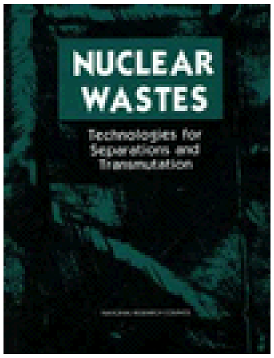
Free Executive Summary



Nuclear Wastes: Technologies for Separations and Transmutation

Committee on Separations Technology and Transmutation Systems, National Research Council

ISBN: 978-0-309-05226-9, 592 pages, 8.5 x 11, hardback (1996)

Disposal of radioactive waste from nuclear weapons production and power generation has caused public outcry and political consternation. Nuclear Wastes presents a critical review of some waste management and disposal alternatives to the current national policy of direct disposal of light water reactor spent fuel. The book offers clearcut conclusions for what the nation should do today and what solutions should be explored for tomorrow. The committee examines the currently used "once-through" fuel cycle versus different alternatives of separations and transmutation technology systems, by which hazardous radionuclides are converted to nuclides that are either stable or radioactive with short half-lives. The volume provides detailed findings and conclusions about the status and feasibility of plutonium extraction and more advanced separations technologies, as well as three principal transmutation concepts for commercial reactor spent fuel.The book discusses nuclear proliferation; the U.S. nuclear regulatory structure; issues of health, safety and transportation; the proposed sale of electrical energy as a means of paying for the transmutation system; and other key issues.

Executive Summary

For over three decades, nuclear technologists have sought to develop practical methods for the safe management and disposal of highly radioactive wastes containing long-lived radionuclides. Some of the proposed solutions have focused on separating the hazardous long-lived radionuclide components of the waste and transmuting them by neutron bombardment to form nuclides that would be either stable or radioactive with a much shorter half-life. The Department of Energy's (DOE) financial support has been given in the past and/or sought for in the future by several proponents with proposals to develop separations technology and transmutation (S&T) systems. The Committee on Separations Technology and Transmutation Systems (STATS) of the National Research Council was formed at the request of DOE to evaluate the state of the art of S&T concepts. The purpose is to determine if S&T alternates offer advantages over the current government policy for the disposal of commercial spent fuel arising from the "once-through" light-water reactor (LWR) fuel cycle. The committee, in further fulfillment of its mandate, also reviewed processing options for the safe management of high-level waste (HLW) generated by the defense programs, in particular, addressing the special problems in dealing with such wastes at the DOE facility in Hanford, Washington.

THE "ONCE-THROUGH" FUEL CYCLE

The present national plan is to store and "decay cool"[1] the spent fuel at reactor sites for a decade or more and then to ship it to a monitored retrievable storage (MRS) facility where it would be temporarily stored and eventually encapsulated and shipped to a geological repository. It is called the "once-through" fuel cycle because the spent fuel is not reprocessed and thus not recycled. All the other fuel cycles involving S&T systems reviewed in this report require reprocessing with its associated implications.

An advantageous feature of the direct disposal of the spent reactor fuel in a repository without reprocessing is that if reducing conditions exist in the repository, the actinides are not readily moved in groundwater pathways; they are quite insoluble under such conditions. However, for some invasive scenarios, e.g., human intrusion or under oxidizing conditions in the repository, actinide release may occur from the repository and cause some risk. Otherwise, the principal doses to humans after long periods of time are due mainly to the fission products technetium (^{99}Tc) and iodine (^{129}I) that are water soluble and so are moved through groundwater pathways.

Currently, DOE is examining a site at Yucca Mountain, Nevada, to determine if it can be licensed as the first HLW repository. The U.S. Nuclear Regulatory Commission (NRC) regulations for a licensed repository require that the encapsulation of the spent fuel remain effective for at least 300 to 1,000 years, which is a subordinate requirement to the longer limits on release rates—typically 10,000 years or more. By statute,[2] the first repository is limited to a loading of 70,000 Megagrams of heavy metal (MgHM) until a second repository begins operation. Current designs call for 62,000 MgHM of the total capacity to be allocated for the commercial LWR spent fuel expected to be produced by the year 2010. This capacity will provide for approximately 60% of the spent fuel expected to be discharged from the

[1] During the storage period, some of the short lived heat emanating radionuclides will decay, thus reducing considerably the heat output from the spent fuel.

[2] The U.S. policy governing the disposition of spent fuel from commercial reactors is provided by the Nuclear Waste Policy Act of 1982 and the Nuclear Waste Policy Amendments Act of 1987.

existing LWRs. The rest of the capacity would be devoted to vitrified defense HLW. This capacity is not expected to be sufficient for the disposal of the total amounts of defense wastes produced. By coincidence, it happens that the 62,000 MgHM happens to be the amount to be produced in the spent fuel of the LWRs by the year 2010.

THE S&T CONCEPTS

The committee has reviewed the three principal transmutation concepts for commercial reactor spent fuel for which considerable information is available. These concepts use a light-water reactor (LWR), an advanced liquidmetal reactor (ALMR), or an accelerator-driven subcritical nuclear reactor concept for producing neutrons called the accelerator transmutation of waste (ATW). Two other proposals, the particle bed reactor (PBR) and the Phoenix accelerator-driven reactor concept, did not have sufficient detail for an adequate comparison with the principal three. The sixth proposal, the Clean Use of Reactor Energy (CURE), is a study of S&T with fast reactors and LWRs, and does not rely on one specific transmutation scheme. The PBR, Phoenix, and CURE concepts are discussed in the appendices but do not appear in any detail in the main report. However, the issues raised by the PBR and Phoenix proposals and the CURE study are covered in the evaluation of the principal three concepts.

In comparing the principal concepts, the committee assumes that the mission of each is to provide for preparation and transmutation of about 600 Mg of transuranics (TRUs) contained in the 62,000 MgHM of existing LWR spent fuel, as well as packaging and storage of selected fission products contained in the accumulated spent LWR fuel that is otherwise destined for the first geologic repository. The LWR and the ALMR concepts are also evaluated for their abilities to transmute only the plutonium fraction of the TRUs. The prospective benefits and deficiencies for waste disposal of such evaluations are examined for the full S&T and for the once-through LWR fuel cycle.

To develop some figures of merit for comparison among the different S&T concepts, the committee looked at two different scenarios relative to the present once-through LWR fuel cycle. The first, called the declining nuclear power or "phase-out" scenario assumes that the TRUs and selected fission products are transmuted and that all nuclear facilities are shut down as quickly as practicable, consistent with S&T requirements. The second, called the continuing nuclear power scenario, assumes that the amount of nuclear power in the United States stays constant, i.e., at about its present level of 100 GWe. In that scenario, some fraction of the reactors would be operated to transmute the TRUs in the accumulated LWR spent fuel, but with some continuing TRU production. These alternate scenarios are analyzed to indicate the implications of transmutation on the power profiles and TRU inventories in the fuel cycle over time and the implications for waste disposal.

OVERALL CONCLUSIONS

The committee found no evidence that applications of advanced S&T have sufficient benefit for the U.S. HLW program to delay the development of the first permanent repository for commercial spent fuel. The committee believes that the thermal neutron flux of a LWR and the fast flux of an ALMR could be used to transmute the TRU isotopes in spent reactor fuel. If the proposed ATW could operate with the currently proposed characteristics, its thermal flux would also be effective in the transmutation of the TRUs. The fission products ^{99}Tc and ^{129}I could also be transmuted by either the LWR or the ATW. The high thermal flux of the ATW would be an advantage in this process. Although a significant fraction (90 to 99%) of many of the most troublesome isotopes could be transmuted, this reduction of key isotopes is not complete enough to eliminate all the process streams containing HLW, so the need for a HLW repository is not eliminated. However, the total HLW storage capacity required would be reduced. Transmutation, thus, would have little effect on the need for the first repository.

In view of the above, the committee concluded that the once-through LWR fuel cycle should not be abandoned. Further, this has the advantage of preserving the option to retrieve energy resources from the wastes for an extended period of time. This can be achieved by adopting a strategy that will not eliminate access to the nuclear fuel component of the waste for a reasonable period of time, say about 100 years, or by preserving easy access to the repository for a prescribed period of time, or by extending the operating period of the repository.

A reason for supporting continued use of the once-through fuel cycle is that it is more economical under current conditions. Some analysts predict that future demand for uranium—and as a consequence its price—may increase to a point where recycling becomes economically competitive. Should this happen, the choice of once-through fuel cycle would have to be reexamined (see Appendix F).

The committee concludes that over the next decade the United States should undertake a sustained but modest and carefully focused research and development program on selected S&T technologies, with emphasis on improved separations processes for separating LWR and transmuter fuels beyond the existing plutonium and uranium extraction (PUREX) process and for fuels containing more actinide elements and selected fission products. These conclusions apply for either the continuing or phase out modes of the S&T systems.

DETAILED FINDINGS AND CONCLUSIONS

Findings Regarding Potential Radiological Effects of S&T

Thermal neutrons produced by an LWR or ATW could reduce the amount of ^{99}Tc and ^{129}I and thus reduce long-term doses from repository water pathway releases. The fast neutrons from the ALMR do not effectively transmute these two long-lived fission products. However, modifications of core design involving specially moderated fuel assemblies could reduce the fission product inventories of these two fission products.

The transmutation of actinides using an LWR, ALMR, or ATW could reduce the doses from repository water pathway releases. To the extent that reducing conditions dominate within or very close to the waste package, the actinides are expected to be insoluble and the doses so small that transmutation would have little effect. If oxidizing conditions were to dominate within a waste container and externally, neptunium might be sufficiently soluble so that transmutation could reduce neptunium doses substantially (see chapter 2 and Appendix G for details).

The transmutation of actinides using an LWR, ALMR, or ATW could reduce the repository doses resulting from certain invasive scenarios, e.g., volcanoes, human intrusion, etc. Many of these scenarios can also be dealt with to some extent by the choice of disposal site and repository designs. It must be recognized that this approach requires the balancing of many attributes.

To the extent that actinides are used as reactor fuel, the amount of uranium that needs to be mined, and therefore short-term radiation exposures from mining and milling, will be reduced. However, there will be a short-term increase in radiation exposure from reprocessing and other fuel-cycle activities not part of the once-through cycle. The population doses from each of these sources are thought to be small compared to natural background doses.

If the radioisotopes of concern were separated from the spent fuel and incorporated into a waste form better than spent fuel, reductions in long-term dose may be possible. This would involve the chemical processing needed to prepare insoluble compounds of the radionuclides of interest and integrating them into glass or some other matrix. All of this may be within the capability of modern chemical technology, but remains to be demonstrated. Qualification of a new waste form would require a significant research and development effort.

Conclusion Estimates of changes in dose from any of the above actions are small. The National Council on Radiation Protection and Measurements estimates 0.3 latent cancer fatalities/GWe-yr from the whole LWR fuel cycle. The estimate of the Oak Ridge National Laboratory for the dose reduction is 0.06 cancer fatalities/GWe-yr from the whole LWR fuel cycle. These calculations include a dose commitment integrated 1,000 years into the future from milling operations (see Chapter 6). Taken alone, none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation.

Findings Regarding Separations Technology

Separations Technology Requirements for ALMR and LWR

For aqueous separations a combination of PUREX solvent extraction processes for actinides up to plutonium followed by a TRU extraction process for actinides above plutonium (TRUEX) could be used. Further research and development would be required before an economic commercial-scale TRUEX-like plant for S&T applications could be built.

If the proposed S&T systems' goal of eliminating HLW were to be achieved, the overall process losses would have to be reduced below those of current commercial systems.

ALMR/IFR proposes to develop pyroprocessing of ALMR and LWR spent fuel to reduce cost. The process has been demonstrated on a few kilogram scale for metallic fuel. Work has been done on gram quantities of simulated UO_2 fuel. Work on pyroprocessing of kilogram amounts of UO_2 continues in order to determine if the desired savings can be achieved.

Some remaining problems of pyroprocessing of UO_2 are conversion of oxide to metal, separation of cladding, and processing low concentrations of TRU.

Promising work is under way on improved separations systems. As yet none has been tested at the pilot-plant scale (details in Appendix D).

Separations Technology Requirements for the ATW

The goal of ATW is to transmute the inventory of radioactivity so all TRU waste leaving the site could be treated as LLW. The program calculates that process losses of 0.02% for plutonium and neptunium, and 0.0003% for americium and curium, must be achieved for both the LWR spent fuel and the on-line reprocessing system to be successful. To date, such levels have not been achieved on a commercial scale.

The aqueous ATW has very short cooling times so the separations must take place in very high radiation fields that would cause serious degradation of both water and organic agents. Processing using molten metals or salts avoids the problems of radiation degradation because these systems are very resistant to radiation damage.

Other severe problems are shared by both the aqueous and molten-salt processing proposals. They include severe decay heating from some of the separated actinides and nonuniform phase and thermal mixing in both slurry and molten salt.

Conclusion A number of the LWR and ALMR goals that depend on separations technology have yet to be fully demonstrated. Of particular importance is a reduction in the overall process losses during separations. Thus, research and development in separations technology must be an essential part of any program to develop S&T.

For ATW, processes based on molten-salt and molten-metal systems are very radiation-resistant and would not be subject to radiation-induced reagent degradation as is the case for aqueous systems. The ATW separations concepts that have been proposed are beyond demonstrated technology and are questionable in the intermediate term.

It is improbable that the ATW system would be able to achieve the goal of no long-lived HLW output because the unavoidable process losses would lead to contamination of various parts of the system. Eventually, these items would have to be treated as HLW or treated by additional expensive processes.

Findings Regarding Transmutation Technology

Current Status of LWR, ALMR, and ATW

The LWR has several thousand reactor years of experience as a power generator. If fission product transmutation were to be done using LWRs, modifications would be mainly in the fuel cycle and blanket. There would be a high level of confidence that the system would meet design objectives.

The ALMR would be based on breeder reactor technology that has been under development for over three decades. Design and prototype experience are sufficient to allow a high degree of confidence that a successful transmuter could be designed and built. Considerable research and development would be required (1) to assure that the low breeding ratio of a burner would not create safety problems and (2) to assure that the changes in fuel composition caused by burn-up would not adversely affect performance and safety.

The ATW system offers a higher burn-up rate but has a design that departs from previous experience by wide margins in a number of areas. These include on-line reprocessing of fluid targets, fluences of energetic particles yielding 100 displacements per atom, and very high thermal neutron fluxes: greater than 10^{15} neutrons/cm^2s. The designers of the ATW propose either slurry or molten-salt systems. Both types have had serious materials problems at the end of their abbreviated development programs. The target and the subcritical assemblies must dissipate as much as 8,000 MW of thermal power, raising difficult cooling problems.

Conclusion The ATW is in a far less developed state than the LWR or the ALMR. To prove the viability of the concept would require extensive research and development. Some of the design criteria are at the limits of what has been achieved. The system includes a large accelerator to produce neutrons, an 8,000-MW subcritical reactor, an on-line reprocessing system, and the operation of a 1,600-MWe power plant. To achieve reasonable on-line availability of such a system would be a major challenge.

Relative Capabilities of the Concepts for TRU Transmutation

Since TRUs can be transmuted in either a fast or thermal neutron spectrum, any of the three concepts could be used to transmute TRUs. The neutron source of choice will depend upon the composition of the TRUs and the desired end point of the irradiation. Some of the important considerations are discussed below. It should be noted that the transmutation of long lived fission products (e.g., ^{99}Tc and ^{129}I) is most readily accomplished by thermal neutrons from the LWR and ATW concepts. It would be possible, however, to have a neutron moderating target region in a ALMR to transmute these fission products.

ALMR

The ALMR transmuter has been proposed to reduce the amount of TRUs in waste below the limiting amount that could be released to the environment according to Environmental Protection Agency (EPA) standard 40CFR191—until recently the assumed standard for a Yucca Mountain repository.[3] For ^{239}Pu, the most abundant radionuclide to be transmuted, the corresponding amount proposed in the waste would be less than 0.03% of that in LWR spent fuel. The ALMR/IFR project has not described how such low losses could be attained in any of its published reports.

For the ALMR, the limiting breeding ratio is 0.65; below this, there may be safety problems because of a positive void reactivity coefficient. For an ALMR with a 0.65 breeding ratio and fueled with TRUs from LWRs for the constant power scenario, it would take about two centuries of operating time to reduce the inventory of the residual TRUs to about 1% of the inventory in the reference LWR once-

[3] Although the EPA 40CFR191 standard no longer applies to the proposed Yucca Mountain repository, it is possible that such release limits, or the equivalent thereof, could still become part of the new standard. Also, the ALMR/IFR project makes the assumption that EPA release limits applicable to LWR spent fuel could be used as such for HLW generated in transmutation.

through fuel cycle of the same electrical power. The first century of constant-power operation could reduce the TRU inventory fraction to about 14% of the original. In a declining power scenario, the TRU inventory fraction could be reduced to as low as 9% in 100 years.[4]

LWR

To achieve the EPA standards of 40CFR191 for a constant power scenario, the LWR transmuter would require slightly less time than would the ALMR of 0.65 breeding ratio. However, the lower per-cycle processing loss required for americium and curium would be less than is achievable with present technology. In the declining nuclear power scenario the LWR transmuter could similarly reduce the actinide inventory fraction to about 9% in 100 years.

The length of time to reduce TRU inventories in a plutonium-burning LWR relative to the once-through LWR fuel cycle would be shorter than that for the nonbreeding ALMR.

ATW

The ATW depends on very low per-cycle process losses to achieve a high TRU inventory reduction. However, the frequent processing of the fluid fuel will result in the build-up of plutonium and neptunium in the ATW waste to as much as 0.4% of that in the spent-fuel waste of the reference LWR once-through fuel cycle of the same electrical power production capacity.

It is estimated to take 1,400 years and 90 years, respectively, for the constant and declining power (phase-out) scenarios to reduce the TRU inventories in the aqueous ATW reactor to the levels required by EPA standards. For the nonaqueous ATW the corresponding times would be 350 years at constant power and about 50 years with declining power.

The inventories of residual plutonium, neptunium, americium, and curium in the ATW reactor systems would require disposal in a geologic repository, as would other ATW waste such as Zircaloy pressure tubes from the aqueous ATW.

It would be impossible for ATWs to effectively eliminate all long-lived radionuclides to a degree that important residual radioactivity would persist no longer than a human lifetime as has been asserted by the ATW proponents.

Conclusion The proposed S&T systems require many decades to centuries to achieve a significant net reduction in the total TRU inventory relative to that of a once-through LWR fuel cycle. Comparing S&T systems using LWRs, ALMRs, and ATWs of the same electrical power production capacity, the ATW projects the highest TRU consumption rates. TRU consumption rates for an ALMR increase significantly as its breeding ratio is lowered to 0.65 from the conventional value near unity. The LWR—specially designed for burning plutonium— would have a net TRU consumption rate similar to an ALMR of 0.65 breeding ratio. As an alternative to S&T of all TRUs, reprocessing the LWR spent fuel and recycling only the plutonium to LWRs or ALMRs—using improved low-loss waste forms for the other HLW constituents—would be simpler and perhaps somewhat less expensive to implement.

Findings Regarding Feasibility, Development, and Deployment

LWR

Current LWR designs could be modified for transmutation of most actinides and the more troublesome fission products. This system has the shortest time and lowest cost to complete development and full-scale demonstration of technical performance and system costs—about 8 to 10 years at a level of effort very roughly estimated at perhaps $50-$100 million per year, exclusive of the cost of construction of any major test facilities.

ALMR

The ALMR, under development for decades as a fast breeder reactor, could be modified to operate as a TRU transmuter. Transmutation of fission products is not practical with an ALMR. An ALMR/IFR with integral pyroprocessing of its spent fuel has not yet been demonstrated at pilot-scale, but it may be more economical than an aqueous system. Considerable experimental and calculational effort at breeding ratios of less than unity (required for actinide burning) would be necessary to develop the proposed ALMR/IFR concept.

Compared to an LWR, an ALMR/IFR has a somewhat higher cost to complete development and demonstration—about 15 to 20 years at a level of effort very roughly estimated at twice the cost of LWR per year, exclusive of the cost of construction of any major test facilities. This falls between the LWR and ATW estimates.

ATW

The ATW poses major engineering and materials challenges due to the extraordinary operating conditions in the reactor and beam target. Heat removal is a major issue for development as well as for safety and licensing. Also, the possibility of reactor transients, unevaluated in any detail at

[4] The "inventory reduction fraction" is the ratio of the TRU inventory in the transmuter, fuel cycle, and waste to that in the spent fuel of a reference LWR once-through fuel cycle of the same electrical production.

present, may require means of reactivity control beyond that afforded by merely turning off the accelerator. The ATW concepts use fluid fuels, which involve unproved technologies for fuel fabrication and on-site reprocessing and which raise a number of operational and safety issues for which detailed analyses have not yet been done. Questions have been raised about whether it would be simpler to make the subcritical assembly a critical assembly, thus eliminating the need for the accelerator and beam target and resulting in simpler core designs and more economical systems (see Chapter 4). Extensive research and development would be required even to ascertain whether an ATW is technically feasible. If found to be so, the ATW may require more than 20 years of development at an uncertain but relatively higher cost for development and full-scale demonstration.

Time Scale for Deployment. Assuming that development can be completed and that favorable institutional arrangements can be achieved, the licensing, construction, and initial operation of an S&T system based on LWRs or ALMRs of sufficient scale to *begin* to affect spent-fuel emplacement in a geologic repository would require one to two decades after a demonstration of system feasibility.

To permanently achieve the benefits of S&T to the repository and nuclear fuel cycle, the system would have to operate for many decades. If the system was not producing the desired results and it was decided to stop transmutation, it may, in principle, be possible to convert the LWRs and ALMRs in service back to the most optimum fuel cycle. In this case, some of the investment in reactors may not be lost. However, the recycling equipment, including the reprocessing plants, fuel fabrication facilities, and other equipment might be a loss. In addition, it is doubtful that ATWs would be used for electricity production in view of the very low thermal efficiency attainable.

Conclusion The S&T systems differ widely in their state of technological maturity and present a broad spectrum of development issues, risks, costs, and schedules. The most mature system concept for transmuting TRUs, that which uses LWRs, needs fuel-cycle development and would require about a decade and significant financial resources to reach the point of deployment. Compared to the LWR system, an ALMR/IFR system for transmuting TRUs would require more financial resources and take longer, perhaps a decade and a half, to reach the point of deployment. The ATW concepts require major development before the chances of success can be realistically assessed. An S&T system of appropriate scale must be operated for many decades to achieve the permanent benefits to the repository and other parts of the nuclear fuel cycle. If S&T operations were shut down early, facilities related to recycling (i.e., reprocessing and refabrication plants) are likely to be a loss.

Findings Regarding System Integration

The Nature of an S&T System

An S&T system capable of having a significant effect on the waste disposal problem would require a number of large nuclear facilities. The facilities needed include 10 to 20 transmuting nuclear reactors that would substitute for a like number of once-through LWRs, so that the total amount of electricity production would be the same. In addition, one or two reprocessing plants, remotely operated fuel fabrication capacity, and waste-packaging facilities would be required. Mechanisms for transportation between the facilities would have to be developed and implemented. Since the feedstocks of one part of the system are dependent on the output of the other parts, efficient operation will depend on integrated operation of the various parts. Those feedstocks that are in transit or storage are not being irradiated, and therefore, the overall transmutation rate is lowered. The usual practice of maintaining a stockpile of feedstock between the stages in the process will thus incur a penalty in transmutation rate. For this reason, integrated operation of the system to maximize the plant transmutation rate will be a difficult problem.

Conclusion An S&T system would require integrated operation of a number of facilities: about 80 LWRs, 20 transmuters, 2 reprocessing plants, and a few refabrication plants as compared to about 100 LWRs in the once-through system. The integrated operation of the system for the optimum transmutation rate will present an additional difficult problem for the S&T cycle.

Findings Regarding Economics

Issues

Implementation of an S&T system for nuclear waste burning would cost more for the same electrical production capacity than the corresponding system using the same type of reactor but optimized for power production. This occurs because (1) reprocessing would be required for a transmutation system but not necessarily for a system without transmutation, (2) reprocessing would be made even more expensive than normal recycling of uranium and plutonium because of the need to recover additional elements (e.g., neptunium, iodine, technetium), and (3) the need to operate a transmutation device with a lower breeding ratio than would be adopted for operation without transmutation. The most sensitive incremental cost factor at present is that of reprocessing spent LWR and other fuel to feed the S&T system.

Implications of Fuel Reprocessing Costs

The committee's review of cost data for reprocessing LWR spent fuel yielded an estimate of unit costs of $810 to $2,110/kg, depending on the type of financing and assuming construction in the United States (see Chapter 6). The Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA/OECD) estimated that a reprocessing cost of $720/kg would result in a 14% increase in fuel-cycle cost of LWRS, as compared to a once-through fuel cycle, assuming government-type financing in Europe. The reprocessing cycle would add about 0.8 mill/kWh to the generating cost and about 1.5% in the total generating cost of wholesale electricity (i.e., busbar cost of electricity).

Studies of the actinide-burning fuel cycle supported by the U.S. Department of Energy have included cost estimates based on reprocessing facilities owned and financed by private capital. Consequently, the cost of reprocessing facilities, the fuel-cycle cost, and the cost of electricity would be greater than that estimated for government-owned facilities. To illustrate the importance of financing, we consider the effect on the NEA/OECD cost estimates for the LWR reprocessing fuel cycle resulting if reprocessing facilities were located in the United States and constructed and operated as a private venture with industrial financing. We adopt the estimated cost of $2,100/kg for a contemporary aqueous-technology reprocessing plant constructed in the United States (see Appendix J). The cost increment over the once-through fuel cycle would be about 4 mills/kWh, an increase of about 70% in the fuel-cycle cost and about 8% increase in the total generating cost of wholesale electricity.[5] At the present price of reprocessing services (about $1,000/kg—see Appendix J for details of a range of prices), the gross cost just for reprocessing 62,000 MgHM of LWR spent fuel would be $62 billion.[6] The total gross cost for recycle will be even greater when additional costs for fabricating recycle mixed-oxide (MOX) fuel are included.

It is predicted by some that the price of uranium will increase as resources are consumed and that by the second half of the next century the cost penalty for recycling may disappear. If this occurs, an economic benefit for recycling is expected to develop for breeder reactors. Even after the end of the next century, it would be expected that an economic benefit for a transmutation fuel cycle using an ALMR would develop.

The era of parity would be postponed if the future growth of nuclear power worldwide is less than expected, and it would arrive sooner if growth is more than expected. The deployment of an S&T system to improve waste disposal before an era of parity would need to be justified on the basis of benefits to nuclear waste disposal or to other parts of the nuclear fuel cycles.

There is also the possibility that the cost for reprocessing and transmutation could be used instead to improve waste forms for the once-through fuel cycle and the conservative design of the repository. This alternative has not been explored by this committee.

Pyroprocessing and Cost Perspective

The ALMR/IFR project estimates that it can achieve a twofold or more reduction in the cost of reprocessing spent LWR fuel using pyroprocessing technology compared to the use of aqueous separations technology. The committee believes that improvements in pyroprocessing may be possible but will have to be verified by research and development. Assuming the feasibility of pyroprocessing of spent LWR fuel, the design information for a commercial-scale reprocessing (IFR) facility needed to make cost estimates is not available.

Conclusion The excess cost for an S&T disposal system over once-through disposal for the 62,000 MgHM of LWR spent fuel is uncertain but is likely to be no less than $50 billion and easily could be over $100 billion if adopted in the United States. The additional cost of generating wholesale electricity could increase from 2 to 7% for a total increase of about $25 to over $80 billion.[7]

Findings Regarding Effects on Repository Capacity and Program

The Need to Dispose of Fission Products and Residual Wastes

All of the transmutation concepts require a geologic repository for at least some long-lived fission product radionuclides and for waste from some process losses and contaminated salvage materials.

Transmutation and Repository Capacity

Transmutation of the TRUs would reduce significantly the waste heat generation after a few hundred years in the

[5] Fuel-cycle costs include the costs of ore, enrichment, fabrication, waste disposal and reprocessing if reprocessing occurs. It does not include the costs of the nuclear reactor and its operations.

[6] Should the actinide recovery lead to a simpler licensing process for the repository and the fuel reprocessing recover both the plutonium and uranium for possible electricity production, there would be a reduction in this cost. Also, if actinide recovery (and presumably elimination) proved to be necessary to allow the use of the Yucca Mountain repository, then the avoided costs of having to find another site would be large.

[7] The current charge of the repository program is approximately 1 mill/kWh or about $30 billion for the current fuel cycle.

repository, offering possibilities of increasing repository loading by a factor of four to five. But, transmutation is only one of several means (some of which do not involve S&T) of increasing the waste disposal capacity of a repository.

The repository loading can be increased without transmutation, such as by staggered loading, but the presence of actinides limits this increase to about 20%. In this method, alternate drifts and boreholes are filled over for a number of years; later, the remaining empty ones are filled (see Chapter 6). This approach is best suited for the period when strontium and cesium dominate the heating, i.e., over the first few centuries.

Some believe that a geologic repository sited at Yucca Mountain should be maintained hot in order to keep it dry. In this case, sustained high heat loading would be a benefit, and removal of the TRUs to reduce the heat loading would not be desirable.

In addition to the limit in repository size resulting from the technical issues, there is a statutory limit that could possibly be changed. Increase in repository capacity would increase the calculated long-term individual dose from that repository, although it would reduce the number of people that might receive doses from multiple repositories.

Conclusion Transmutation could increase the effective capacity of the first repository and thus delay the need for a second repository. In most cases, however, there are other ways to achieve the same end without using transmutation.

Findings Regarding Nontechnical Issues

Institutional and Public Policy Considerations

Embarking on any S&T system would pose difficult institutional and public policy problems. These include (1) the funding, operation, and overall management of a large and complex program of an extraordinarily long duration involving a linkage of commitments among many private and governmental organizations; and (2) the siting, licensing, and regulation of many major interdependent nuclear facilities. Public acceptance of such a system seems highly questionable under present conditions.

Legislative and Administrative Constraints

Creation of a S&T system would require major legislative and administrative steps to establish the policy basis for a national commitment to expenditures on the order of tens of billions of dollars needed to cover the net incremental cost of S&T until the increasing cost of uranium makes it economic. The operations would link numerous organizations over a period of many decades to centuries. Siting approval would require consent of federal, state, and local jurisdictions.

Financing

If private industry is to participate, plans, decisions, and expenditures to ensure the continuing integrity of the S&T systems have to be coordinated among and agreed upon by many private, federal, and, state organizations and agencies to ensure that such long-term commitments are prudent investments. In view of the history of nuclear power and commercial reprocessing in the United States, federal guarantees are likely to be necessary before private industry agrees to be involved with the construction and operation of the required S&T facilities.

Proliferation Issues

Widespread implementation of S&T systems could raise concerns on international proliferation risks. Since a number of the countries using nuclear power are committed to reprocessing, this may not be a decisive factor. It would, however, require the United States to change its policy against reprocessing.

Public Acceptance

If the current attitudes continue, siting a large number of nuclear facilities would likely raise considerable public opposition. There is no reliable basis for knowing whether an informed public would regard S&T as a significant and worthwhile improvement over the once-through LWR fuel cycle. The experience with nuclear programs of the past 20 years, however, strongly suggests that developing such public support will be difficult.

Conclusion The construction and operation of an S&T system would require, in addition to several new types of facilities, the resolution of major institutional, public policy, and public acceptance issues. For S&T to make a significant reduction in the amount and character of the radioactive waste slated for a geologic repository, a sustained, long-term national commitment would be necessary. The U.S. government would also have to accept the lead management and financial responsibility, with a cohesive national intent and commitment. The last two decades of U.S. government-led nuclear programs provide little confidence that such conditions can be established and maintained. Based on the experience of licensing recent power reactors, it is also highly questionable whether the degree of public support needed could be obtained now or in the near future.

Findings Regarding Research and Development

Scope for Research and Development

A research and development program in selected nuclear technologies, including pilot-scale demonstration of advanced separations, could serve a threefold purpose: (1) prepare the technical basis for alternative waste forms for the radionuclides in spent LWR fuel; (2) undergird more efficient future use of fissionable resources (e.g., using a breeder reactor), of which nuclear waste S&T could be an integral part; and (3) facilitate effective access to and influence on nuclear technology research and development programs being conducted in the rest of the world.

Conclusion A sustained but modest, carefully focused program of research and development over the next decade, emphasizing advanced separations technologies, could provide a sound basis for future decisions on nuclear waste S&T. Such a program does not now exist in the United States and needs to be developed. Following successful laboratory-scale development, engineering pilot-scale demonstration would be necessary.

Findings Regarding Defense Wastes

Of all the radioactive and mixed (hazardous and radioactive) wastes arising from the production of nuclear energy, weapons research, and production, the HLW stored in tanks is of the greatest importance.

The concentration of TRUs in most defense wastes is several orders of magnitude lower than in commercial HLW, and the total amount of TRUs are much smaller than in spent reactor fuel. For this reason it is not practical to transmute these wastes. However, since separations technology has an impact on the treatment and management of the defense wastes, the committee examined several treatment options in detail.

There are a number of ongoing programs for specific treatment of such wastes. The magnitude and diversity of the tank waste problems are greater at Hanford than at other DOE defense sites and are the cause of much local and national concern. For these reasons, the committee has treated Hanford as a case study of U.S. defense waste and has made specific conclusions and recommendations for the waste at Hanford.

Safety of Hanford Waste Storage Tanks

The safety of some of the Hanford tanks has been a major concern because they contain heterogeneous mixtures of gaseous hydrogen, organic compounds, ferrocyanides, sodium nitrate, and heat-generating radionuclides that are potentially reactive. The tanks that pose safety concerns have been identified. Characterization of their contents and mitigating measures are well under way.

Characterization of Hanford Tank Wastes

The present core sampling program for the heterogeneous contents of the Hanford tanks can be expedited but would give only unrepresentative analytical data for many tanks. Although appropriate sampling and analysis is necessary for safety concerns and some process planning, the data from production records for many tanks could be sufficient to start the removal and processing of their contents. Analysis of the resulting solutions and solids would yield representative data far more useful for further process development.

Retrieval, Separation and Treatment Potential for Hanford Tank Wastes

Leaving all the Hanford tank waste in place is not a viable option due to immediate and future safety problems and to public concerns. A promising conventional technique, caustic sludge washing, should remove more than 95% of the contents by dissolution and hydraulic disintegration of the solids. The solution removed would contain much of the ^{137}Cs and some of the ^{90}Sr, the removal of which would produce a waste that is approximately equivalent to the Nuclear Regulatory Commission Class C low-level waste category and contain 80-90% of the original tank solids after evaporation. The waste could then be stored. The remaining fraction of the retrieved waste, representing possibly 10% of the original waste volume, could be vitrified for geological disposal. Further separations, such as PUREX/TRUEX, could reduce the vitrified HLW to about 5% of the original volume. More extensive separations that would reduce the volume to 0.5% have been suggested. Such extensive advanced processing appears to be quite expensive and reliant on processes tested only on a laboratory scale. A research and development program tailored to the actual washed residues is under way to evaluate the technical and economic issues associated with the separation processes that could follow caustic sludge washing.

Conclusion Operations required to separate the Hanford tank wastes into a large-volume, low-activity portion destined for on-site disposal and a small-volume, high-activity portion destined for the repository are justified, primarily on economic grounds. At a minimum, justified operations include waste retrieval, sludge washing, and separation of key radionuclides from the large-volume portion. Further research and development on the processes and justification for additional separations involving the sludges is warranted.

For the 250,000 M^3 of Hanford tank waste, a relatively simple "sludge-wash" process should be implemented to reduce the volume of high-level waste to about 25,000 M^3. Research and development should continue on additional pretreatment (e.g., separations) options, and these should be implemented if they prove cost effective or are required to meet regulatory or institutional requirements.

The extensive further processing necessary to isolate the small amount (less than 1 Mg) of TRUs for transmutation would be unjustified.

PRINCIPAL RECOMMENDATIONS

The committee recommends the following:

- None of the S&T system concepts reviewed eliminates the need for a geologic repository. DOE should continue efforts to develop a geologic repository for spent LWR fuel.
- The current policy of using the once-through fuel cycle for commercial reactors, with disposal of the spent fuel as HLW, should be continued.
- Fuel retrievability should be extended to a reasonable time (on the order of 100 years) to avoid foreclosing alternative fuel strategies that may be in the national interest.
- Research and development should be conducted on selected topics to support the cost-effective future application of S&T of commercial spent fuel and separations for defense waste applications.

A sustained, but modest, and carefully focused program of research and development over the next decade could prepare the technical basis for advanced separation technology for the radionuclides in spent LWR fuel and for decisions on the possible applications of S&T as part of the more efficient future use of fissionable resources. The research and development effort should focus on the factors that strongly influence fuel-cycle economics, especially the costs of reprocessing spent LWR fuel, minimalization of long-lived radionuclides to secondary wastes in the reprocessing cycle, and on the need to minimize the possible increase in proliferation risks that could result from the commercial use of plutonium in recycle fuels.

NUCLEAR WASTES

Technologies for Separations and Transmutation

Committee on Separations Technology and Transmutation Systems

Board on Radioactive Waste Management

Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1996