United States General Accounting Office

GAO

Report to the Chairman, Subcommittee on Energy, Committee on Science, Space, and Technology, House of Representatives

December 1993

NUCLEAR SCIENCE

Developing Technology to Reduce Radioactive Waste May Take Decades and Be Costly

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Resources, Community, and
Economic Development Division

B-254881

December 10, 1993

The Honorable Marilyn Lloyd
Chairman, Subcommittee on Energy
Committee on Science, Space,
and Technology
House of Representatives

Dear Madam Chairman:

As you requested, this report presents the status of U.S. efforts to develop a technology (called waste transmutation) that might be able to reduce the volume and radioactivity of nuclear waste that would have to be buried in a deep geological repository. The possible implementation of waste transmutation is decades away and faces a number of challenges that may prevent its practical application to the existing radioactive waste problem. In addition to the report, we are forwarding to you supplemental material containing technical descriptions and analyses of the transmutation concepts described in this report.

As arranged with your office, unless you publicly announce its contents earlier, we will make no further distribution of this report until 30 days after the date of this letter. At that time, we will send copies to the Secretary of Energy and the Director, Office of Management and Budget. We will also make copies available to others on request.

This work was performed under the direction of Victor S. Rezendes, Director of Energy and Science Issues, who can be reached on (202) 512-3841, if you or your staff have any questions. Other major contributors to this report are listed in appendix I.

Sincerely yours,

J. Dexter Peach
Assistant Comptroller General

Executive Summary

Purpose

Radioactive waste is a major negative legacy of commercial nuclear power and the production of nuclear weapons. The difficulty of adequately disposing of this long-lived radioactive waste and the public's perception of its dangers are among the reasons why the nuclear industry has stopped growing. Current national policy calls for disposal of high-level radioactive waste related to nuclear weapons production and spent (used) fuel from commercial nuclear reactors in a deep geological repository. Some scientists believe, however, that the Department of Energy (DOE) should attempt to transmute (change) this waste into a less radioactive form before burying it. Transmutation might result in certain benefits, such as reducing the volume and radioactive life of some of the waste to be buried.

Concerned about the nuclear waste problem in the United States, the Chairman of the Subcommittee on Energy, House Committee on Science, Space, and Technology, asked GAO to determine the status of U.S. research to transmute radioactive waste. Specifically, GAO was asked to (1) identify U.S. efforts to develop waste transmutation technology, (2) determine the estimated timing and cost of this development, and (3) assess the prospects for practical application of transmutation to highly radioactive defense waste and to spent fuel from existing commercial reactors.

Background

DOE is responsible for the final disposal of both spent fuel and highly radioactive defense waste. Commercial power plant operators currently store most spent fuel in pools of water near the reactor. DOE stores defense-related radioactive waste primarily in underground tanks. When a repository becomes available, current national policy calls for DOE to transfer the spent fuel and defense waste to that repository for permanent disposal. DOE plans to open a deep geological repository in 2010.

Spent fuel contains a relatively small number of long-lived radioactive elements that are responsible for the long period that this waste is required to be confined in a repository. If DOE could transmute these elements to stable ones or ones with shorter radioactive life spans, it might reduce the long-lived hazards of the waste and increase the capacity of the repository. DOE could use a reactor's or an accelerator's nuclear reactions to transmute these long-lived elements. However, DOE would have to first reprocess the spent fuel to separate the long-lived elements and then incorporate them into new fuel (or a target for an accelerator to bombard). The fuel would be burned, reprocessed, refabricated, and burned again in a continuous cycle. Although the transmutation process might eventually produce a waste that has a much shorter radioactive life, residual high-level wastes and radioactive elements that cannot be transmuted would still need to be buried in a repository.

Although transmutation could be considered for treating defense-related nuclear waste, current plans call for DOE to separate the waste into high- and low-level components and dispose of the high-level component in a deep geological repository.

Results in Brief

DOE's radioactive waste managers are not pursuing the transmutation of waste because they believe that it is too costly and unnecessary. However, some of DOE's national laboratories and DOE's Office of Nuclear Energy have developed concepts to use advanced reactors or accelerators to transmute radioactive waste, but the research necessary to prove that these concepts are technically and economically feasible has not been done. The concepts have concentrated on the transmutation of spent fuel because most proponents of the concepts consider that the much larger and increasing volume of commercial spent fuel makes it a more likely candidate for transmutation than existing defense waste. DOE has asked the National Research Council to review these concepts and report its findings to DOE by July 1994.

Preliminary, incomplete estimates from proponents of waste transmutation show that it could cost many billions of dollars to develop and field the first spent fuel processing and transmutation system. According to data supplied by the proponents, this first system, driven by a reactor or an accelerator, could begin commercial operation by about 2015. However, according to most of the proponents, additional systems would be required to treat the inventory of spent fuel, and treatment would cost additional tens of billions of dollars and take decades or more to complete. Some of the transmutation costs might be recouped by generating and selling electricity.

In essence, any practical application of transmutation is at least decades away, and a number of constraints would slow or prevent application should it be actively pursued. These include current funding constraints; the high cost and long time needed to develop and implement transmutation; and the technical, institutional, and public challenges that would need to be overcome. Moreover, DOE's waste managers, industry representatives, and others currently believe that transmutation is not necessary or cost-beneficial.

Principal Findings

Technical and Economic Feasibility of Waste Transmutation Is Unproven

DOE managers who are responsible for the disposal of radioactive defense waste and commercial spent fuel are not in favor of transmuting waste before it is buried in a repository. They believe it unnecessary and costly and note that a repository will still be needed, even if transmutation of some of this waste is successful. Some of DOE's national laboratories and DOE's Office of Nuclear Energy, however, have identified concepts for the transmutation of radioactive waste. The proposed concepts involve reactor- or accelerator-driven systems: the Advanced Liquid-Metal Reactor/Integral Fast Reactor (ALMR/IFR) program sponsored by the Office of Nuclear Energy and involving the General Electric Company and the Argonne National Laboratory; the Accelerator Transmutation of Waste program at the Los Alamos National Laboratory; the Phoenix accelerator program and the Particle-Bed Reactor program at the Brookhaven National Laboratory; and the Clean Use of Reactor Energy program at the Hanford Reservation.

With the exception of the ALMR/IFR, all of the transmutation concepts are based on theoretical studies. The ALMR/IFR transmutation concept is further along because it has been funded as part of the DOE Office of Nuclear Energy's program to develop a liquid-metal breeder reactor. The other concepts have received no direct DOE funding, but proponents claim advantages over the ALMR/IFR. None of the concepts, including the ALMR/IFR, has been proved to be technically or economically feasible. ALMR/IFR program officials hope to provide partial proof of the technology's feasibility by 1998.

Although DOE has shown little active interest in most of the transmutation concepts, it has asked the National Research Council to study the benefits and costs of different transmutation concepts and report its findings by July 1994.

Transmuting Existing Waste Is Expected to Be Costly

Although U.S. research on radioactive waste transmutation is not far enough along to develop accurate cost and schedule estimates, proponents have provided preliminary estimates. While the estimates are incomplete, they provide a sense of the relative cost of and schedule for transmuting existing spent fuel waste.

Analysis of data supplied by proponents shows that they could develop and field their first transmutation system and start commercial operations by about 2015. (Demonstrations of the component systems would occur a few years earlier.) A complete system would include a reactor or accelerator to transmute reprocessed spent fuel, a spent fuel reprocessing and waste separation facility, a fuel refabrication facility, and storage facilities for the spent fuel (prior to processing) and residual wastes from the fuel reprocessing and transmutation. In addition, some concepts propose building a power plant to generate and sell electricity to help offset the costs of transmutation. Proponents estimate that it may cost several billion dollars to develop and construct a reactor or accelerator that would be able to transmute reprocessed spent fuel from existing reactors. Additional billions would be needed for a fuel reprocessing and refabrication facility, storage facilities, and a power plant.

After the first system is fielded, most proponents estimate that many more—perhaps about 20 or more—might be needed to treat existing spent fuel that will have accumulated by 2030, when the current generation of reactors will have been retired or replaced. Analysis of proponents' data shows that this effort would cost additional tens of billions of dollars and take decades to as many as 200 years, depending on the transmutation concept.

Any Practical Application of Transmutation Is Decades Away

DOE may find it impractical to develop transmutation technology primarily to treat existing waste because of a number of problems and circumstances, including high costs, possibly modest benefits, and technical and institutional challenges.

Any transmutation research and development is likely to be stretched out over many decades because of a lack of interest and funding to aggressively pursue it. Those who have transmutation concepts to sell are enthusiastic. However, DOE's nuclear waste disposal managers, representatives from the power industry, and some who have studied transmutation believe that it is not necessary or cost-beneficial to transmute existing waste. They emphasize that even if DOE is able to transmute the waste, a repository will still be needed. In addition, the current national policy calling for direct disposal of commercial spent fuel would have to be changed to allow fuel reprocessing and transmutation before burial.

Critics of proposals to transmute waste also note that none of the proposed transmutation concepts has been proved to be technically or economically feasible. Furthermore, they emphasize that DOE would have to research and develop efficient and economic methods for reprocessing and separating the waste before transmutation can occur. In addition, DOE would have to overcome other challenges, including licensing requirements and public acceptance, before it could field a transmutation system.

On the other hand, many critics and proponents of transmuting existing waste seem to agree that, if transmutation could be proven to be technically and economically feasible, it might be an attractive design feature for future power plants, if U.S. demand for nuclear power continues and increases in the next century.

Recommendations

GAO makes no recommendations in this report.

Agency Comments

As requested, GAO did not obtain written agency comments. However, GAO did discuss the contents of this report with DOE's Acting Director of the Office of Strategic Planning and International Programs, Civilian Radioactive Waste Management; DOE's Associate Deputy Assistant Secretary, Office of Technology Development, Environmental Restoration and Waste Management; DOE's Director of the Office of Nuclear Energy; and the National Research Council's project director for the transmutation portion of its ongoing study. GAO incorporated their views, where appropriate.

DOE's waste disposal managers and representatives of the National Research Council agreed with the report's conclusions. The Director of DOE's Office of Nuclear Energy said that it was too early to make accurate estimates of the cost of transmutation and was concerned that conclusions about the potential cost of transmutation may discourage support for further research involving the ALMR/IFR system. The cost and schedule estimates used in this report are based on information supplied by the transmutation concept developers. In addition, most of the concept developers (excluding those in the Particle-Bed Reactor program) reviewed GAO's analyses and presentation of this information. The cost and schedule estimates are preliminary and incomplete, but they do provide a sense of the potential magnitude of implementing a U.S. program to transmute radioactive waste.

Contents

Abbreviations

ALMR	Advanced Liquid-Metal Reactor
ATW	Accelerator Transmutation of Waste
BNL	Brookhaven National Laboratory
CURE	Clean Use of Reactor Energy
DOE	Department of Energy
EPRI	Electric Power Research Institute
GAO	General Accounting Office
HLW	high-level waste
IFR	Integral Fast Reactor
LANL	Los Alamos National Laboratory
LLW	low-level waste
LWR	light-water reactor
PBR	Particle-Bed Reactor
PUREX	plutonium-uranium extraction
TRU	transuranics
TRUEX	transuranic extraction

Introduction

Commercial nuclear power plants produce spent (used) nuclear fuel as a radioactive waste product when they burn nuclear fuel to generate electricity. The production of nuclear weapons has also produced spent fuel, most of which has been reprocessed to reclaim the uranium and plutonium contained in it. This reprocessing of the defense fuel has generated liquid and solid wastes classified as high-level radioactive waste.[1] Spent nuclear fuel and high-level waste are very radioactive and must be isolated from the environment for thousands of years. Nuclear power plants and weapons' facilities have generated tens of thousands of tons of these wastes since the 1940s. However, the Department of Energy (DOE) has not developed a permanent disposal method or site for these wastes. Currently, commercial nuclear power plant operators store spent fuel on site near their reactors. Defense-related nuclear waste is primarily stored in underground tanks or bins. The Congress addressed the disposal problem in the Nuclear Waste Policy Act of 1982 (P.L. 97-425), as amended in 1987, which requires DOE to develop a repository for permanent disposal of spent fuel and high-level radioactive waste.

Current national policy, reiterated in September 1993 by the Secretary of Energy, calls for the "direct" disposal of spent fuel and high-level radioactive waste in a deep geological repository. Some scientists, however, believe that it would be advantageous to transmute (change) spent fuel and high-level radioactive waste to a less radioactive and less toxic waste form before burying it in a repository. Transmutation might result in certain benefits, such as (1) reducing the volume and greatly reducing the radioactive life of the waste that must be buried and (2) ensuring less risk in certain situations, such as human intrusion into the repository. Transmutation of radioactive waste is not a new notion. However, research and development to make transmutation technology available and economical for the possible treatment of radioactive waste has not been done.

This chapter discusses the general process proposed for transmuting commercial spent fuel and high-level radioactive waste from the production of nuclear weapons and the claimed advantages of transmutation. Subsequent chapters discuss (1) some specific concepts for transmutation, (2) the cost of and schedule for developing these concepts

[1]The Department of Energy (DOE) defines "high-level waste" as the highly radioactive material that results from reprocessing spent fuel. On the other hand, the Nuclear Regulatory Commission defines it as both processed and unprocessed spent fuel. For the purposes of this report, we are using DOE's definition and making a distinction between spent fuel and high-level waste. When the high-level waste has been generated as a result of DOE's nuclear weapons production activities, we may also refer to it as "defense" or "weapons" waste.

and treating "existing"[2] radioactive waste, and (3) the practicality of transmutation as a technology to manage radioactive waste. A glossary of terms is included at the end of the report.

Background

Transmutation is the conversion of one element into another, such as the old story of possibly changing lead into gold. However, transmutation cannot be accomplished chemically. For transmutation to occur, the nucleus of an atom of an element must be changed, an event that can occur only through a nuclear reaction in a reactor or particle accelerator or through radioactive decay. When a radioactive atom absorbs a neutron, the resulting reaction can convert the atom into a different one that is stable (nonradioactive) or into products that have shorter radioactive lifetimes. For example, transmutation can convert technetium-99 (a radioactive fission product) into the stable element ruthenium by absorbing a neutron.

Transmutation Applied to Commercial Spent Nuclear Fuel

U.S. commercial light-water nuclear reactors (LWRS) generate about 2,000 metric tons of spent nuclear fuel each year. The current inventory is about 28,000 metric tons. DOE estimates that this inventory will increase to about 61,000 metric tons by 2010, when a waste repository is scheduled to open.[3] The current statutory capacity limit for this repository is 70,000 metric tons.

The present U.S. policy for handling spent fuel from a commercial nuclear power plant is to store the fuel elements in a facility at plant sites and/or at a federally owned storage facility until a repository for permanent disposal of the spent fuel becomes available. DOE will then transfer the fuel to that repository for permanent disposal. The Environmental Protection Agency, which sets the general environment standards for disposal of highly radioactive wastes in repositories, believes that the waste should be contained in the repository for at least 10,000 years.

[2]In this report, existing spent fuel is defined as that inventory of spent fuel produced by the current generation of commercial reactors up until 2030, when DOE expects that these reactors will have been retired and/or replaced. Existing defense high-level radioactive waste is that generated from the materials and methods used to produce plutonium and tritium for nuclear weapons and currently stored at DOE facilities. Much of this waste was produced when spent fuel from nuclear materials production reactors was reprocessed to extract plutonium for further use.

[3]In our report entitled Nuclear Waste: Yucca Mountain Project Behind Schedule and Facing Major Scientific Uncertainties (GAO/RCED-93-124, May 21, 1993), we estimate that the scheduled opening of a repository may slip by 5 to 13 years.

A small number of radioactive isotopes contained in the spent nuclear fuel of reactors are responsible for the required long confinement times for radioactive wastes. Table 1.1 lists the most important of these long-lived radioactive isotopes (radioisotopes).

Table 1.1: Long-Lived Radioactive Isotopes Contained in Spent Nuclear Fuel

Isotope	Type	Half-life in years
Neptunium-237	Transuranic[a]	2,000,000
Plutonium-239	Transuranic	24,000
Plutonium-240	Transuranic	6,563
Americium-241	Transuranic	432
Americium-243	Transuranic	7,400
Curium isotopes	Transuranic	up to 15,600,000
Technetium-99	Fission product[b]	210,000
Iodine-129	Fission product	17,000,000

[a]Transuranic elements are man-made radioactive isotopes produced from uranium during nuclear reactor operations.

[b]Fission products are the radioactive fragments (by-products) formed by nuclear fission in a reactor—the "ash" of nuclear power production.

Spent fuel contains uranium, transuranic elements, and fission products. Plutonium is, perhaps, the best known transuranic. As shown in table 1.1, transuranic elements have very long radioactive lives. DOE must consider this longevity when designing disposal methods for this radioactive waste.

Reducing the time that a repository would contain significant inventories of radioactive materials requires eliminating uranium and the radioactive isotopes in table 1.1 from the disposed-of waste. Uranium isotopes in the spent fuel waste have half-lives ranging into billions of years. A group of radioactive isotopes, including transuranics plus uranium, are referred to as "the actinides." Removal of the actinides from the spent fuel would reduce the average radioactive lifetime of the waste to be buried in the repository.

Another concern with repository burial is the possible leakage of soluble radioactive elements. Although actinides retain much higher toxicity levels for much longer periods than fission products, actinides are not very soluble, whereas the fission products, technetium and iodine, are. Thus, the long-term risks of leakage from a repository are not so much from actinides as from long-lived, soluble fission products, such as those in table 1.1. Consequently, transmutation of the long-lived fission products before the waste is buried would lower the long-term risk from leaks. (DOE repository officials consider this risk of leakage to be already extremely low.)

Two spent fuel fission products—cesium-137 and strontium-90—with relatively short half-lives (about 30 years) also require special consideration, because they are the principal heat sources in the wastes during the early period of decay. Radioactive isotopes give off heat energy as they decay. The amount of decay heat limits the volume of waste that can be put into a geological repository. If the heat load can be reduced by transmuting part of the waste and/or allowing the principal heat sources to cool down (cesium-137 and strontium-90 probably cannot be transmuted) before burial, the capacity of a repository might be increased. In turn, increased capacity might lead to the need for fewer repositories.

Proposed Waste Treatment Process for Spent Fuel

Before transmutation of the spent fuel can occur, it has to be reprocessed, the waste separated into high- and low-level radioactive components, and the actinides and fission products separated from the high-level component. The reprocessing and separating of the waste are more difficult technical problems than transmuting the long-lived elements from the waste. These problems need to be resolved before transmutation can be considered an option for treating waste.[4] DOE is considering both aqueous processes, such as the plutonium and uranium extraction (PUREX) system that has been used in the separation of defense waste,[5] and a new process called "pyroprocessing" now being developed, which uses electrorefining to separate elements of the reprocessed spent fuel.

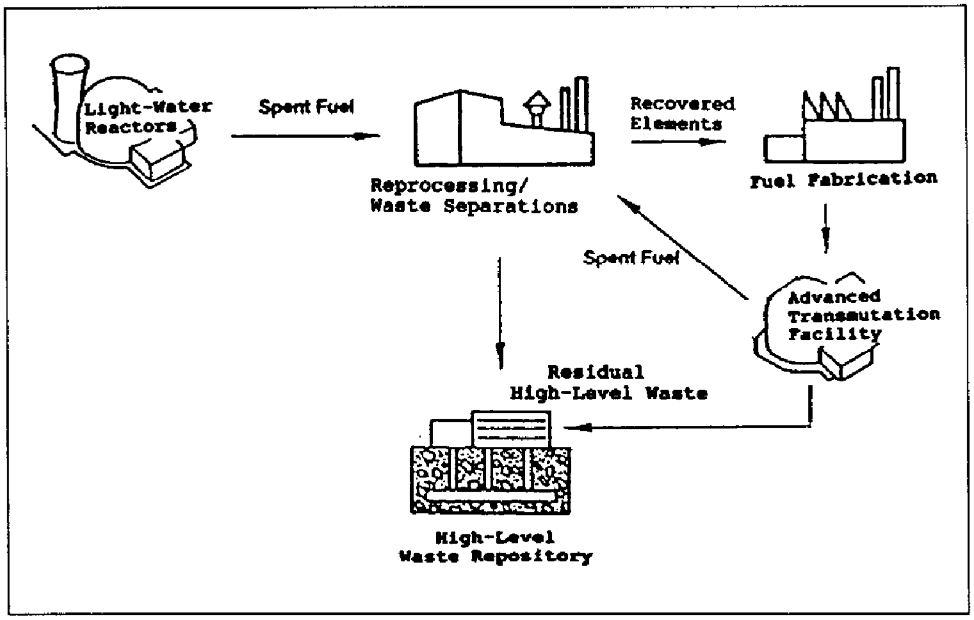
Once the waste has been separated, fissionable elements extracted from the high-level component can be incorporated into new fuel. The fuel can then be used in a reactor or accelerator, where nuclear reactions can change the long-lived actinides and, possibly, some fission products into short-lived or stable isotopes. Not all of these isotopes would be changed in a single pass; thus, the process may have to be repeated many times to complete the burning of the long-lived components of the waste. Transmutation proponents suggest using an advanced reactor design

[4]Transmutation is only one of the possible waste treatments that could be used after the spent fuel is reprocessed and separated. For example, the separated waste streams could be disposed of at that point, or some waste could be immobilized in a form like glass before disposal.

[5]Another aqueous process called transuranic extraction (TRUEX) is also being developed to separate the transuranics from high-level waste.

(more advanced than light-water reactors)[6] or an accelerator for this process. Figure 1.2 shows a possible waste transmutation process for treating spent fuel wastes.

Figure 1.1: Processing and Transmuting Spent Fuel



Source: GAO's composite of DOE's diagrams.

The advanced transmutation facility shown in figure 1.1 could be a reactor or accelerator that might also be used to generate electricity. The sale of this electricity could help to offset the cost of the waste treatment. In addition, as shown, residual high-level waste from fuel reprocessing and transmutation operations, including elements of high-level waste that cannot be transmuted, would have to be disposed of in a repository.

Transmutation Applied to Defense Waste

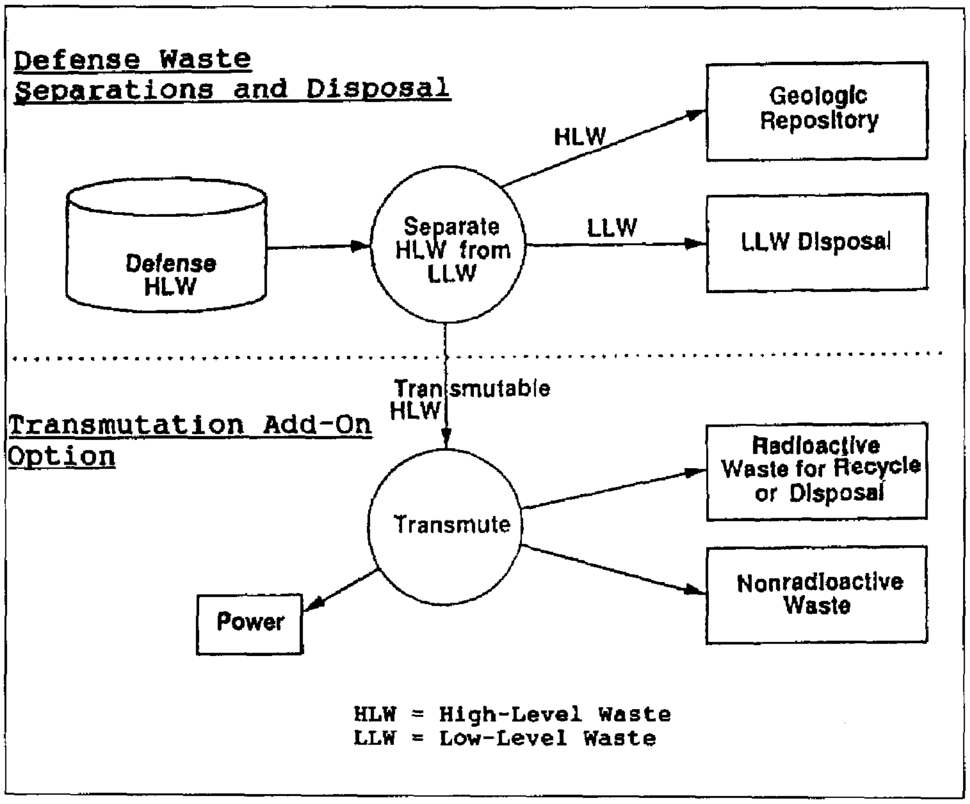
A second category of high-level nuclear waste is the defense waste currently stored in tanks at several DOE facilities, primarily the Hanford Reservation in Washington; the Savannah River Plant in South Carolina; and the Idaho National Engineering Laboratory in Idaho. For example,

[6]The National Research Council is examining the potential use of light-water reactors for transmutation, as part of its transmutation study. Officials from DOE's Office of Nuclear Energy suggest using an advanced reactor, such as the liquid-metal-cooled reactor, because they (and others) believe that commercial light-water reactors would be less efficient as waste burners.

Hanford has about 61 million gallons of high-level waste stored in 177 tanks—about 63 percent of DOE's total volume and 37 percent of its radioactivity. DOE has already processed most of the defense waste to remove the plutonium and unused uranium. However, the waste still contains small amounts of uranium, plutonium, minor transuranics, and many fission products, including long-lived ones. DOE's disposal plan for these defense wastes is to remove them from the tanks and separate them into high- and low-level components. DOE would then immobilize the high-level waste in a suitable material (for example, glass) and send it to a geological repository for disposal. The low-level components would be immobilized in a suitable material for storage at the site. As with the commercial wastes, the assumption is that a repository that can contain the high-level waste for thousands of years will be available.

Figure 1.2 shows a possible transmutation option for the treatment of high-level defense waste.

Figure 1.2: Transmutation Option for High-Level Defense Waste



Source: DOE.

Objectives, Scope, and Methodology

The Chairman of the Subcommittee on Energy, House Committee on Science, Space, and Technology, requested that we obtain information on the status of U.S. research into the possible transmutation of radioactive waste. Specifically, the Chairman asked us to

- identify current U.S. efforts in the research and development of radioactive waste transmutation technology;
- determine the estimated timing and cost for developing and implementing transmutation, including any planned demonstration projects; and
- assess the prospects for the practical application of the transmutation technology to existing commercial spent nuclear fuel and highly radioactive defense waste.

We conducted work primarily at DOE headquarters, Washington, D.C.; the Argonne National Laboratory in Illinois and Idaho; the Los Alamos National Laboratory, New Mexico; the Brookhaven National Laboratory, New York; and the Hanford Reservation, Washington.

To determine current U.S. research efforts in transmutation, we analyzed pertinent documents and articles and held discussions at DOE headquarters with waste management program officials from the Office of Environmental Restoration and Waste Management and the Office of Civilian Radioactive Waste Management and representatives of the Office of Nuclear Energy. We also visited the Hanford Reservation and three national laboratories that had developed transmutation concepts and discussed these concepts with their developers. In addition, we held discussions with representatives of the National Research Council and members of a Research Council panel established to study radioactive waste separation and transmutation options.

To estimate the cost and time for development and implementation of the different transmutation concepts, we held discussions with the developers of each concept and obtained documents relating to cost and schedule data for each of the concepts. Much of these data could be used directly to provide preliminary estimates of cost and timing. In some cases, we had to analyze the data provided by the developers to make estimates of the cost and schedule to implement transmutation. In each case, we had the concept developers review our analysis and presentation of their respective concepts.[7] All of these estimates are acknowledged by the developers and us to be very preliminary because transmutation is in the

[7]Developers of a proposal to use a high-temperature, gas-cooled reactor to transmute spent fuel did not respond to our request that they review our presentation of their concept. The four other concept developers did comply with our request.

early research stage. Nonetheless, we have presented these preliminary estimates in our report to give the reader a sense of the potential magnitude of the cost and schedule for development and implementation of radioactive waste transmutation.

To determine the practicality of developing and applying transmutation to spent fuel generated by existing nuclear power plants and to existing highly radioactive defense waste, we examined the technical, institutional, and financial problems that this technology has to overcome to be successfully applied. These problems have been identified by the technical community and have been reported in pertinent documents. We also examined current critiques by nuclear industry representatives and the results of recent studies, including one commissioned by DOE's Office of Civilian Radioactive Waste Management and performed by DOE's Lawrence Livermore Laboratory concerning the potential for practical application of transmutation to spent fuel. In addition, we discussed the question of the practical application of transmutation with the promoters of each concept and some members and managers of the National Research Council panel that is currently studying waste separation and transmutation for DOE.

Dr. George W. Hinman, D.Sc., provided technical assistance in performing this review, including developing a technical supplement, which is the basis for much of this report. Dr. Hinman is currently the Director of the Office of Applied Energy Studies at Washington State University and has over 40 years experience in the nuclear energy field in industry, government, and academia.

If you would like to obtain the technical supplement to this report, fill out and mail the postcard at the beginning of this report. If the postcard is missing, send your name and address with your request for the supplement entitled Nuclear Science: Developing Technology to Reduce Radioactive Waste May Take Decades and Be Costly (GAO/RCED-94-16S) to

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Room 1842
441 G Street, N.W.
Washington, D.C. 20548

We discussed the contents of this report with DOE representatives, including the Acting Director of the Office of Strategic Planning and International Programs, Civilian Radioactive Waste Management; the

Associate Deputy Assistant Secretary for the Office of Technology Development, Environmental Restoration and Waste Management; and the Director of the Office of Nuclear Energy. (The Office of Nuclear Energy sponsors one of the concepts for transmuting radioactive waste.) In addition, we discussed our report and conclusions with the project director of the National Research Council's ongoing study of waste transmutation, who strongly agreed with the report's conclusions. The representatives from DOE's radioactive waste management groups also agreed with our report's conclusions. The Director of the Office of Nuclear Energy agreed that transmutation still has to be proven to be technically and economically feasible. However, he said that he is concerned that transmutation research may not be pursued because, in his opinion, premature judgments are being made about the potential costs of transmutation. He commented that it is too early to make accurate estimates of the cost of transmuting commercial spent fuel. Our report's description of the transmutation concepts and preliminary estimates of the costs and schedules for developing and implementing these concepts were reviewed by the concept developers. These preliminary estimates are presented in our report to provide a sense of the potential magnitude of the cost and length of time needed to develop and implement transmutation. Others with whom we discussed our report and/or who have also studied the transmutation of radioactive waste agree with the magnitude of these preliminary estimates. The concept developers, DOE representatives, and the National Research Council study representative provided additional information and clarifications, which were incorporated where appropriate. As requested, we did not obtain written agency comments. We performed our review between July 1992 and August 1993, in accordance with generally accepted government auditing standards.

DOE's Radioactive Waste Managers Have Not Supported Transmutation Research, but Various Proposals Are Being Studied

The DOE managers who are responsible for the disposal of commercial spent nuclear fuel and highly radioactive defense waste are not actively considering transmutation as a possible method for treating existing waste. However, a number of DOE laboratories have proposed waste transmutation concepts, and DOE's Office of Nuclear Energy is developing an advanced power reactor that may be able to transmute its spent fuel waste. All of these proposed transmutation concepts require more research to determine whether they are technically and economically feasible. DOE has asked the National Research Council to examine transmutation concepts.

DOE's Radioactive Waste Managers Do Not Support Transmutation as a Means to Solve Existing Waste Problems

DOE's defense and commercial radioactive waste management officials are generally skeptical about the technical and economic feasibility of waste transmutation. More importantly, they believe that it is not necessary and not economically justifiable to transmute the spent fuel from existing commercial reactors and high-level defense waste before it is put into a repository.[1] They believe that transmutation is unnecessary because the radioactive waste can be safely disposed of without first transmuting it. They point out that a geological repository will be designed, certified, licensed, and monitored to ensure that disposed waste is safely contained for thousands of years. Furthermore, they argue that it is not economically justifiable to transmute waste, since a repository will still be needed, even if transmutation is successfully developed, to dispose of residual high-level wastes from the transmutation process and high-level waste that cannot be transmuted.

Nevertheless, DOE has concluded that it should obtain an independent assessment of the benefits and costs of the different waste transmutation concepts being proposed. Thus, in 1991, DOE commissioned the National Research Council (the Research Council) to study the status of radioactive waste separation and transmutation research.

[1]The potential cost of transmuting existing radioactive waste and the practicality of this proposed waste treatment strategy are discussed in chapters 3 and 4, respectively.

The National Research Council's Study of Transmutation Proposals

The Research Council's report on radioactive waste separation and transmutation, which is expected to be published in July 1994, will examine radioactive waste treatment research efforts in the United States and other countries. According to the Research Council personnel who manage the study, the report will include (1) a technical and cost-benefit analysis of separating radioactive wastes into different waste streams (that is, high-level and low-level) before disposal and (2) a technical and cost-benefit analysis of waste separation followed by transmutation. The study panel of experts is also charged with analyzing the potential impact of successful development of waste separations and transmutation technology on the nation's repository strategy for disposal of radioactive waste. In addition to examining the potential for transmutation of waste using advanced reactors and accelerators, the Research Council will also examine the potential for using light-water reactors to transmute their own spent fuel and to burn up plutonium extracted from nuclear weapons.

Managers of the Research Council's study told us that the study panel has found that much research remains to be done in developing technologies for radioactive waste separation and transmutation. Specifically, the study managers said the panel believes that some of the U.S. proponents of transmutation may have exaggerated the potential benefits and underestimated the costs and the technical and institutional problems involved with their proposed method for transmutation; or more likely, the proponents have not done enough actual research to determine the technical and economic feasibility of their proposals.

Transmutation Concepts Focus on Spent Fuel

Although radioactive defense waste is also a candidate for transmutation, the developers of the transmutation concepts have mainly concentrated on the possible treatment of commercial spent fuel. The proponents of transmutation consider unprocessed spent fuel a larger and more likely candidate for transmutation. In addition, DOE's waste managers have told transmutation proponents that DOE has already selected the scheme for disposal of defense waste—separation and disposal after immobilization. These managers are concentrating on developing methods to characterize, separate (into high-level and low-level wastes), and immobilize (for example, in glass for high-level waste) defense wastes prior to disposal.

The remainder of this chapter describes the five concepts that have been identified as methods for possible transmutation of radioactive waste. The basic setup for each concept to process and transmute spent fuel is similar to that shown in figure 1.1; the advanced transmutation facility shown in figure 1.1 may be either a reactor or an accelerator.

More Research Is Needed to Determine Feasibility of Proposed Waste Transmutation Concepts

Four national Laboratories have identified five concepts for the transmutation of radioactive waste. All of the concepts require more research to determine whether they are technically and economically feasible. The proposed concepts include three reactor- and two accelerator-driven transmutation systems: the Advanced Liquid-Metal/Integral Fast Reactor (ALMR/IFR) program (sponsored by DOE's Office of Nuclear Energy) at the General Electric Company and the Argonne National Laboratory; the Particle-Bed Reactor program at Brookhaven National Laboratory; the Westinghouse-Hanford Clean Use of Reactor Energy (CURE) program at the Hanford Reservation; the Accelerator Transmutation of Waste (ATW) program at Los Alamos National Laboratory; and the Phoenix accelerator program at Brookhaven National Laboratory. The ALMR/IFR transmutation concept is furthest along. However, the other concepts claim greater transmutation capabilities than the ALMR/IFR.

ALMR/IFR Transmutation Concept Is Further Along Than the Other Options

Although the ALMR/IFR transmutation concept is still very much in the research stage, it is the most developed because it has been part of a larger program that has historically received substantial funding. DOE's ALMR/IFR transmutation efforts have been part of DOE's effort to develop and field an advanced power reactor. This effort extends back into history more than a decade and includes the Clinch River breeder reactor project. DOE's planned ALMR would be cooled by liquid metal (sodium), use metal fuel (a mixture of plutonium, uranium, and zirconium), and be able to breed its own fuel, if necessary. Besides this unique and advanced design, the reactor would also have a "closed fuel cycle." In the closed fuel cycle, spent fuel from the reactor would be reprocessed, and the actinides would be separated from the other wastes (the fission products), incorporated into new metal fuel, and fed back into the reactor. This process would enable the reactor to eventually burn up (transmute) its spent fuel actinide waste.

The ALMR/IFR Transmutation Process Applied to Light-Water Reactor Spent Fuel

Promoters of the ALMR/IFR concept believe that they can reprocess and separate into different components the spent fuel from existing commercial light-water-cooled reactors and then incorporate the high-level actinide wastes in new metal fuel that can be used in the

ALMR/IFR. The ALMR/IFR system would burn this fuel, reprocess it, separate it, refabricate it, and burn it again in a continuous cycle until the actinides are destroyed.

ALMR/IFR program officials are developing a nonaqueous system, called pyroprocessing, for separating spent ALMR metal fuel into different components. A key step in the process uses electrorefining to separate the usable actinides from the spent fuel fission products. Program officials claim that pyroprocessing will be less expensive and more efficient than the currently more developed aqueous (chemical solvent) methods. Others in the nuclear industry are skeptical and are waiting for ALMR/IFR developers to provide proof.

Although the ALMR/IFR may prove to be an effective burner of actinides, it cannot transmute the fission products contained in spent fuel. According to program officials, these fission products will be separated out for direct burial or other treatment. Proponents argue that the ability to reprocess spent LWR fuel and use its actinides as a fuel in the ALMR/IFR is likely to be less hazardous to human health and cost less than mining and milling new uranium ore for reactor fuel.[2] Others argue that fuel reprocessing and other processes involved with the transmutation of spent LWR fuel may be as hazardous to workers as mining and milling uranium.

In May 1992, at the direction of the former Secretary of Energy, the National Research Council issued a report specifically on the option of using the ALMR/IFR for transmutation of radioactive waste.[3] The report concluded that the ALMR/IFR transmutation system had the potential to reduce the amount of actinide waste from spent fuel that would have to be buried in the repository. However, the Research Council stated that the ALMR/IFR system for transmuting and eventually destroying spent fuel waste would likely be costly and take many decades to complete.

Specifically, the Research Council reported that it would take 20 ALMR/IFRS 100 years or more to destroy 90 percent of the LWR actinide waste inventory that is expected to exist in 2010, when a geological repository is scheduled to open. Residual high-level wastes, including the long-lived fission products contained in spent fuel, would still have to be disposed of in a repository.

[2]Operating the ALMR/IFR as a fuel-breeding reactor would also diminish the need for mining and milling uranium ore, and on a much larger scale.

[3]Interim Report of the Panel on Separations Technology and Transmutation Systems, the National Research Council, May 1992.

Less-Developed Concepts Claim Advantages Over the ALMR/IFR

The four other transmutation concepts—two reactor and two accelerator systems—although not as well explored as the ALMR/IFR, claim some advantages over it. Specifically, the promoters of each of the other concepts claim that their concept will be able to transmute not only actinides but also some of the long-lived fission products from spent fuel. In addition, the accelerator concepts claim to be safer than the reactor-driven concepts because, unlike the reactors, they do not need to sustain a nuclear chain reaction and can be shut down instantly if a problem occurs. These concepts, although possibly promising, have not been researched beyond theoretical studies, mainly because of a lack of funding.

Brookhaven Laboratory's Particle-Bed Reactor as a Waste Burner

Brookhaven's Particle-Bed Reactor (PBR) is so named because the fuel is contained in small, graphite-coated particles that form the "particle bed." Brookhaven had been developing the PBR for the Air Force as a possible propulsion system for space flights. According to program officials, the Air Force ordered Brookhaven to stop its PBR propulsion efforts in 1993 as part of the administration's cost savings program. Brookhaven scientists, however, had also proposed using the PBR to transmute radioactive waste and recommended to DOE that a research and development program be started to investigate this possibility.

The PBR is a proposed small, high-temperature, helium-cooled reactor. Although only brief conceptual studies have been done, Brookhaven officials believe that the PBR would effectively transmute both actinides and fission products. These officials believe that the PBR concept is more attractive than the ALMR/IFR because, according to program officials, the PBR is expected to be able to destroy both actinides and fission products, while accumulating very low residual waste inventories from burn cycle to burn cycle. The ALMR/IFR maintains a large actinide inventory in its core and may take decades or more to completely burn up the inventory of actinides built up in spent LWR fuel.

Hanford's Clean Use of Reactor Energy Concept

The Westinghouse-Hanford's Clean Use of Reactor Energy concept involves an integrated system of chemical processing and reactor transmutation to eliminate most long-lived waste components from high-level radioactive waste. CURE proposes examining a variety of chemical processing and transmutation systems. However, CURE highlights a system that uses aqueous processing (for example, PUREX or TRUEX) and separation of spent LWR fuel combined with fissioning of transuranic elements in an oxide-fueled, liquid-metal-cooled reactor. This differs from the ALMR/IFR proposal to use pyroprocessing and a metal-fueled reactor. In addition, the CURE reactor would transmute the long-lived fission products iodine-129 and technetium-99.

The CURE concept is based on theoretical studies; proponents suggest that the U.S. government, perhaps in collaboration with other countries, start a research and development program to investigate and develop this concept.

Los Alamos National Laboratory's Accelerator Transmutation of Waste

The Los Alamos National Laboratory (LANL) proposes using a particle accelerator to transmute radioactive waste. This LANL concept, referred to as the Accelerator Transmutation of Waste program, uses a linear accelerator to bombard a "target" fabricated from LWR spent fuel actinides and long-lived fission products and thus transmute these elements. In addition, as discussed in chapter 3, ATW program officials are the only transmutation proponents (discussed in this report) who have seriously considered transmuting defense radioactive waste.

ATW program officials claim several advantages for their method of transmuting waste. First, unlike a reactor, the ATW does not need to maintain a nuclear chain reaction to operate, and it can be shut down instantly. Thus, proponents claim that the ATW will be safer to operate because it has a much lower chance of a nuclear accident. In addition, more rapid transmutation is possible with smaller inventories of actinides than need to be maintained in the ALMR/IFR fuel cycle. Furthermore, unlike the ALMR/IFR, the ATW claims to also transmute some fission products. For example, the ATW would transmute into stable isotopes the fission products iodine-129 and technetium-99, which have half-lives of 17 million and 0.2 million years, respectively.

Brookhaven National Laboratory's Phoenix Transmutation System

Brookhaven National Laboratory officials have proposed that the laboratory's Phoenix accelerator be used to transmute waste. The Phoenix would be part of a larger radioactive waste treatment system that the officials are proposing. The system would include processing and separating spent commercial nuclear fuel into key components. The Phoenix system would transmute some of these components, others would be stored for later use, and still others would be deposited into a repository after the separation process.

The Phoenix concept, like the ATW concept, proposes to use a linear accelerator to transmute "minor" actinides (neptunium, americium, and curium) and the fission product iodine-129. The Phoenix concept relies heavily on the PUREX and TRUEX chemical processing systems to prepare the accelerator target material from spent LWR fuel and to reprocess the accelerator-bombarded nuclear material targets after they have been irradiated. Unlike the ATW, the Phoenix would not transmute plutonium or uranium. Instead, these would be separated from the processed spent fuel and stored for possible future use. The plutonium and uranium might be used as fuel in current or future reactors.

Brookhaven officials claim that only one Phoenix system (or perhaps two) would be needed to transmute the inventory of minor actinides that would be contained in the spent fuel generated by the current generation of commercial reactors. These officials also believe that the proposed Phoenix waste treatment system could reduce the risk period for radioactive toxicity of high-level waste from the current 10,000 years down to approximately 30 years.

Conclusion

Proponents of the five transmutation concepts present optimistic claims for the potential application of transmutation technology to the existing radioactive waste problem. However, with the exception of ALMR/IFR, very little actual research and development has been done to verify claimed transmutation capabilities and benefits. Furthermore, no determination has been made of the economic and technical feasibility of any of the concepts, including the ALMR/IFR concept. It is difficult to verify any claims about the potential capabilities and benefits of any of the proposed waste transmutation concepts without sufficient research to document these attributes. Perhaps the forthcoming National Research Council study will resolve some of this uncertainty.

Preliminary Estimates to Develop and Implement Transmutation Are High

Preliminary data from the proponents of each transmutation concept represent very early and incomplete estimates, but these estimates show that it could cost billions of dollars (in 1993 dollars)—perhaps as much as $29 billion, depending on the concept selected—to develop and construct an initial system that could transmute LWR spent fuel. Additional tens of billions of dollars would be needed to build the additional systems that would be used to transmute the accumulated inventory of spent fuel from existing light-water reactors. An analysis of data supplied by the proponents of the various concepts shows that initial commercial operations to transmute light-water reactor spent fuel could begin about 2015 and could take until 2050 to 2240 (depending on the method and extent of transmutation) to treat the spent fuel that would have accumulated by 2030.[1] According to data from the developers of transmutation concepts, the actual processing and transmutation of the spent fuel could cost additional tens of billions to over $100 billion dollars. However, transmutation proponents believe that part or all of these costs could be recouped by generating and selling electricity, assuming that the price of the electricity generated is competitive with other possible sources.

The following is a discussion of the estimated cost of and schedule for developing and implementing each of the proposed transmutation systems. The proposals are for systems that would transmute spent fuel; only the ATW system has studied the possibility of transmuting defense waste. The estimates are very early and unverified estimates made by the proponents of each transmutation concept or, in some cases, made by us using information supplied by the proponents. The estimates from each proposal are not comparable because they are incomplete and represent estimates of somewhat different strategies for treating the waste. We are presenting these estimates only to give the reader a sense of the potential cost and time requirements for transmuting spent fuel waste.

ALMR/IFR's Estimated Cost and Schedule

DOE's preliminary cost estimates for an ALMR/IFR system to transmute LWR spent fuel are incomplete. However, DOE's cost estimates to develop and construct just the power reactor and a facility to recycle its metal fuel exceed $5 billion (in 1993 dollars). Additional facilities costing billions of dollars more would also be needed for a complete system to transmute the LWR spent fuel.

[1] DOE expects that all of the current generation of U.S. nuclear power reactors will have been retired and/or replaced by 2030 and will have generated about 90,000 metric tons of spent fuel.

DOE developed a draft 5-year ALMR/IFR program plan in response to a requirement of the Energy Policy Act of 1992. In the plan, program officials estimated that approximately $900 million would be needed from 1993 to 1998 for reactor design and development, fuel-cycle research and development, and LWR spent fuel recycle research. Additional funding would be required, including about $2.9 billion to construct the first ALMR power reactor and about $1.3 billion for a facility to recycle the reactor's metal fuel. However, to transmute LWR spent fuel, the ALMR/IFR system would also need a reprocessing and refabrication facility for LWR spent fuel, as well as facilities to temporarily store spent fuel waiting to be processed and residual waste waiting to be buried. A DOE program manager said that an official estimate of the cost of an LWR reprocessing facility has not been made because a detailed design of a possible facility has not been done this early in the program. However, he said that such a facility could cost several billion dollars.[2]

ALMR/IFR program officials believe that with "adequate" funding they could demonstrate a complete system by about 2010 and then field a first commercial ALMR/IFR transmutation system and start treating LWR spent fuel waste by 2014. Data provided by ALMR/IFR officials show that an additional 200 years, 18 more ALMR/IFR systems, and additional tens of billions of dollars might be needed to treat the existing inventory of spent fuel. Proponents of the ALMR/IFR believe that all of these costs could be offset by sales of electricity, assuming that the cost of generated electricity is competitive with other possible sources.

A Scenario for ALMR/IFR's Treatment of Existing LWR Waste

ALMR/IFR program officials describe a scenario involving 19 ALMR/IFR plants to transmute the inventory of spent fuel from the current generation of LWRs that will have ceased operation by 2030. DOE estimates that by 2030 this generation of LWRs will have produced an inventory of about 90,000 metric tons of spent fuel waste—about 875 metric tons[3] of which will be actinides. The ALMR/IFRs would use these actinides as fuel. Data from the ALMR/IFR scenario show that the inventory of actinide wastes from the spent fuel could be reduced to less than one metric ton by 2240. Residual waste from the reprocessing and high-level waste that could not be transmuted would still require repository burial. However, program

[2]DOE's Office of Nuclear Energy is currently using an estimated cost for reprocessing a unit of LWR spent fuel in lieu of actually estimating the development and capital cost of a LWR fuel reprocessing facility.

[3]The scenarios considered in this report for transmutation of spent fuel assume that all of the actinides are available for transmutation—none would have been buried in a repository.

officials say that the volume and long-term radioactivity of this waste will be greatly reduced when compared with the original spent fuel.

Each of the 19 ALMR/IFRS would cost about $4 billion (1993 dollars), including a power reactor and a metal fuel recycling facility, according to program officials. However, program officials propose that the 19 ALMR/IFRS replace any existing LWRS scheduled for retirement and replacement.[4] In addition, they believe that the sale of electricity generated by the ALMR/IFR would offset transmutation costs. LWR fuel reprocessing facilities and temporary storage facilities would be needed at additional capital costs. Program officials have not estimated the cost or number of these facilities. However, program reports indicate that it could cost as much as $32 billion (1993 dollars) to transmute the inventory of LWR spent fuel that will have accumulated by the year 2030. ALMR/IFR program officials say that transmuting costs could be added to the price that they would charge customers for the electricity to be generated by the operation.

During the discussion of our draft report with officials from DOE's Office of Nuclear Energy (sponsor of the ALMR/IFR), they told us that they were concerned that critics' estimates of the costs to develop and operate the ALMR/IFR were too high. DOE civilian waste managers, the Electric Power Research Institute, and even the National Research Council in its interim report state that ALMR/IFR's development and transmutation costs are likely to be quite high, stretching into the tens of billions. Officials from DOE's Office of Nuclear Energy told us that to counter these claims of high costs, they commissioned the Oak Ridge National Laboratory to do an ALMR/IFR cost feasibility study using assumptions and input data provided by their office. The results of this June 1993[5] study show that it may be less expensive to operate ALMR/IFRS than light-water reactors if the capital costs of the two types of plants are the same and if there is (1) a resurgence in the U.S. demand for nuclear power in the next century, (2) a large increase in the cost of uranium used to fuel light-water reactors, and (3) if the ALMR/IFR program is able to develop and operate its pyroprocessing system (for separating actinides from spent light-water reactor fuel) for a much lower cost (about one-third) than aqueous separation. Others, including DOE's radioactive waste managers and representatives of the National Research Council's study panel, are skeptical about a large rise in the cost

[4]If this replacement does not occur, then each new ALMR/IFR would represent additional billions of dollars in unscheduled capital costs.

[5]ALMR Deployment Economic Analysis, Oak Ridge National Laboratory, June 1993.

of uranium fuel and a much lower cost for pyroprocessing than is obtainable with aqueous processing systems.

Budget Cuts May Affect Planned Demonstration Project and Stretch Out ALMR/IFR Development

Although funding for the ALMR/IFR program may be affected by the administration's effort to reduce the cost of government operations, program officials hope to at least obtain enough funding in fiscal year 1994 and subsequent years for fuel-cycle research, including demonstrating that a pyroprocessing system can be used to separate LWR spent fuel into actinides and fission products. Program officials hope to complete this demonstration by 1998. The funding needed to completely support the ALMR/IFR program amounts to about $140 million to $150 million (in 1993 dollars) annually. Most of this amount is operating costs for support facilities. However, ALMR/IFR program officials expect that about $30 million of this annual amount would go to fuel-cycle research, including demonstrating the pyroprocessing of LWR spent fuel. ALMR/IFR program officials emphasize that unless sufficient funding is obtained, the accomplishments envisioned in their draft program plan (discussed above) may be stretched out for decades or completely lost. ALMR/IFR program officials expect to revise their program plan after the budget process for fiscal year 1994 is completed.

ATW's Estimated Cost and Schedule

ATW officials at the Los Alamos National Laboratory estimate that it would cost about $2.9 billion (1993 dollars) to develop the ATW, including an estimated $2.1 billion to construct an accelerator. This preliminary estimate does not include the cost to develop and construct a facility to reprocess the spent fuel from the LWRS and to fabricate targets (for accelerator bombardment) from the separated actinides and fission products of the spent fuel. ATW officials assume that with DOE's support and funding they could have a demonstration plant finished by fiscal year 2007—about 14 years from start to finish. Analysis of program data shows that with a successful demonstration of the ATW and additional funding, program officials could construct and start operating a full-scale transmutation plant by about 2016.

A Scenario for ATW's Treatment of Spent Fuel From Existing LWRs

If the same scenario described above for the ALMR/IFR is applied to the ATW, 19 ATW transmutation systems could be constructed between 2016 and 2030. These ATW systems could transmute the inventory of spent fuel accumulated to 2030 (including actinides and fission products) by 2055. According to proponents, the ATW system would destroy the LWR spent fuel waste faster and to a greater extent (that is, including fission products) than the ALMR/IFR. Preliminary estimates by ATW program officials show that the cost for transmuting the inventory of spent fuel might exceed $120 billion (1993 dollars). Program officials say that the ATW system would also generate and sell electric power to help offset transmutation costs.

ATW Transmutation of Defense Waste

The ATW is the only transmutation concept that has seriously studied and proposed a transmutation system for defense waste. The ATW program officials developed a theoretical process for possible transmutation of the defense wastes currently stored in tanks at the Hanford Reservation. (Fig. 1.2 portrays the option for transmuting defense waste.) The capital cost of such a system would be similar to that discussed for ATW treatment of spent fuel. However, the system probably would not include an option for generating power. If a power facility is not included, start-up costs would be lower. Net operating costs may increase however, because there would be no sale of electricity to help offset the cost of transmutation. DOE defense waste managers have told ATW program officials that they do not consider transmutation to be necessary or cost-beneficial for treatment of the Hanford tank waste.

Phoenix Transmutation System's Estimated Cost and Schedule

Brookhaven National Laboratory (BNL) officials estimate that it might cost as much as $29 billion (1993 dollars) to develop and field a Phoenix system that could transmute radioactive waste. They believe that $20 billion of this estimated cost may be needed to develop the waste separations' technology, including construction of a large spent fuel reprocessing facility to supply the Phoenix accelerator with material to be transmuted. Also included in the estimate are $1 billion to $2 billion to construct the accelerator and $7 billion for a power plant, if they elect to generate and sell electric power. The officials estimate that it would probably take 15-20 years to put this technology on line.

A Scenario for Phoenix Treatment of Existing LWR Spent Fuel

Brookhaven proposes that the Phoenix be used to transmute only the minor actinides (neptunium, americium, and curium) plus iodine-129 but not plutonium. Therefore, the scenario for spent fuel waste treatment in this case is not comparable to that of the ALMR/IFR. In addition, unlike the other concepts, Phoenix officials propose building one large facility that could service the reprocessing of spent fuel from 75 LWRs. Development and construction of this large reprocessing facility would increase the cost of the first Phoenix system compared with the possible cost of first complete systems for the other concepts, but overall the Phoenix might require only one or two total systems compared with perhaps 20 for the others.

According to concept developers, one full-scale Phoenix system could transmute 2.6 metric tons of minor actinides per year. The total inventory of minor actinides built up in LWR spent fuel by 2030, when the current generation of LWRs is expected to cease operation, is expected to be about 58 metric tons. Therefore, one Phoenix could transmute this inventory of minor actinides in about 25 years. The operation might have to be extended somewhat to complete the simultaneous transmutation of iodine-129. Program officials estimate that if a Phoenix transmutation system was fielded and started operation about 2015, the minor actinides and iodine-129 would be disposed of sometime between 2035 and 2050. However, about 817 metric tons of plutonium from the spent fuel would still remain. Brookhaven officials have not estimated what it would cost for the Phoenix to transmute the minor actinides plus iodine-129.

PBR's Estimated Cost and Schedule

Brookhaven National Laboratory officials estimate that it would cost about $1.3 billion (1993 dollars) and take about 16 years to develop and demonstrate the PBR's transmutation capability. This estimate includes the reactor and particle fuel processing and fabrication system but does not include developing the technology and building a facility to reprocess the spent LWR fuel and refabricate it into particle fuel for the PBR.

BNL officials believe that they could build a transmutation demonstration plant by 2010. Then, if this is successful, 20 PBR transmutation systems could be built over the next two decades. An analysis of program data shows that these PBRs could dispose of the LWRs' minor actinide waste by 2050.[6] However, it might take until 2160 to destroy the much larger inventory of plutonium and the fission products, technetium and iodine. BNL officials describe other transmutation scenarios involving as many as 70 PBRs, with correspondingly shorter times required to treat the inventory of LWR spent fuel. PBR program officials have not estimated what it would cost to operate the PBR transmutation system.

[6]PBR program officials were asked to review our analysis and presentation of the data they provided us on their transmutation concept. However, they did not comment. One program official told us that they were occupied with reorganization after the loss of Air Force funding for their program.

CURE System's Estimated Cost and Schedule

The proponents of the CURE concept at Westinghouse-Hanford estimate that a research program to resolve technical issues involved with transmutation would cost between $74 million and $160 million (1993 dollars), depending on the extent of the research. Proponents, however, have not estimated the cost for construction of a transmutation demonstration plant or a fuel-reprocessing facility or the estimated cost of reprocessing and transmuting existing spent fuel inventories.

According to the developer of the CURE concept, the CURE waste treatment proposal is much more ambitious than the other proposals. For example, CURE considers phasing out U.S. nuclear power over a period of about 100 years and using what it calls "cleanup fast reactors" to completely dispose of all spent fuel inventories. Proponents claim that cleanup reactors would reduce the inventories of the fission products technetium and iodine to one percent of their original amounts in less than 100 years.

Conclusions

The cost of developing and implementing the transmutation technology, including developing the process needed to separate light-water reactor spent wastes prior to transmutation, is expected to be high—tens of billions of dollars or more. This cost would be in addition to funding needed to develop and construct a repository, which most agree will still be necessary even with successful transmutation of existing waste. Consequently, proponents of the transmutation of existing spent fuel will have to make a compelling case for the benefits of transmutation in order to compensate for its high additional cost.

Any Practical Application of Transmutation Is at Least Decades Away

A number of problems and circumstances are expected to delay, or even prevent, any practical application of transmutation technology to the existing radioactive waste problem. These include a mixture of opinions on the feasibility and benefit of transmuting existing waste; the high cost and length of time to develop and field a system to process and transmute existing waste; the technical and institutional problems that would have to be overcome; and the lack of funding and apparent lack of interest by DOE's waste managers and representatives of the electric power industry to aggressively pursue the transmutation technology.

Nevertheless, the ability to transmute waste might be a desirable design attribute for any future generation of nuclear power plants that might be introduced, assuming that transmutation could be proved to be technically and economically feasible and assuming that the demand for nuclear power in the United States will continue and increase. With transmutation capability inherent in their design, future generations of nuclear power plants would be able to destroy much of the radioactive waste that they generate.

Mixed Opinions on the Practicality of Waste Transmutation

A mixture of opinions exists on the practicality of developing transmutation technology to treat existing radioactive waste. Those that have concepts (either reactor-based or accelerator-based) to sell, favor pursuing transmutation. For example, ALMR/IFR program officials are now promoting their reactor primarily on the basis of its potential as a radioactive waste burner. Its original stated purpose was as an advanced power reactor that could breed its own fuel. Others, such as accelerator proponents, would also like to see their programs funded. On the other hand, those in DOE who are responsible for the disposal of radioactive waste seem only remotely interested in transmutation of waste and are not supporting transmutation research. They support the direct burial of radioactive waste or possibly, in the case of high-level defense waste, burial after waste separation but not transmutation. These officials point out that promoting transmutation may obscure the fact that the absolute risk of releases of radioactivity from proposed geologic repositories is very low. In addition, DOE's radioactive waste managers are concerned that all the talk about transmutation may raise false hopes about the need for a repository. Most experts agree that, regardless of any successful demonstration of transmutation, a repository will be needed to dispose of residual waste and the multitude of radioactive isotopes that cannot be transmuted. In addition, critics also point out that proposals to transmute existing high-level defense waste and commercial spent fuel may be inconsistent with current national policy that calls for the direct disposal of these radioactive wastes (without recycling or reprocessing) in a deep geological repository.

Critics of transmutation also cite the results of a recent study by the Lawrence Livermore Laboratory strongly questioning the benefits of waste transmutation.[1] This 1992 report, commissioned by DOE's Office of Civilian Radioactive Waste Management, concluded that the pursuit of transmutation involves large costs and few benefits. Much of this same sentiment is echoed in studies conducted by the electric power industry representative—the Electric Power Research Institute (EPRI)—which has concluded that the costs of transmutation would be high, benefits modest, and acceptability by industry and the public questionable.

Implementation Cost and Time May Make Transmutation Impractical for Existing Waste Problem

As discussed in chapter 3, transmutation technology is expected to cost billions of dollars to develop and tens of billions of dollars or more to apply to existing waste and take decades to hundreds of years to complete. Furthermore, a repository (costing as much as $30 billion, according to DOE) would still be needed to store the residual waste from this treatment process. In addition, the fielding of this technology may not be timely enough to have any effect on the design or schedule of a first repository or even, perhaps, a second repository that might be needed for storage of radioactive waste.

Although the schedule for opening a waste repository may slip further into the future, DOE's current plans call for opening a first repository in 2010 and making a decision on the need and schedule for a second repository between 2007 and 2010. Those promoting waste transmutation estimate that, with sufficient funding and an aggressive DOE program, they could develop an initial commercial system and start transmuting waste by about 2015. Then it could take until 2050 to perhaps 2240 (depending on the concept selected and the extent of transmutation to be performed) to treat the spent fuel from existing LWRs that will have accumulated by the year 2030. A first repository is expected to be needed regardless of any successful demonstration of transmutation. Although the development and subsequent application of transmutation to spent fuel waste could conceivably increase the capacity of this repository, DOE probably will not have transmutation technology developed and implemented in time to affect the design and regulations governing the first repository. In

[1] Impacts of New Developments in Partitioning and Transmutation on the Disposal of High-Level Nuclear Waste in a Mined Geologic Repository, Lawrence Livermore National Laboratory, March 1992.

addition, unless DOE aggressively pursues the development of transmutation technology, it may not be a consideration in the design or scheduling of a second repository.

Furthermore, some waste treatment experts believe that once a repository is built and funds are already committed, there may be little justification to pursue the transmutation of existing waste because the repository will already have been certified as able to safely store radioactive waste for thousands of years. In addition, repository proponents believe that once a first repository has been successfully opened, it will be easier and less expensive to open a second, if needed.

Challenges to Developing and Implementing Waste Transmutation

A number of technical and institutional challenges may prevent or at least delay any demonstration of the practical application of transmutation technology. For example, most technical challenges still must be identified, researched, and resolved, because the transmutation concepts are still in their early stages. Furthermore, institutional challenges, including licensing requirements and public acceptance, must be overcome before DOE can field any transmutation system.

Technical Challenges to Fielding a Transmutation System

All of the transmutation options, except the ALMR/IFR, are at a very early conceptual stage and are essentially unfunded. If funded, they must overcome all of the technical challenges inherent in developing a new technology. Although the ALMR/IFR concept is further developed, program officials must overcome major technical challenges. For example, ALMR/IFR program officials must demonstrate the economic and technical feasibility of the proposed ALMR/IFR fuel cycle, including reprocessing, refabricating, and reburning spent fuel wastes. ALMR program officials believe that their proposed pyroprocessing system will be more economical and more efficient than existing aqueous processing methods. The demonstration of the ALMR/IFR's fuel cycle capability must be thorough enough to convince industry to support the ALMR/IFR.

Since the proposed ALMR/IFR transmutation of waste depends on the successful development and demonstration of the ALMR/IFR as a power reactor, a number of technical challenges to the ALMR/IFR's power generation system also need to be resolved. For example, in order to gain industry support for the ALMR/IFR, DOE must demonstrate that it will be safer and more economical to build and operate than current and planned advanced light-water reactors. This includes demonstrating that the metal fuel that DOE plans to use in the ALMR/IFR is superior to other types. Some, including EPRI, are not convinced that metal fuel is the best fuel to use in a liquid-metal-cooled reactor. EPRI points out that much research and demonstration remains to be done before the nuclear power industry will accept the metal fuel.[2] In addition, further testing of the fuel may be difficult because DOE's test facilities at the Argonne West Laboratory in Idaho may be shut down or perhaps cut back as a cost-savings measure. In addition, DOE earlier shut down its other fuels-testing facility (the Fast Flux Test Facility) at the Hanford Reservation. DOE officials said that testing the fuel in other countries is an option if the Argonne test facility is not available.

EPRI has stated that development and demonstration of metal fuel along with other components, such as steam generators for a liquid-metal reactor power plant, are crucial to industry acceptance of the ALMR/IFR. In its interim report on the ALMR/IFR, the National Research Council, like EPRI, suggests that the ALMR/IFR not be fielded under the guise of its transmutation capability; instead, it should be justified on the basis of a demonstration that it is safer and more economical to operate than light-water-cooled reactors. The Manager of Argonne's IFR program agrees that the ALMR should first prove its merits as a future generation power reactor and is confident that it eventually will, if sufficient funding is obtained.

Institutional and Public Challenges to Fielding a Transmutation System

Because of the lack of popularity of nuclear power in the United States and other institutional and economic barriers, utility companies have not ordered any new reactors for over a decade—the growth of nuclear power in the United States has stopped. In addition, DOE is finding it difficult to establish an interim storage facility and a permanent disposal repository for radioactive waste because of public opposition. Furthermore, there is no guarantee that transmuting waste and thus reducing the radioactivity and volume of waste to be disposed of would make the repository or the use of nuclear power any more acceptable to the public.

Any attempt to field a transmutation system can be expected to encounter similar opposition. Transmutation involves developing, constructing, and licensing a variety of nuclear facilities. New technology reactors and/or accelerators and reprocessing facilities must be acceptable to government institutions and the public. New licensing standards may have to be developed for these new technology facilities. Under some waste

[2]The industry standard is an oxide-based nuclear fuel, not metal fuel.

transmutation scenarios, about 20 systems containing a number of facilities would have to be constructed and licensed. In addition, and perhaps more controversial, a number of facilities that reprocess nuclear materials, including plutonium, would have to be established and licensed. The reprocessing of commercial spent fuel has been institutionally and publicly unacceptable in the United States at least since the 1970s because of perceived nuclear materials proliferation and public-risk concerns. This policy against reprocessing commercial fuel was reiterated by the administration as recently as September 1993.

DOE Has Little Interest in Transmuting Existing Radioactive Waste

DOE's waste management groups have not supported the funding of transmutation research because, as discussed above, they consider it unnecessary and uneconomical for the treatment of the existing radioactive waste problem. DOE's Nuclear Energy Office is the only DOE group providing any funding for transmutation research, and this is only for the ALMR/IFR concept. This funding helps to keep the nuclear energy group's main program—the development of a liquid-metal fast breeder reactor—alive. The administration and some members of the Congress tried to terminate funding for the program for fiscal year 1994, but the Congress enacted $145 million to support the program for the fiscal year. The administration immediately sought to rescind much of this funding. DOE program officials expect that obtaining future funding for the ALMR/IFR will continue to be difficult. These officials said that without full funding, the program will be pushed off further into the future, by as much as several decades or, perhaps, never finished.

No office in DOE has championed any of the other transmutation concepts, nor have they received significant funding. Some of the concepts have obtained small amounts of discretionary funding[3] support from their respective laboratories to maintain a small effort.

Possible Future Benefits of a Proven Transmutation Technology

Although opinions are mixed on the feasibility and practicality of transmuting highly radioactive defense waste and the spent fuel from current commercial nuclear reactors, many in the nuclear field agree that the capability to transmute waste would be an attractive design attribute for any future generation of nuclear power plants. This capability would allow nuclear power plants to burn much of their own waste and thus reduce the volume of high-level waste that would need to be buried.

[3]These laboratory discretionary funds are actually part of the overall funding that a laboratory receives from DOE each year.

Eventually it might lead to down-sizing repositories, building fewer of them, or even using nongeological ways of safely disposing of waste. Those holding this opinion caveated their statement with an assumption that the technical, economic, and institutional problems to implementing radioactive waste transmutation could eventually be overcome and the use of nuclear power would continue and eventually expand in the United States. For example, the manager of Argonne's IFR portion of the ALMR/IFR program has stated publicly that development of waste transmutation technology should be pursued only if it is believed that nuclear power will increase in the United States.

Conclusions

If nuclear power continues to be used in the United States and if waste transmutation could be proved technically and economically feasible, not as much long-lived radioactive waste would be produced if future power needs are met by using a new generation of power producers that are designed to economically burn their own waste. However, at this point, it appears that it may not be practical to pursue transmutation primarily to address the existing radioactive waste problem. A number of constraints are expected to slow or prevent practical application. These include current funding constraints and the high cost and long time needed to develop and implement transmutation; the technical, institutional, and public challenges that would need to be overcome; and, perhaps most important of all, DOE waste managers', industry representatives', and others' belief that transmutation is not necessary or cost-beneficial. DOE's consideration of these constraints and the forthcoming results of the National Research Council's study on waste separation and transmutation may provide DOE with guidance on how and to what extent to pursue transmutation technology.

Major Contributors to This Report

Resources, Community, and Economic Development Division, Washington, D.C.

Jim Wells, Associate Director
Robert E. Allen, Jr., Assistant Director
Jack H. Paul, Evaluator-in-Charge
William J. Mohan, Evaluator

Glossary

Accelerator	A device that increases the velocity and energy of charged particles, such as electrons and protons; also referred to as a particle accelerator. In a "linear" accelerator, particles are accelerated in a straight path.
Actinides	The elements with atomic numbers above 88 (actinium, element 89). The actinide series includes uranium, atomic number 92, and all the man-made transuranic elements. See "transuranic."
Atom	A particle of matter indivisible by chemical means. The smallest unit of a chemical element, approximately 1/100,000,000 inch in size, consisting of a nucleus surrounded by electrons.
Atomic Nucleus	The central core of an atom, made up of neutrons and protons held together by a strong nuclear force.
Breeder Reactor	A nuclear reactor that produces more fissionable fuel than it consumes.
Critical	Capable of sustaining a nuclear chain reaction.
Decay Heat	The heat produced by the decay of radioactive nuclides.
Fast Breeder Reactor	A fast reactor that produces more fissionable material than it consumes. See "fast reactor."
Fast Neutrons	Neutrons with energies greater than 100,000 electron volts (considered very high energy).
Fast Reactor	A reactor in which the fission chain reaction is sustained primarily by fast neutrons. See "fast neutrons."
Fission	The splitting of a nucleus into two approximately equal parts, which are nuclei of other elements, accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously but usually is caused by nuclear absorption of neutrons.

Fission Products	The radioactive fragments (by-products) formed by nuclear fission in a reactor—the "ash" of nuclear power production. Technetium and iodine radioisotopes are examples of fission products found in spent fuel.
Fuel	Fissionable material used or usable to produce energy in a reactor.
Fuel Cycle	The series of steps involved in supplying fuel for nuclear power reactors. It includes mining, refining, enrichment, original fabrication of fuel elements, their use in a reactor, chemical processing to recover fissionable material remaining in spent fuel, enrichment of the fuel material, and refabrication into new fuel elements. Waste disposal is a final step.
Fuel Reprocessing	The chemical or metallurgical treatment of spent (used) reactor fuel to recover the unused fissionable material, separating it from radioactive waste. The fuel elements are chopped up and chemically dissolved. Plutonium and uranium and possibly other fissionable elements are then separated out for further use.
Half-Life	The period of time required for the radioactivity of a substance to drop to half its original value; the time that it takes for half of the atoms of a radioactive substance to decay. Measured half-lives vary from millionths of a second to billions of years.
Isotope	An isotope of an element is one of two or more forms of the element that differ in their atomic weights (number of neutrons in the nucleus of the element).
Light Water	Ordinary water.
Linear Accelerator	A long straight tube (or series of tubes) in which charged particles (ordinarily electrons or protons) gain in energy by action of oscillating electromagnetic fields.
Minor Actinides	The transuranic elements minus plutonium. Usually this term is used to refer to neptunium, americium, and curium. Some also refer to these as

the "minor" transuranics. Plutonium is the dominant transuranic, but these minor transuranics contribute comparable radioactivity in spent fuel.

Neutron
An uncharged particle with a mass slightly greater than that of a proton. The neutron is a strongly interacting particle and a constituent of all atomic nuclei except hydrogen.

Nuclear Reaction
A reaction involving a change in an atomic nucleus, such as fission, fusion, neutron capture, or radioactive decay, as distinct from a chemical reaction, which is limited to changes in the electron structure surrounding the nucleus.

Nuclear Reactor
A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential component is a core containing fissionable fuel. It is sometimes called an atomic "furnace"; it is the basic machine of nuclear energy.

Nucleus
The central core of an atom, made up of neutrons and protons held together by nuclear force.

Nuclide
Any species of atom that exists for a measureable length of time. The term is used synonymously with isotope. A radionuclide is a radioactive nuclide.

Proton
A particle with a single positive unit of electrical charge and a mass that is approximately 1,840 times that of the electron. It is the nucleus of the hydrogen atom and a constituent of all atomic nuclei.

PUREX Process
The plutonium and uranium extraction (PUREX) process is an aqueous process used in several foreign commercial and U.S. defense programs for separating out elements in spent nuclear fuel.

Pyroprocessing
Nonaqueous processing carried out at high temperatures. An example of this is the relatively new technology being developed for reprocessing

spent fuel mainly from liquid-metal reactors that would use a metal alloy fuel, as opposed to the oxide-based fuel that is used in current commercial reactors. It consists of three steps: electrorefining to separate the useful fuel materials (including actinides) from the radioactive fission products; cathode processing, which further purifies the metal product of the electrorefining; and injection casting to refabricate the reclaimed useful fuel materials into new fuel rods.

Radioactive

Referring to the spontaneous transformation of one atomic nucleus into a different nucleus or into different energy states of the same nucleus.

Radioactive Decay

The spontaneous transformation of one atom into a different atom or into a different energy state of the same atom. The process results in a decrease, with time, of the original number of radioactive atoms in a sample.

Radioactive Waste

Equipment and materials (from nuclear operations) which are radioactive and for which there is no further use. The waste is generally classified as high-level, low-level, or transuranic, depending on the composition and intensity of the radioactive constituents.

Radioisotope

A radioactive isotope. An unstable isotope of an element that decays spontaneously, emitting radiation. Radioisotopes contained in the spent fuel resulting from the production of nuclear power generally fall into two categories: fission products and transuranic elements (known as transuranics, actinides, or TRU), and activation products produced by neutron absorption in structural materials in the spent fuel.

Recycling

The reuse of fissionable material, after it has been recovered by chemical processing from spent reactor fuel.

Spent Fuel

Nuclear reactor fuel that has been irradiated (used) to the extent that it can no longer effectively sustain a chain reaction and therefore has been removed from the reactor for disposal. This irradiated fuel contains fission products, uranium, and transuranic isotopes.

Subcritical

Not capable of sustaining a nuclear chain reaction, but involving some degree of multiplication of neutrons.

Target

Material subjected to particle bombardment (as in an accelerator) in order to induce a nuclear reaction.

Thermal Neutrons

Low-energy neutrons that have come to thermal equilibrium with the material in which they are moving. Most have energies of less than a few tenths of an electron volt. Current commercial reactors use thermal neutrons.

Transmutation

The transformation (change) of one element into another by a nuclear reaction or series of reactions.

Transuranic

An element above uranium in the Periodic Table of elements—that is, one that has an atomic number greater than 92. All transuranics are produced artificially (during a man-made nuclear reaction) and are radioactive. They are neptunium, plutonium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium.

TRUEX

A chemical solvent process under development to extract transuranics from high-level waste.

Waste Separation

The dividing of waste into constituents by type (for example, high-level, low-level) and/or by isotope (for example, separating out plutonium and uranium). The waste may be separated by a chemical solvent process such as PUREX or by any of a number of other chemical or physical processes.

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