force.

Resource utilization

Resource utilization can be defined as the amount of resource--be it uranium, thorium, or plutonium--required to fuel a reactor during its expected lifetime. The spectral shift control reactor, heavy water reactor, and high temperature gas reactor are not breeders and, therefore, do not have the important advantage of producing more fuel than they consume. All three reactors, however, are more efficient fuel users than current light water reactors and could operate on a variety of fuel cycles, including (1) the uranium once-through fuel cycle, 1/ (2) a fuel cycle where uranium is recycled but plutonium is not, (3) a fuel cycle where both uranium and plutonium are recycled, or (4) a thorium fuel cycle.

Breeder reactors can be designed to operate on different fuel cycles; however, it is the uranium fuel cycle which generally appears to offer the highest breeding ratios, and, therefore, the most efficient use of fuel. A breeding ratio is a measure of the quantity of nuclear fuel produced compared to the quantity consumed. The higher the ratio, the more excess nuclear fuel the reactor produces.

For the uranium fuel cycle, the highest breeding ratio among conventional breeders is estimated for the gas-cooled fast reactor, followed closely by the liquid metal fast breeder reactor. The molten salt breeder reactor has a considerably lower estimated breeding ratio but because of certain operating characteristics, its lifetime demand for new nuclear fuel is low.

According to DOE program officials, the light water breeder reactor would probably operate on a thorium fuel cycle and would be a marginal or "breakeven" breeder, producing just enough fuel to sustain itself. However, until enough primary fuel--uranium-233--is available to provide a full fuel load (it is not a naturally occurring substance), the light water breeder reactor would require large amounts of highly enriched uranium to be used to create uranium-233 from thorium.

Like the conventional breeder systems discussed above, the external neutron source breeders--the accelerator and fission-fusion breeder concepts--theoretically rate very well on resource utilization. In fact, such systems could be significantly more effective in quickly increasing the amount of

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1/A once-through fuel cycle is one which does not involve fuel recycle or reprocessing.

nuclear fuel available. Their rate of producing excess fissile fuel is expected to be substantially greater than even the gas-cooled fast reactor or the liquid metal fast breeder reactor. Conventional breeders would generally not provide enough excess fuel to support more than a small number of other reactors--about one breeder for every three or four other reactors in most estimates. Each of the external neutron source breeders could provide enough fuel to operate a much larger number of fission reactors--estimates of up to 6 reactors fueled from an accelerator breeder and 20 to 50 reactors fueled from a fission-fusion breeder, have been cited in different studies. The external neutron source breeders could possibly operate on a once-through fuel cycle.

With respect to the gaseous core reactor concept, analysis of anticipated performance has not been done in as much detail as for other systems so there is some uncertainty about the quantities of material that would be involved in such a system. However, conceptually it was designed to be a breakeven breeder if the thorium fuel cycle is used.

Licensability

Of the nonbreeder technologies, only the high temperature gas reactor has received detailed licensing reviews by the Nuclear Regulatory Commission, and two such reactors--one small and one medium size--have been licensed to operate. In addition, a large high temperature gas reactor concept was reviewed and had reached the stage of licensing where favorable licensing reports had been issued by the Nuclear Regulatory Commission. Further licensing actions were not taken, however, because the contracts for the large high temperature gas reactors were cancelled.

The spectral shift control reactor has never been proposed for licensing. However, the physical aspects of the reactor are similar to current light water reactors with the coolant and the added equipment to handle and store the heavy water being the major differences. The Nuclear Regulatory Commission staff believes that the spectral shift control reactor is fundamentally licensable, although a number of issues have to be evaluated and resolved.

Heavy water reactors have never been licensed in the United States. However, the Nuclear Regulatory Commission staff told us that there is no technical reason why heavy water reactors of the Canadian design could not be licensed, although a number of issues would have to be evaluated and resolved, including:

--The suitability of some materials used in the reactor.

--The acceptability of the emergency core cooling systems.

--The acceptability of confinement designs.

--Potential refueling accidents.

--Tritium 1/ control and exposures.

Licensing efforts for breeder reactors are not as developed as for light water reactors. The most extensive breeder licensing experience in the United States has been related to the liquid metal fast breeder reactor. A small liquid metal fast breeder reactor--the Enrico Fermi Atomic Powerplant--was a licensed reactor which was completed in 1963. The Fast Flux Test Facility, to be completed in 1979, will be the first major plutonium-fueled fast reactor. The facility was evaluated and approved for construction by the Nuclear Regulatory Commission staff and the Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards. In August 1978, the Nuclear Regulatory Commission staff completed a review of the startup and operation of the Fast Flux Test Facility. Even though DOE has the final responsibility for the design and safe operation of the Fast Flux Test Facility and there was no requirement for a license to be issued by the Nuclear Regulatory Commission, the Commission's staff review in most areas was equivalent to a licensed case. The Advisory Committee on Reactor Safeguards also reviewed the Fast Flux Test Facility and, in its report to the Commission dated November 8, 1978, agreed with the staff's conclusions and recommendations to DOE. An April 1977 licensing evaluation of the Clinch River Breeder Reactor indicated that a safe design was possible but some of the specific design features would require modification. The Nuclear Regulatory Commission has conducted no further review activities related to the Clinch River Breeder Reactor.

The Nuclear Regulatory Commission and its Advisory Committee for Reactor Safeguards performed a safety evaluation of a small light water breeder reactor demonstration project at the Shippingport Atomic Power Station in Pennsylvania and found the design acceptable. However, it is currently not clear whether the light water breeder reactor concept can be scaled to large reactors without significant design changes.

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1/Tritium is a radioactive isotope of hydrogen.

The licensability of gas-cooled fast reactors has not been determined because design specifications have not been established. No safety criteria exist for gas-cooled fast reactors, and safety criteria for similar reactor technologies are still evolving. In 1974 the Nuclear Regulatory Commission and its Advisory Committee on Reactor Safeguards performed a licensability review of a demonstration-size gas-cooled fast reactor proposed by General Atomic. The review showed that such a plant is potentially capable of being designed and built so that it can be operated without undue risk to the health and safety of the public. However, the question of licensability was not answered, in part, because the review identified a number of unresolved safety issues.

The gas-cooled fast reactor design has some inherent safety characteristics which may make licensing less difficult. These include the use of a prestressed concrete vessel to help ensure primary confinement and the use of a helium coolant which does not undergo phase changes, is transparent, noncorrosive, chemically inert, and has good neutron absorption characteristics.

The molten salt breeder reactor concept differs so much from other reactor systems that it would introduce a whole new series of licensing considerations. The outstanding difference is that in present plants the fuel and the great proportion of the radioactive products remain in the core, whereas in a molten salt reactor they would circulate as a fluid from the core through a heat exchanger, a processing plant, and storage tanks. Guaranteeing the containment of the liquid fuel will be a central safety issue. The Nuclear Regulatory Commission staff told us that achieving three layers of containment, which is customary practice, may be difficult with the radioactivity widely distributed throughout the molten salt breeder reactor system. On the other hand, a comparative study of advanced reactors by Battelle Columbus Laboratory gave the molten salt breeder reactor the highest rating for its containment capability while the one fast breeder reactor examined, the gas-cooled fast reactor, rated lowest.

Somewhat mitigating any concern with radioactivity releases in the molten salt breeder reactor is that the inventory of radioactive materials which might be released as the result of an accident will be significantly lower than that in the fuel of most other types of reactors because the on-line reprocessing will separate out many fission products.

The two external neutron source breeder systems are at such an early conceptual stage that attempts to identify licensing issues would be largely speculative. The gaseous core reactor is also at such a preliminary state that licensing issues would be identifiable only after further research and development work has been done.

Environmental acceptability

All three nonbreeder systems should be as environmentally acceptable as light water reactors. To the degree that each is more fuel efficient than current light water reactors, the front end of the fuel cycle has less impact on the environment. However, each of the systems have some unique features which would impact on the environment in ways that light water reactors do not.

The spectral shift control reactor's environmental impact relates principally to the need to control tritium created through the use of heavy water. If it is operated on the thorium fuel cycle, it would require considerably less mining and milling than light water reactors. Mining and milling thorium has less environmental impact than uranium, principally because it is usually found in more concentrated deposits.

Although enrichment services are not needed for heavy water reactors because natural uranium is used as the primary fuel, such reactors operate at a lower thermal efficiency than light water reactors and produce a considerable amount of tritium. A study by Battelle Colombus Laboratory concluded that the heavy water reactor, as currently operated in Canada, would probably not meet United States environmental standards. The Nuclear Regulatory Commission staff told us that the generation of tritium in the heavy water reactor system, and its normal and potential accidental release to the environment is a matter which could require significant attention. They added that the Canadian experience in controlling tritium releases indicated a favorable outlook, but the onsite environmental levels encountered by operating personnel, particularly maintenance personnel, would require a detailed evaluation.

In addition, generic evaluation of the environmental effects of commercial-size heavy water production facilities--such as water use and possible releases of poisonous gases--might be required if either the spectral shift control reactor or the heavy water reactor were to be introduced in the United States.

The major environmental advantages of the high temperature gas reactor include its high thermal efficiency which results in low fuel consumption, relatively low levels of nuclear waste, and small amounts of waste heat. Smaller amounts of radioactive releases during normal plant operation means less restricted land area around a high temperature gas reactor, while reduced waste heat means that the high temperature gas reactor could use 25 to 30 percent less cooling water than current light water reactors. However, the high temperature gas reactor presents an added environmental problem. During reactor operation, radioactive carbon-14 is produced by the irradiation of the graphite fuel elements. If high temperature gas reactor fuel is reprocessed, this carbon-14 would have to be isolated and contained.

In general, in routine operations breeder reactors appear to be more environmentally acceptable than the light water reactor. According to the preliminary report of the Nuclear Regulatory Commission's ad hoc task force, the:

--Liquid metal fast breeder reactor should be environmentally acceptable. There would be considerably less mining of uranium ore for the liquid metal fast breeder reactor than for current light water reactors. The liquid metal fast breeder reactor also has a 25-percent reduction in environmental heat rejection compared to current light water reactors. Further, very little liquid waste would be discharged from the plant.

--Environmental impact for the light water breeder reactor is less favorable than the liquid metal fast breeder reactor and about equal to the light water reactor.

--Environmental acceptability of the gas-cooled fast reactor is about the same as the liquid metal fast breeder reactor, with the possibility that the effect of waste heat on the environment might be lower for the gas-cooled fast reactor.

The Nuclear Regulatory Commission would not comment on the environmental acceptability of the molten salt breeder reactor, the fission-fusion or accelerator breeders, and the gaseous core reactor. These concepts are too early in development to allow specific focus on environmental issues.

Cost and schedule to commercialize

The light water reactor and, to an extent, the liquid metal fast breeder reactor have been the emphasis of nuclear power for the last 25 years. No other reactor concept has been fully developed and, because of the relative success of of these two technologies over those 25 years, the need to advance some of the other concepts has not existed. Nevertheless, the projected cost and schedule to commercialize other technologies now appears to have taken on significance.

All three of the nonbreeder systems could probably cost less, and take less time to commercialize than most of the breeder reactors. Each of the nonbreeder systems is at a different state of development and, therefore, will require somewhat different amounts of time and effort to commercialize, although all could conceivably be available for commercialization prior to the year 2000.

Of the nonbreeder technologies reviewed, only the high temperature gas reactor has generated significant industrial interest. Over $1.1 billion has been invested in its research, development, and demonstration--$750 million by General Atomic Company, $125 million by private utilities, and $268 million by the Federal Government.

In the 1950s and 1960s, it took the light water reactor 12 years to evolve from the first commercial demonstration reactors to the startup of the first large commercial plants. In the 1960s and 1970s the high temperature gas reactor has already taken more than 10 years to progress from a small to an intermediate size demonstration plant. Cancellation of orders for high temperature gas reactors due to changes in electricity demand and economic situation caused heavy curtailment of progress toward commercialization.

It is difficult to estimate the amount of time necessary to commercialize the spectral shift control reactor and the heavy water reactor, primarily because there is little commercial interest in either of these technologies in the United States. If a major effort is made to encourage their development, however, the time needed could be as little as 10 to 15 years before the first commercial size demonstration plant is in operation in the United States.

Since little developmental work has been done on the spectral shift control reactor, its commercialization would likely require a large demonstration plant first, with full-scale commercialization at a much later date. The spectral shift control reactor has not been commercially developed, and only a small experimental reactor has been built. However, its close relationship to the light water reactor should shorten development time and lessen related costs.

The commercial status of heavy water reactors has been well established in Canada, which could help to speed its introduction in the United States. However, an Electric Power Research Institute study concluded that the heavy water reactor would not be licensable and, therefore, not commercializable in the United States without extensive design changes, analysis, and testing. The Nuclear Regulatory Commission staff has not reviewed that study. However, the Commission's ad hoc task force concluded that it is reasonable to expect that a heavy water reactor based on the Canadian system would be licensable in the United States.

No breeder system has been fully developed. Some, however, are much further along than others. Obviously, the less developed a system is, the more it is likely to cost and the longer it is likely to take to commercialize.

The light water breeder reactor is a modified light water reactor on the thorium fuel cycle. It is being developed by DOE without any commercial or utility participation. DOE's program is focused on the demonstration project at Shippingport, Pennsylvania, that recently began operating. The project will operate for about 3 years, after which the core will be analyzed to determine the extent to which breeding has occurred.

A major justification for developing the light water breeder reactor is that this reactor concept relies partially on current light water reactors which have operated for more than 20 years. This allows DOE to concentrate its light water breeder reactor development efforts on a breeding technology without the uncertainties and cost of developing a totally new reactor system. However, the light water breeder reactor is based on the thorium fuel cycle and, in addition to light water breeder reactor demonstration projects, commercial scale fuel cycle facilities would have to be designed, developed, and demonstrated.

The current demonstration project will not answer all questions concerning the uncertainties of the light water breeder reactor. According to Nuclear Regulatory Commission estimates, solving safety issues for a large size light water breeder reactor would require at least a medium size research effort to evaluate such issues as emergency core cooling system criteria, fuel/coolant interaction, post accident heat removal, and core stability. In addition, many aspects of the thorium fuel cycle will require review and analysis.

The first successful demonstration of a liquid metal fast breeder reactor was achieved by the Experimental Breeder Reactor in 1951. It was replaced by the Experimental Breeder Reactor-II in 1965, which is the only currently operating liquid metal fast breeder reactor in the United States. A small liquid metal fast breeder reactor, the Enrico Fermi Fast Breeder Reactor, experienced an accident in 1966 which resulted in a partial core meltdown. The reactor was repaired and operated until 1972. The next step in the U.S. liquid metal fast breeder reactor program will be the Government-owned Fast Flux Test Facility. It is a 400 megawatt (thermal) reactor without electricity-generating equipment. The latest estimate for its initial operation is 1979.

Before the President proposed to defer the date when the liquid metal fast breeder reactor would be commercialized, planning called for testing and demonstrating the reactor technology by focusing on two principal facilities. First, the Clinch River Breeder Reactor, a 380-megawatt (electric) demonstration reactor, was to be built by mid-1985. It was expected to cost about $2.1 billion, of which $1.9 billion was being supplied by the Government and the rest by industry. The Government then intended to build a larger, near-commercial size reactor (about 1,500 megawatts) which was scheduled for operation in the 1990s. The final phase of liquid metal fast breeder reactor development was to have been a so-called commercial breeder reactor which would have been the first liquid metal fast breeder reactor project initiated by reactor vendors and utilities.

Now that the program no longer has high priority, the liquid metal fast breeder reactor schedule and costs are uncertain. However, the liquid metal fast breeder reactor could still be commercialized before the year 2000 if it again receives high priority.

No gas-cooled fast reactor has ever been built, but many countries have been doing development work since the early 1960s. In the United States, the General Atomic Company has done some initial design and development work. Oak Ridge and Argonne National Laboratories have also been involved. General Atomic's efforts have been supported by DOE and a group of public utilities which formed a users organization called Helium Breeder Associates to encourage the development of the gas-cooled fast reactor as a backup system for the liquid metal fast breeder reactor.

Design work, safety studies, and other evaluations of the gas-cooled fast reactor are being performed in Great Britain, Switzerland, Sweden, Belgium, and West Germany. West Germany and the United States have agreed to share information and work jointly on development of the gas-cooled fast reactor to ease the financial burden of such a project. The General Atomic Company has proposed to have a 300-megawatt demonstration plant on line by 1986-88, using its own funds with support from DOE, the gas-cooled fast reactor utility group, Southwest Public Service Company, and West Germany.

Molten salt reactor systems were researched at Oak Ridge National Laboratory in the 1950s, and the Molten Salt Reactor Experiment, an 8-megawatt (thermal) reactor, operated successfully at the Laboratory from 1965 to 1969. However, the program was funded at a level far below that of the liquid metal fast breeder reactor and in fiscal year 1973, the Atomic Energy Commission terminated the molten salt program. Congressional appropriations not requested by the administration led to reactivation of the program at a low level of support during fiscal year 1974. This support continued for about 2-1/2 years until the program was again terminated at the end of fiscal year 1976. Currently, there are no funds in DOE's fiscal year 1978 or 1979 budgets specifically for the molten salt breeder reactor.

The three most serious problems that have hampered molten salt breeder reactor development are:

--Damage to the main reactor vessel and piping material from exposure to fission products in the fuel.

--Production of large amounts of tritium capable of being released to the environment.

--Better progress in the liquid metal fast breeder reactor program, resulting in a lower development priority for the molten salt breeder reactor.

Both accelerator and fission-fusion breeders are currently only conceptual systems. Each can be expected to require extensive development work, progressing through experimental and engineering scale test facilities to the construction of a prototype plant to provide a final test of the feasibility of the concept.

Both systems would be substantially more complex than conventional fission reactors because the blanket portion is combined with an accelerator or a fusion reactor, both of which will be very complex systems.

Critics of the fission-fusion breeder concept contend that the system would combine the worst problems of both technologies. Advocates dispute this view, contending that the problems will be significantly less severe in each part of the combined system than they would be in the separated pure systems and pointing out that the physical conditions required to produce large numbers of fusion neutrons are less difficult to attain in a fission-fusion system than in a pure fusion system. The accelerator for an accelerator breeder could be based principally on technology used in present operating research accelerators.

The costs to develop either of these concepts are certain to be measured in billions of dollars. Costs cannot be reasonably estimated at this time, however, because a number of issues, including safety and environmental impacts, have not been defined well enough to accurately estimate development requirements.

Most work in the United States on the gaseous core reactor concept has been analyses and laboratory studies of chemistry, materials, fluid dynamics, and energy conversion processes in order to define potential operating conditions. At this time there are no plans to carry development beyond the current experiments to initial detailed design studies.

Proliferation resistance

All three nonbreeder systems produce weapons usable material on either a uranium or thorium fuel cycle. The accessibility of such material depends mainly upon the extent that the fuel cycle involves enrichment or reprocessing. Since two of the systems could also use a weapons grade material as their initial fuel, these aspects would add to proliferation concerns.

The spectral shift control reactor on a thorium fuel cycle--the cycle which provides the best fuel utilization--could use highly enriched uranium for its startup. This is an attractive weapons material which can be chemically separated from the fuel mixture. The most fuel efficient high temperature gas reactor also uses a high quality weapons material as startup fuel. The proliferation resistance of the spectral shift control reactor and the high temperature gas reactor could be improved by use of a less enriched startup fuel but only by sacrificing fuel efficiency. In addition, lower enriched fuels produce more plutonium.

The natural uranium heavy water reactor offers no access to weapons material on the front end of its fuel cycle. However, it does create substantially greater amounts and better quality plutonium than the light water reactor.

On the back end of the fuel cycle, the high temperature gas reactor has some inherent proliferation benefits as compared to the light water reactor when both are using low enriched uranium fuel. For example, the high temperature gas reactor produces less and lower grade plutonium. The recovery of sufficent material for a small nuclear device would require the reprocessing of only two light water reactor fuel elements as compared to 240 high temperature gas reactor fuel elements.

Breeder systems (except for the external neutron source breeders) would eventually require reprocessing and, therefore, offer some risk. The light water breeder reactor, the gaseous core reactor, and the molten salt breeder reactor offer proliferation risks over and above those normally associated with spent fuel reprocessing. The light water breeder reactor uses highly enriched uranium--a high quality weapons material--to to start the reactor on the thorium cycle and uses and creates a better quality weapons material--uranium-233--than breeders on a uranium-plutonium fuel cycle. The gaseous core reactor and the molten salt breeder reactor would have reprocessing systems at each reactor. Therefore, control of fuel inventory would be very difficult. The startup cycles for the light water breeder reactor and the molten salt breeder reactor could be operated with low or moderately enriched uranium but this would extend the time required to achieve a breeding cycle.

The liquid metal fast breeder reactor and the gas-cooled fast reactor have similar fuel cycles and both will create large quantities of weapons usable material. Of all the breeder systems, however, the external neutron source systems are expected to have the highest rates of fissile fuel production. Such systems are predicted to operate most efficiently using uranium-238 to create plutonium. Because each such breeder could provide fuel for a relatively large number of other reactors, a smaller total number of them would be needed in comparison to conventional breeder reactors, thus offering a reduction in the number of original weapons material sources for the same quantity of supplied fuel.

Safeguardability

Safeguardability of nonbreeder systems depends largely on the fuel cycle used. The spectral shift control reactor with low-enriched uranium fuel and no recycle would require safeguards comparable to the current light water reactor fuel cycle, although the plutonium content of the spent fuel would be 10 to 12 percent greater than for the light water reactor. On the other hand, if the spectral shift control reactor is on a thorium cycle, safeguards may have to begin with fresh fuel fabrication because the reactor could be initially fueled with a weapons usable material. In addition, reactor operation produces another weapons usable material--uranium-233--which must be safeguarded.

Although the heavy water reactor uses natural uranium as fresh fuel, its spent fuel contains twice as much plutonium as light water reactor spent fuel. It is also higher grade plutonium. Consequently, the heavy water reactor would require safeguards at least as stringent as those required for the light water reactor. Both the spectral shift control reactor and the heavy water reactor make use of heavy water, which needs to be safeguarded. Because highly enriched uranium-235--a material already suitable for weapons--would be used in the high temperature gas reactor, accountability of fuel materials and protection of the enrichment plant, the fabrication plant, reactors, and the front end fuel shipments are more important in the high temperature gas reactor's fuel cycle than in the light water reactor's fuel cycle.

Any fuel cycle involving reprocessing of spent fuel will require a high level of safeguards with little distinction for the reactor technologies involved. All breeder fuel cycles will reprocess and recycle bred nuclear fuel, thus, such fuel cycles are inherently more difficult to safeguard than once-through fuel cycles. In addition, both thorium and plutonium fuel cycles contain toxic radioactivity. In the case of either fuel cycle, the principal safeguards risks arise mainly from increased commerce and not from any fundamental new safeguards problems.

Some of the breeder systems may require a high quality weapons usable material to start up their breeder cycle and, thus, they are inherently more difficult to safeguard on the front end of their fuel cycles than other breeder systems. Generally, breeder systems on thorium fuel cycles would require high grade weapons material during their startup cycles while breeder systems on plutonium-based fuel cycles would not. For example, during its prebreeding-cycle, the light water breeder reactor will require additional safeguards because the fresh fuel stored onsite to provide for frequent refueling contains a high-grade weapons material. The molten salt breeder reactor also requires a high-grade weapons material during its startup cycle. However, this would occur only once in the life of a molten salt breeder reactor. Its fuel cycle does not include the fuel fabrication and transportation steps that solid fuel reactors require.

## Economics

All of the systems would prospectively cost more to build than a light water reactor; however, depending principally on their fuel efficiency and the price of uranium, their fuel cycle costs could be lower.

The relative economics of the spectral shift control reactor are largely dependent on the future cost of uranium and heavy water. Improved uranium utilization would decrease the overall fuel cycle costs, but the addition of heavy water would increase operating and capital costs.

The need for heavy water production facilities is an added capital cost affecting the heavy water reactor. In addition, heavy water reactor capital costs are generally believed to be about 20 percent higher than a light water reactor, due principally to the larger size of the plant. Heavy water reactor fuel cycle costs may be relatively favorable because the use of heavy water is offset by the use of natural, instead of enriched, uranium fuel.

High temperature gas reactor capital cost estimates vary considerably from study to study and are very difficult to normalize. In general, the studies indicate that the direct cost of the nuclear portion of the high temperature gas reactor is higher than current light water reactors, although potential savings in the nonnuclear portion of the plant could compensate for some of the difference. Most estimates of high temperature gas reactor fuel cycle costs show a small savings relative to the light water reactor when recycling is used.

Breeder reactors are expected to cost considerably more than light water reactors. However, because of their varying abilities to create rather than consume fuel, most are expected to have fuel cycle cost advantages over nonbreeding nuclear technologies.

Although the overall capital costs of the light water breeder reactor will be comparable to a light water reactor, the relative fuel cycle costs will be higher because of the reactor's requirements for high fuel inventory, frequent refueling, and low power efficiency. An existing light water reactor could be converted to a light water breeder reactor by replacing the vessel head, core, and a number of related reactor systems. However, utilities would not likely retrofit a light water reactor since the power efficiency of the light water breeder is less than a light water reactor and the reactor would have to be taken out of the utility's power grid during modification--perhaps a year or longer.

Differences in projected capital costs of the gas-cooled fast reactors and other reactor concepts are based on physical differences in plant designs. The gas-cooled fast reactor is in a very early development state, and there is a high degree of uncertainty associated with the projected figures. The gas-cooled fast reactor offers the potential for substantial savings on fuel cycle costs over the light water reactor. However, until a better understanding is gained of the future availability and price of uranium, the costs of recycling and the actual operational characteristics of the gas-cooled, fast reactor, fuel cycle cost differentials are conjectural.

The principal cause of capital cost differences between molten salt breeder reactors and light water reactors will be the integral chemical processing system required for the molten salt breeder reactor. A major comparative study concluded that the cost of the processing plant will account for almost the entire margin of increased cost over the light water reactor.

Molten salt breeder reactors can be expected to have fuel cycle costs substantially lower than those for light water reactors. An estimate by Ebasco Services, Inc., showed that compared to a light water reactor, breeder reactors would have a fuel cycle cost of less than 40 percent that of light water reactors. Because the chemical processing plant is part of the capital cost of a molten salt breeder reactor, the fuel cycle cost will be lower compared to solid fueled systems involving reprocessing. A molten salt breeder reactor's fuel cycle cost will also be reduced compared to solid fueled reactors because it requires no fuel fabrication work.

The economics of accelerator, fission-fusion breeder reactors, and the gaseous core reactor are hard to predict because of their very early state of development and uncertain designs. There are indications that fission-fusion systems are likely to have substantially higher capital costs than accelerator systems. However, this may be compensated somewhat by higher fuel breeding output from the fission-fusion system. Also, production of electricity from a fission-fusion system may exceed that from an accelerator driven system; potentially enough to match or even overcome the accelerator's capital cost advantage. There is a general view that these systems may be capable of producing fuel at costs of about twice current fuel prices. Thus, only at some future time, when lower cost natural uranium deposits are depleted and more expensive sources must be used, will either of these technologies begin to approach commercial competitiveness.

Because the fuel for the gaseous core reactor is in gaseous form, it would not have fuel fabrication costs as high as those of solid fueled systems. In addition, because the spent fuel is continuously being reprocessed and recycled into the reactor core, there would be no fuel fabrication and enrichment costs beyond the startup fuel.

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Those technologies that are being considered as possible candidates for becoming the cornerstone of the next generation of nuclear power vary greatly in their respective stages of development. Many of these technologies are only conceptual and have not yet been defined or analyzed in sufficient detail to assure that they are even theoretically capable of operating as predicted. Thus, before an informed, well-thought-out decision can be made relative to which one or more of these candidates should become the heir(s) apparent to the light water reactor, more information will be needed.

In this connection, there are a number of studies currently underway which are aimed at evaluating the various alternative reactor concepts and fuel cycles. Two of the more important studies are (1) the International Nuclear Fuel Cycle Evaluation and (2) the DOE initiated Nonproliferation Alternative Systems Assessment Program.

The International Nuclear Fuel Cycle Evaluation is being conducted as a program by about 40 nations. The program has the primary goal of furthering the development of alternative nuclear fuel cycles which do not provide direct access to nuclear weapons material. The program also seeks to provide the necessary political and institutional framework for achieving greater international cooperation in civilian nuclear power proliferation activities. The scope of the program deals with three separate but related aspects: (1) energy and resource requirements, (2) fuel assurances, and (3) alternative fuel cycle and reactor system evaluations. The evaluation of alternative fuel cycle and reactor systems will be conducted in a piecemeal fashion by individual working groups. All such studies are due to be completed by late 1979.

The Nonproliferation Alternative Systems Assessment Program was initiated by DOE in April 1977. The program is intended to provide both technical input to the International Nuclear Fuel Cycle Evaluation and overall direction to the U.S. program to develop commercial nuclear power. DOE expects to issue a report on the program in December 1979.

# CHAPTER 5

## CONCLUSIONS AND MATTERS FOR CONSIDERATION BY THE CONGRESS

Technical alterations to the uranium fuel cycle, institutional actions, and alternative nuclear fission technologies have all been proposed as means to reduce the risk of nuclear proliferation. Technical alterations include coprocessing and/or spiking spent reactor fuel, colocating vulnerable nuclear fuel cycle processes, adopting a new spent fuel reprocessing method (such as the Civex process), and employing the use of thorium as the primary nuclear fuel. Institutional actions include treaties, trade agreements, and international organizations. Alternative nuclear fission technologies are the nuclear fission technologies other than the currently used light water reactor.

Proposed technical alterations alone, or in combination, will not make the uranium fuel cycle reprocessing technology proliferation-proof. All of the proposed alterations have weaknesses which could allow a national diversion of weapons material with existing or slightly advanced technology. The Civex process and spiking would only deter terrorist diversion. In addition, none of the proposed alterations has been developed beyond the experimental state. However, while nothing yet proposed can guarantee a zero risk of proliferation, these alterations may reduce the current risk of nuclear proliferation. The best opportunity for reducing the risk of proliferation appears to involve combinations of approaches. The keystone may be colocation, which would place most of the vulnerable parts of the fuel cycle in a strictly controlled environment and would largely eliminate any proliferation risks associated with transportation. In combination with one or more of the other approaches, access to plutonium could be made more difficult, time consuming, and costly.

The thorium fuel cycle does not appear to offer a solution. The thorium fuel cycle has its own unique proliferation risks and most of the thorium fuel cycle technology is not yet demonstrated. Major costs and/or risks are also present because changing from the uranium to the thorium fuel cycle would require modification to the existing industrial base.

Institutional means--treaties, trade agreements, and international organizations--like the technical alterations, cannot guarantee that proliferation will not occur. They can, however, lower the overall risk of nuclear proliferation. Recent actions, such as a tightening of controls over spent fuel by suppliers of nuclear materials and facilities, have somewhat strengthened the international controls over nuclear proliferation. In addition, the United States is implementing the Nuclear Non-Proliferation Act of 1978. The contribution this act will make toward reducing the risk of nuclear proliferation is currently being evaluated by GAO, pursuant to one of the requirements contained in this act.

Regardless of the value of the act, we cannot overemphasize that one nation, even as powerful and influential as the United States, cannot unilaterally provide assurance against weapons proliferation. However, if nuclear energy is going to remain an important source of energy and a viable energy alternative to be pursued in the future, the United States has no other choice but to push for the worldwide adoption of additional institutional measures which would decrease the potential for proliferation of nuclear weapons, including those measures which would facilitate colocation and international management of nuclear facilities.

The selection of the next generation of nuclear power is surrounded by confusion and uncertainty. The candidate technologies vary greatly in their state of development. Some are already or are very close to being commercially available in the United States. Others are only conceptual and are not yet defined or analyzed in sufficient detail to permit meaningful comparison. This might suggest that all or many of the systems should be pursued until they are closer to commercialization at which time a more informed choice might be made. Unfortunately, this is not practical mainly because each demonstration facility can cost hundreds of millions of dollars, and the pursuit of multiple technologies could delay realizing a usable technology to help meet mid-term energy needs.

An alternative to a broad scale program would be to determine which systems appear most likely to meet our future requirements and limit development support only to the most promising candidates. One means of determining the most promising candidates is the degree of proliferation risk from the related commercial nuclear power system. While we recognize the importance of efforts to avoid nuclear weapons proliferation, such risk, however, should not be the sole determinant in deciding which nuclear systems should be developed and deployed principally because no system is absolutely proliferation-proof. A variety of criteria should be considered in order to identify and balance each technology's advantages and disadvantages.

Our assessment of nuclear systems used a broad range of evaluation factors. We found that no one system was clearly superior to the others. A decision on which nuclear system is best to pursue appears to depend upon the relative weight assigned to each of the evaluation factors. There are currently two comprehensive studies being conducted concerning the topic of alternative fission technologies. DOE is conducting the Nonproliferation Alternative Systems Assessment Program and is also supporting the International Nuclear Fuel Cycle Evaluation. The final results of these studies should prove helpful in making any final choice of which second generation nuclear fission technology to pursue.

## MATTERS FOR CONSIDERATION BY THE CONGRESS

Nuclear fission research and development, with the objective of developing a technology superior to that used in current generation light water reactors, is an important part of our Nation's energy program. Most of the technologies being explored will take many years to develop to the point of commercialization and all will be expensive. In addition, none of the alternatives is clearly the most desirable when viewed in light of the criteria listed in this report.

For more than 25 years, the Congress has supported development of the liquid metal fast breeder reactor. In April 1977 the President proposed reduced funding for the liquid metal fast breeder reactor program and cancellation of the Clinch River Breeder Reactor project. Despite the President's proposal, the Congress has supported continuation of the liquid metal fast breeder reactor program and has provided funding to maintain the option of building the Clinch River Breeder Reactor. It is quite likely that the issues surrounding the Clinch River Breeder Reactor will again be considered during the 96th Congress. Such consideration requires an evaluation of the liquid metal fast breeder reactor program measured against the alternatives to this reactor concept. We believe the results of the studies currently being conducted under the Nonproliferation Alternative Systems Assessment Program and the International Nuclear Fuel Cycle Evaluation, together with this report, should prove useful in making such an evaluation.

In the interim period, however, we recommend that the Congress, through its oversight responsibilities and its annual authorization and appropriation processes continue to maintain DOE's research and development efforts relating to the liquid metal fast breeder reactor concept at a sufficiently viable level so as to not preclude the option of building a liquid metal fast breeder demonstration reactor.

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