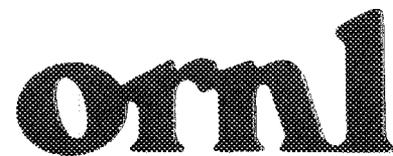


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ORNL/TM-11650

**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

**Historical Perspective, Economic
Analysis, and Regulatory Analysis
of the Impacts of Waste Partitioning-
Transmutation on the Disposal of
Radioactive Wastes**

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Chemical Technology Division

HISTORICAL PERSPECTIVE, ECONOMIC ANALYSIS, AND REGULATORY ANALYSIS
OF THE IMPACTS OF WASTE PARTITIONING-TRANSMUTATION ON THE DISPOSAL
OF RADIOACTIVE WASTES

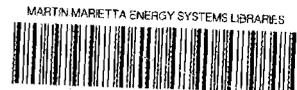
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ABSTRACT

Partitioning-transmutation, sometimes called actinide burning, is an alternative approach to high-level radioactive waste management. It consists of removing long-lived radionuclides from wastes and destroying those radionuclides, thus reducing the long-term hazards of radioactive waste. It was studied in detail in the 1970s. New developments in technology and other factors are resulting in a reexamination of this waste management option. This report consists of three papers which (1) summarize the historical work, (2) update the analysis of the costs of waste disposal, and (3) describe current regulatory requirements which might be impacted by P-T. The papers provide a starting point for future research on P-T.

HISTORICAL PERSPECTIVE, ECONOMIC ANALYSIS, AND REGULATORY
ANALYSIS OF THE IMPACTS OF WASTE PARTITIONING-TRANSMUTATION
ON THE DISPOSAL OF RADIOACTIVE WASTES

1. Introduction

One method to manage radioactive wastes is to partition (separate) long-lived radionuclides from various waste streams and transmute (convert) those radionuclides to short-lived or stable isotopes. This technique reduces the long-term risks of radioactive wastes entering the biosphere while increasing short-term risks by the additional process required for partitioning/transmutation. This technical option for waste management was investigated at ORNL between 1976 and 1979. The general conclusions of those studies were that short-term costs and risks of partitioning/transmutation exceeded long-term gains in reducing the risks in geological disposal of radioactive waste. The conclusions were dependent upon technology and assumptions.

In the last several years, the Department of Energy has been investigating advanced fuel cycles for Liquid Metal Reactors (LMRs). With these advances, there has been a renewed interest in partitioning/transmutation. The current proposed concept for partitioning/transmutation is as follows:

1. An LMR would be used to transmute long-lived radionuclides (actinides) to shorter-lived fission products. With the hard spectrum of an LMR, actinides become either fissile fuel for the reactor or fertile material.
2. LMR spent fuel would be reprocessed using a pyrochemical process developed at Argonne National Laboratory. It is proposed that the pyrochemical process may be able to remove essentially all long-lived actinides from the waste for recycle into an LMR.
3. LWR spent fuel would be reprocessed using modified conventional techniques with all actinides recycled into LMRs.

Because of ORNL's experience in this area, ORNL was requested to prepare papers addressing particular issues associated with partitioning/transmutation. These papers will provide background information for DOE to prepare various white papers and other program papers. This document contains the three related papers prepared at ORNL. These papers are:

1. "Historical Perspective of Partitioning-Transmutation," by A. G. Croff (Chapter II).
2. "Cost Analysis for Disposal of Waste From a P/T Fuel Cycle," by C. W. Forsberg (Chapter III).
3. "Legal and Regulatory Issues for Evaluation of Potential for Actinide Partitioning and Transmutation," by D. C. Kocher (Chapter IV).

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Chapter II
HISTORICAL PERSPECTIVE OF PARTITIONING-TRANSMUTATION

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This chapter provides a summary of previous work concerning partitioning-transmutation (P-T), with emphasis on the actinides. First, a general description of P-T is presented. Then, the results of P-T studies before 1976 are summarized. This is followed by a somewhat more detailed summary of a major evaluation of P-T performed by Oak Ridge National Laboratory (ORNL) during 1976-1979, and work performed in Europe in parallel with this. Finally, a brief characterization of more recent activities is given.

2.1 INTRODUCTION

Partitioning, when conducted for waste management purposes, is defined as treatment designed to reduce the levels of chemical elements having undesirable, long-lived isotopes in radioactive wastes to a greater extent than that dictated by normal economic considerations and to ensure the recovery of these elements in a form suitable for some alternative disposition.

The concept of partitioning the long-lived nuclides is incomplete from a waste management standpoint without specification of a method for handling them after recovery. One such method is transmutation.

Transmutation is defined here as a process whereby long-lived nuclides are converted to shorter-lived or stable isotopes by bombardment with subatomic particles, such as neutrons from nuclear power reactors. Partitioning and transmutation, when taken together, form a waste management concept which would be capable of reducing the amounts of certain long-lived, toxic species normally present in radioactive wastes and converting them to shorter-lived or less toxic species. Thus the goal of P-T would be to decrease the long-term (>1000 years) toxicity, and hence the risk, of the radioactive wastes consigned to a repository

by recovering and eliminating a major portion of the long-lived nuclides initially present in the wastes.

2.1.1 Partitioning

All known methods for accomplishing partitioning would involve the application of various chemical or physical separation techniques to recover and purify the long-lived radiotoxic components.

The elements generally considered to be candidates for partitioning are the actinides (esp. neptunium, plutonium, americium, curium, berkelium, and californium), technetium (i.e., ^{99}Tc), and iodine (i.e., ^{129}I). Since relatively little is known about most potential partitioning processes, it is not presently possible to define the degree to which these elements could be removed from radioactive wastes in an actual partitioning process with any degree of certainty or to favor a final set of flowsheets. Instead, tentative goals are typically specified (Table 2.1). These goals define the residual amounts of the actinides and iodine in high-level radioactive waste (HLW) based on the amounts present in the spent reactor fuel. If such reduction factors could be realized, the long-term ingestion toxicity index of a unit volume of solidified-level waste would be reduced to a value which is within the range of the toxicity indices of an equal volume of naturally occurring radioactive materials. Lower losses would be required to generate a non-transuranic "HLW" (i.e., less than 100 nCi/g).

Even though the goals are only stated for high-level wastes, the actinide contents of other waste streams would have to be reduced to as-yet-undefined levels for these wastes to have comparable long-term indices. This reduction would be necessary because (1) a large fraction of the overall fuel cycle actinide losses would typically occur in intermediate- and low-level waste streams produced by mixed-oxide fuel fabrication and reprocessing operations, and (2) if these wastes were not included in the partitioning process, the net result might be to remove actinides from the high-level waste and then lose them to low- and intermediate-level wastes. As a result of these considerations, it is evident that any meaningful partitioning process would have to encompass all actinide-contaminated waste streams.

Table 2.1. Tentative partitioning goals for losses of HLW glass

Element	Loss as a percentage of element fed to the reprocessing plant
U	0.1
Np	5.0
Pu	0.01
Am, Cm, Bk, Cf	0.1

The Purex process has been examined as the basis for the development of reprocessing plant partitioning in most previous work because of its widespread acceptance and use in commercial reprocessing. However, the nature of many of the waste streams that would be produced by currently envisaged Purex flowsheets makes achievement of any meaningful degree of partitioning very difficult or impossible. Therefore, it is not logical to attempt to achieve partitioning by simply operating on the waste streams produced by the Purex process. Fundamental changes may be required in various stages of the process per se (i.e., dissolution or solvent extraction) to effect the desired separations. It should be noted that partial partitioning might be implemented without altering the reprocessing flowsheet, simply by treating the various waste streams individually to recover as much of their actinide content as practicable. The losses obtained with such an approach would almost certainly be markedly larger than the goals listed in Table 2.1. It should be noted that partitioning processes would also be required at mixed-oxide fuel fabrication plants because of the plutonium and americium (^{241}Am) contents of the wastes generated there.

2.1.2 Methods for Handling Partitioned Nuclides

Transmutation. As was noted previously, the concept of partitioning the actinides is incomplete from a waste management standpoint without specification of a method for disposing of them after recovery. One method for handling them would be transmutation.

In a generalized P-T scenario, the normal spent-fuel discharge from a nuclear reactor would be allowed to decay for a period of time at the reactor before shipment to the reprocessing plant. On arrival at the reprocessing plant, it would be allowed to decay further before being reprocessed via techniques designed to accomplish partitioning. The reprocessing plant outputs would consist of: (1) the separated economic values that were present in the spent fuel (uranium, plutonium, thorium), in slightly larger amounts than those obtained in nonpartitioning reprocessing due to the increased recovery, (2) separated or mixed "waste actinides" (neptunium, americium, curium, berkelium, and californium) plus possibly the iodine and technetium called "waste nuclides" hereafter, and (3) radioactive wastes with reduced iodine, technetium, and actinide contents. The waste would be immobilized and disposed of in a manner appropriate for each waste type. The economic values would be recycled in the normal manner typical of the fuel cycle being considered. The waste nuclides would be refabricated either homogeneously dispersed in the normal reactor fuel or concentrated in selected fuel rods or assemblies. The radioactive wastes from the fabrication plant would also be partitioned to reduce waste nuclide losses. The waste nuclides from all sources would then be inserted into the transmutation device and irradiated, transmuting the ^{129}I to stable ^{130}Xe , ^{99}Tc to stable ^{100}Ru , and the waste actinides to fission products. After irradiation, the remaining waste nuclides would be stored for an interim period before and after transport to a reprocessing plant if it were not co-located. If the waste nuclides were homogeneously dispersed in the normal fuel, the untransmuted portions would be recovered in the fuel reprocessing-partitioning plant and refabricated with new fuel material for recharging to the transmutation reactor. If the waste nuclides were concentrated into targets, they would probably be reprocessed separately from the spent fuel to avoid dilution with the large actinide mass of different elemental composition. The waste nuclides would then be refabricated in concentrated form into rods or assemblies and reinserted into the transmutation device. In either case (homogeneous or concentrated), the cycle would be closed and the waste nuclides would be recycled until they were either transmuted or lost to a waste stream during reprocessing or refabrication.

Alternatives to Transmutation. Partitioning is unique in that it would reduce the waste nuclide content of radioactive wastes, and make them available for disposal (or elimination) by a different method than that for the other

radioactive wastes. Although transmutation is the means considered in this report, at least two other approaches could be pursued: extraterrestrial disposal and alternate geologic disposal. These alternatives are outside the scope of this chapter and will be considered only briefly.

As presently conceived, extraterrestrial disposal would involve partitioning and fabricating the waste nuclides into a stable form and rocketing them into space using a space shuttle. The waste would then be launched in a separate vehicle to its final destination. Possible final destinations are high-earth orbit, the moon, and solar orbit. The extraterrestrial concept would be advantageous in that it could handle nuclides which are not amenable to transmutation because of their nuclear properties (e.g., ^{14}C) and would avoid the buildup of waste actinide inventories in the fuel cycle. Potential disadvantages of the concept would be the relatively large number of launches required in an expanded nuclear economy, the high specific cost of transporting the undesirable materials into space, and the reliability of the technique.

Alternate geologic disposal would involve disposal of waste nuclides in a location separate from the bulk of the radioactive wastes, particularly the heat-generating wastes (high-level and fuel assembly hardware). The theory behind this concept is based on the assumption that the heat generated by the wastes may increase the probability or consequences of repository failure before the long-lived nuclides could decay to innocuous levels. Therefore, it has been proposed that the waste nuclides be emplaced in a repository physically removed from the heat-generating wastes to reduce the likelihood of their release. It is important to note that no studies made to date have indicated that heat-generating wastes would impair the integrity of a repository.

2.1.3 Fuel Cycle Impacts of Partitioning-Transmutation

The previous subsections considered the two major aspects of P-T, the partitioning and transmutation operations per se. However, implementation of P-T could have additional effects on nuclear fuel cycle operations. The fuel cycle impacts of P-T are herein defined as the significant differences that would occur in nuclear fuel cycles with and without P-T, excluding the reprocessing and refabrication plant modifications required to accomplish partitioning and the in-

reactor effects of transmutation.

The potential fuel cycle impacts of P-T that have been identified are as follows:

1. increased biological shielding thicknesses due to increased waste actinide neutron activity;
2. increased health effects from operational effluent releases (chemical, radiological, and thermal);
3. delay of near-term fuel cycle operations until P-T could be implemented;
4. higher fuel cycle cost;
5. decreased long-term waste;
6. the need for an extensive research, development, and demonstration program to commercialize P-T;
7. conflicts between new requirements that might result from implementation of P-T and presently existing laws, regulations, and treaties;
8. the possible use of the waste actinides (i.e., ^{238}Pu , $^{242,244}\text{Cm}$, and ^{252}Cf) to "spike" strategic nuclear materials to reduce the likelihood of diversion, and
9. The importance of lengthened out-of-reactor fuel decay times on breeder reactor fuel inventory doubling times.

It should be emphasized that these are potential fuel cycle impacts of P-T and that some of these effects might be reduced to virtually zero through appropriate technical or political decisions.

The pervasive nature of these impacts, coupled with the problems associated with P-T, results in an extremely complex fuel cycle since a dual actinide recycle (e.g., U + Pu and Np + Am + Cm) is necessary and the impacts could affect every part of the fuel cycle.

2.1.4 Analysis of Incentives for Partitioning

The final phase of an overall evaluation of P-T would involve placing all of the above ramifications on a common basis and comparing them to determine whether implementation of the concept is worthwhile. This phase is designated as an analysis of the "incentives for partitioning."

Ideally, determination of the incentives for P-T would be based on a risk-cost/benefit analysis in which the risks and benefits were expressed in monetary terms to place them on the same basis as the costs. This procedure would involve calculating: (1) the increased risk of morbidity and mortality that might result from implementing P-T because of potential increases in emissions of noxious materials during routine operations and as a consequence of accidents, (2) the (presumed) decrease in the risk of morbidity and mortality resulting from a decrease in the waste nuclide content (i.e., long-term toxicity) of the wastes in a repository, and (3) the increase in nuclear fuel cycle costs that would result from building the additional facilities necessary to implement P-T.

2.2 PRE-1976 P-T STUDIES

Studies have been made of various selected aspects of P-T since the mid-1960s. The most common type of study involved actinide transmutation calculations followed by calculation of the toxicity index of the high-level waste with and without transmutation of the actinides. (Note: The toxicity index is the amount of water required to dilute all of the isotopes in a unit volume of waste to their Radionuclide Concentration Guide values given in 10 CFR 20.¹) The conclusion reached in most of these studies was that the toxicity, and therefore the risk, due to high-level wastes (HLW) in a repository could be reduced by factors of 100 to 200 for waste decay times greater than 1000 years.² However, these studies generally ignored partitioning, the more realistic impacts of transmutation on the transmutation device, and other fuel cycle impacts of P-T.

2.2.1 Partitioning

Very limited studies of partitioning processes and technology were conducted during 1973-1975 (see refs. 3 and 4). The principal results of these studies were: (1) an evaluation of previous work and synthesis of this work into reprocessing plant flowsheets for partitioning actinides from the waste streams, and (2) recommendations concerning the approaches that should be used in future partitioning studies. Although laboratory investigations of the recommended processes were begun, they were terminated before significant results could be obtained.

2.2.2 Transmutation

The first documented suggestion that transmutation of radioactive waste constituents might be a useful waste management option was made by Steinberg⁵ in 1964. Except for another study by Steinberg in 1967 concerning the possible transmutation of fission products with GeV proton-induced spallation neutrons,⁶ the study of waste transmutation languished until 1972, when a report⁷ by Claiborne initiated an avalanche of transmutation studies by many different organizations. Table 2.2 gives a list of the principal investigator(s), the investigator's affiliation(s), a brief description of the transmutation studies conducted, and a description of any generally available documentation for the

Table 2.2 Summary of fission and fusion reactor transmutation studies

Investigator(s) (Organization)	Description	References
<u>Controlled Thermonuclear Reactor (CTR) Transmutation Systems</u>		
W. C. Wolkenhauer (PNL)	Physics of transmuted ^{90}Sr and ^{137}Cs in a CTR	8
W. C. Wolkenhauer, B. R. Leonard, B. F. Gore (PNL)	Evaluated potential of a CTR for transmuted fission products and actinides	9
B. F. Gore, B. R. Leonard (PNL)	Physics of transmuted massive amounts of ^{137}Cs in a CTR blanket	10, 11
J. Henely, H. W. Meldner (LLNL)	Actinide transmutation in laser-induced fusion reactors	12, 13
J. W. H. Chi, R. R. Holman, R. P. Rose, J. E. Olhaeft, S. Kellman (Westinghouse Fusion Power Systems)	Engineering and physics design of a CTR for actinide transmutation	14- 16
Gary Lang (McDonnell-Douglas); E. L. Draper, T. A. Parish (Univ. of Texas, Austin)	Engineering and physics design of a CTR for long-lived fission product transmutation	17
U. Jenquin, B. R. Leonard (PNL)	Physics of transmuted actinides in a CTR blanket	18
<u>Thermal Fission Reactor Transmutation Systems</u>		
M. Steinberg (BNL)	Physics and economics of transmuted ^{85}Kr , ^{90}Sr , and ^{137}Cs	5

Table 2.2. continued - Page 2

H. C. Claiborne (ORNL)	Discussion of fission product transmutation; investigation of in-reactor and out-of-reactor effects of actinide recycle in a PWR	7
A. S. Kubo	Scoping evaluation of actinide recycle in LWRs	19
Erik Johansson (AB Atomenergi, Malmo, Sweden)	Mass of and radiation levels from actinides recycled in BWRs	20, 21
M. Taube, J. Ligou (Eidg Institut fur Reaktorforschung)	Design of molten-salt (chloride) fast breeder reactor with a thermal column for transmuted ^{90}Sr and ^{137}Cs	22-24
R. Paternoter, M. J. Ohanian (Univ. of Fla.); K. Thom (NASA)	Investigated the use of a gaseous UF_6 cavity reactor with a BeO moderator for transmuted ^{129}I and actinides	25, 26
S. Raman, C. W. Nestor, J. W. T. Dabbs (ORNL)	Physics of actinide recycle in a ^{233}U -Th-fueled transmutation reactor	27
R. Lester, M. Goldstein (BNL)	Investigated fuel cycle actinide inventories resulting from actinide transmutation in LWRs	28
J. D. Clement (Univ. of Ga., Atlanta)	Design and optimization of a gaseous UF_6 cavity transmutation reactor	29
R. B. Lyon (AECL)	Investigated actinide transmutation in CANDU reactors	30

Fast Fission Reactor Transmutation Systems

EURATOM	Assessment of actinide transmutation	31
S. E. Binney, B. I. Spinrad, et al. (Ore, State Univ., Corvallis)	Investigated using oxide-, carbide-, and metal-fueled FBRs for transmuted actinides	32

Table 2.2. continued - Page 3

R. H. Clarke, H. F. MacDonald (CEGB, U.K.); J. Fitzpatrick, A. J. H. Goddard (Imperial College of Science and Technology, U.K.)	Examined using actinide recycle in FBRs to reduce long-term alpha- heating in waste	33
N. J. Keen (Harwell, U.K.)	Investigated actinide transmutation rates in FBR cores	34
R. J. Breen (WARD)	Investigated actinide transmutation rates in oxide- and carbide-fueled LMFBRs	35
S. L. Beaman (GE)	Investigated physics of transmuted actinides from 3 BWRs and 1 LMFBR in an LMFBR	36-42
A. Friedman (ANL)	Irradiation and analysis of plutonium samples in EBR-II for actinides through ^{246}Cm	43
J. Prabalos (Combustion Engineering)	Investigated actinide transmutation in a carbide-fueled LMFBR	44
J. Bouchard (CEA)	Actinide transmutation in an LMFBR	45
W. Bocola, L. Fritelli, F. Gerd, G. Grossi, A. Mouia, L. Tondinelli (CNEN-CSN)	Investigated actinide transmutation in an FBR and the sensitivity of actinide buildup in LWRs	46
<u>Thermal and Fast Reactor Transmutation Systems</u>		
A. S. Jubo (U.S. Army); D. J. Rose (MIT)	Assessment of the incremental cost of actinide transmutation in LWRs and LMFBRs	47
A. G. Croff (ORNL)	Parametric study in in-reactor and and out-of-reactor effects of actinide recycle for LWRs, HTGRs, and LMFBRs	48, 49

Table 2.2. continued - Page 4

T. H. Pigford, J. Choi (Univ. Cal.-Berkely)	Examined overall actinide mass reduction from transmutation in PWR and LMFBR	50
E. Schmidt, J. Cametti (JRC-Ispra)	Investigated actinide transmutation in a LMFBR, including lanthanide- contaminated actinide recycle	51
W. Hage, E. Schmidt (JRC-Ispra)	Detailed review of the in-reactor effects of actinide transmutation; most advanced study to date	52
G. Harte (CEGB-Berkely)	Initial studies of long actinide irradiation durations (20 to 40 years)	53
L. Koch, R. Ernstberger, Kl. Kammerichs (JRC-Karlsruhe)	Studied actinide formation rates in thermal reactors, actinide trans- mutation in thermal and fast reactors, and some fuel cycle impacts	54
F. Duggan	Studied transmutation of individual actinide isotopes in LWRs, HTRs, and FBRs	55
A. Sola	Studied transmutation of individual actinide isotopes in LWRs and FBRs	56
<u>Many Transmutation Studies</u>		
R. C. Liikala et al. (PNL)	Detailed review of actinide and fission product transmutation studies through 1974; transmuta- tion devices considered include particle accelerators, thermonu- clear explosives, fission reactors; investigated actinide transmutation rates in LWRs	57
A. G. Croff (ORNL)	Brief review of fission product and actinide transmutation in many devices	58

Table 2.2. continued - Page 5

<u>Actinide Transmutation Sensitivity Studies</u>		
E. Schmidt (JRC-Ispra)	Examined required actinide reprocessing recoveries and the sensitivity of actinide buildup in several reactor types	59, 60
A. Sola, K. Caruso (JRC-Ispra)	Studied the sensitivity of actinide production and transmutation to nuclear data changes	61
E. Schmidt (JRC-Ispra)	Studied the sensitivity of actinide transmutation to nuclear data uncertainties	62
A. Gandini, G. Oliva, L. Tondinelli (CNEN-Casaccia)	Examined the correlation of integral and differential data and the sensitivity of actinide transmutation to nuclear data	63
<u>Actinide Recycle Strategies and Fuel Cycle Impacts</u>		
P. E. McGrath (G.F.K.-German)	Systems analysis of transmutation	64
A. G. Croff (ORNL)	Definition and discussion of the non-physics, nonpartitioning impacts of partitioning transmutation	65
M. G. Sowerby (AERE-Harwell)	Discussion of studies to determine promising actinide recycle strategies	66

transmutation studies conducted to date. This list has been restricted to those studies principally concerned with transmutation in fission and fusion reactor systems.

The list of transmutation studies presented in Table 2.2 may not be complete, particularly with respect to the non-U.S. contributions. Within the United States, this deficiency is probably a reflection of the large number of organizations conducting transmutation studies without any organized system for communication and exchange of information. The non-U.S. organizations conducting such studies are typically allied with the national governments. Much of the work done by these organizations was not published, and the published material generally circulates sporadically. The transmutation studies that have been conducted in Japan, Canada, France, Sweden, Italy, Germany, the United Kingdom, and the Netherlands are, for the most part, modest. The largest of the non-U.S. transmutation studies was conducted at the URATOM Joint Research center in Ispra, Italy (further discussion below).

Evaluation of the transmutation literature cited in Table 2.2 leads to the conclusion that the transmutation studies conducted thus far have not been coordinated, resulting in considerable duplication in some areas, omissions in others, and an incomplete assessment of P-T as a waste management concept. There are exceptions to this, most notably the ERDA-sponsored fast reactor actinide transmutation studies,³⁸⁻⁴⁴ the EPRI-sponsored fusion reactor transmutation studies,¹⁴⁻¹⁸ and the program at the Joint Research Center in Ispra, Italy,^{20-25,31,52,60-62} which represent coordinated efforts to investigate the feasibility and effects of P-T. Despite these efforts, the fact that nearly all previous transmutation studies have concentrated on selected in-reactor impacts (transmutation rates, breeding ratio penalties, etc.) means that more information is still required if a defensible evaluation of the incentives for P-T is to be completed.

2.2.2.1 Transmutation Devices

The large number of proposed transmutation devices (cf. ref. 57) made it necessary to limit the scope of the literature review to fission and fusion reactors. In considering realistic transmutation scenarios, the number of

transmutation devices was reduced even further to make analysis of the number of transmutation systems tractable. Accordingly, the devices considered were restricted to commercial and projected commercial PWRs and LMFBRs. The fusion reactor was eliminated because of the long-range nature of a fusion reactor economy and the current uncertainty regarding fusion reactor design. Special fission reactor transmutation devices (e.g., a high-flux fast reactor with a thermalized central region, ref. 23) were not considered because (1) a detailed reactor design would be required before analysis of the device and its attendant fuel cycle could begin, and (2) the research, development, and demonstration costs of a waste management reactor would be very large.

2.2.2.2 Transmutation Candidates

The next important task is to establish a list of nuclides which might be candidates for transmutation. Such nuclides would include those for which the transmutation rate would be many times the natural decay rate and those which would contribute significantly to the waste toxicity. Tables 2.3 and 2.4 compare the time required to eliminate 99.9% of a particular nuclide by both transmutation and decay with that required to eliminate 99.9% of the same nuclide by decay only for eight of the most commonly considered nonactinide transmutation candidates: ^3H , ^{14}C , ^{85}Kr , ^{93}Zr , ^{90}Sr , ^{137}Cs , ^{99}Tc , and ^{129}I . Typical flux levels for the reactor systems considered are 3×10^{13} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ for the PWR and 5×10^{15} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ for the LMFBR. Evaluation of this table leads to several important conclusions. First, ^{90}Sr and ^{137}Cs , the predominant contributors to high-level waste toxicity for the first 1000 years, would be essentially "untransmutable" in commercial fission power reactors. Thus, even if feasible, transmutation of nuclides in the high-level waste with half-lives comparable to or less than ^{90}Sr and ^{137}Cs (ca. 30 years) would not significantly reduce the overall toxicity of the high-level waste (HLW). This means that both ^3H and ^{85}Kr can be eliminated as transmutation candidates because of their relatively short half-lives and small neutron cross sections. Carbon-14 would also be essentially untransmutable because of its extremely small neutron cross section. As a result of these considerations, it is concluded that the toxicity of high-level waste for the first 1000 years would not be amenable to reduction by P-T. Therefore, the list of candidate nuclides will be restricted to nuclides that would contribute significantly to the long-term (>1000 years) toxicity of

Table 2.3. Summary of effective decay times for neutron-induced transmutation of ^3H , ^{14}C , ^{85}Kr , and ^{93}Zr

	^3H		^{14}C		^{85}Kr		^{93}Zr	
Radioactive half-life, years	12.33		5730		10.73		9.5×10^5	
Neutron spectrum	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>
Effective neutron-activation cross section, barns	10^{-6}	10^{-6a}	10^{-6}	10^{-6a}	1.5	0.0087	10.0	0.0394
Time required to eliminate 99.9% of nuclide, years								
Decay only	123	123	57,100	57,100	107	107	9,470,000	9,470,000
Flux ^b = 10^{13}	123	123	57,100	57,100	106	107	2,190	525,000
Flux ^b = 10^{14}	123	123	57,100	57,100	99.6	106	219	55,200
Flux ^b = 10^{15}	123	123	57,100	57,100	61.7	103	21.9	5,560
Flux ^b = 10^{16}	123	123	57,000	57,000	12.8	75.0	2.19	556
Flux ^b = 10^{17}	123	123	57,700	55,700	1.44	20.4	0.22	55.6
Flux ^b = 10^{18}	123	123	45,300	45,300	0.15	2.46	0.02	5.56

^aEstimated.

^bNeutrons $\text{cm}^{-2} \text{sec}^{-1}$.

Table 2.4. Summary of effective decay times for neutron-induced transmutation of ^{90}Sr , ^{137}Cs , ^{99}Tc , and ^{129}I

	^{90}Sr		^{137}Cs		^{99}Tc		^{129}I	
Radioactive half-life, years	29.0		30.1		2.13×10^5		1.59×10^7	
Neutron spectrum	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>	<u>PWR</u>	<u>LMFBR</u>
Effective neutron-activation cross section, barns	1.23	0.000158	0.17	0.039	44.5	0.20	34.5	0.24
Time required to eliminate 99.9% of nuclide, years								
Decay only	289	289	300	300	2,120,000	2,120,000	1.6×10^8	1.6×10^8
Flux ^b = 10^{13}	284	289	299	300	491	102,000	635	90,000
Flux ^b = 10^{14}	249	289	293	298	49.1	10,700	63.5	9,010
Flux ^b = 10^{15}	110	289	243	285	4.91	1,070	6.35	901
Flux ^b = 10^{16}	16.8	288	90.3	195	0.49	107	0.63	90.1
Flux ^b = 10^{17}	1.77	283	12.4	47.0	0.05	10.7	0.06	9.01
Flux ^b = 10^{18}	0.88	289	1.29	5.47	0.005	1.07	0.006	0.90

^aNeutrons $\text{cm}^{-2} \text{sec}^{-1}$.

the waste.

The most significant contributors to the long-term toxicity of the waste will be the actinides, ^{129}I , and ^{99}Tc . The next most toxic nuclide, ^{93}Zr , cannot reasonably be considered a candidate for transmutation for two reasons. First, this isotope will comprise only 20% of the fission product zirconium and less than 20 ppm of the LWR Zircaloy cladding. The mass of fresh fission product zirconium produced by PWR fuel is about 3300 g/MTHM at a burnup of 33,000 MWd/MTHM, 80% of which would be essentially untransmutable because of very small cross sections. This would result in an intolerable mass buildup during recycle. The second reason for the undesirability of ^{93}Zr transmutation is its contribution to the total, long-term waste toxicity would be so small that the other, more toxic nuclides could not be removed (partitioned) from the waste to such a degree that ^{93}Zr would become significant. Thus, even though ^{93}Zr possesses characteristics favorable for transmutation, the combination of isotopic dilution and low toxicity would eliminate it as well as other less toxic nuclides from consideration.

The result of the preceding discussion is that, after elimination of the short-lived, intermediate-lived, and less-toxic, long-lived nuclides, the candidates for transmutation would be the actinides, ^{129}I , and ^{99}Tc .

2.2.2.3 Long-Lived Nuclide Decontamination Requirements

The degree to which the long-lived nuclide content of high-level waste must be reduced to meet some arbitrary criterion has been examined by Claiborne⁶⁷ and by Schmidt.³⁹ The same measure of toxicity was used in each of these studies, and it will be called the toxicity index in this report. The toxicity index is the volume of water required to dilute all of the radionuclides in a unit volume of waste to their respective radionuclide concentration guide (RCG) values.^{1,68} Thus, that index has units of $\text{m}^3 \text{H}_2\text{O}/\text{m}^3 \text{waste}$ (i.e., it is dimensionless). The toxicity of the waste can then be compared with the toxicity index of naturally occurring radioactive minerals. The toxicity index of pitchblende (70% uranium) is about 10^8 , while that of high-grade carnotite ore (0.2% uranium) is about 10^5 . Claiborne's high-level waste decontamination criterion is to reduce the toxicity index of the actinides in the solidified, high-level waste to a level comparable

with the toxicity index of the long-lived fission products after 99.9% of the iodine has been removed. This results in the toxicity index of the solidified, high-level waste being about 5% of that of pitchblende and about 50 times that of carnotite ore after 1000 years of decay. Schmidt's criterion is to reduce the toxicity index of the high-level waste to a level comparable with that of carnotite ore. These criteria are substantially different with Schmidt's DFs^a ranging from 2 to 50 times those of Claiborne and also requiring the recovery of ⁹⁹Tc. A summary of DFs that would be sufficient to meet these criteria for all uranium-plutonium fuel cycle reactor fuels, as determined by Claiborne and Schmidt, is given in Table 2.5 along with DFs that could be attained using current Purex technology. Thorium fuel cycle reactor fuels (e.g., HTGR fuels) would require DFs of 200 for thorium, 20 for protactinium, and 10,000 for uranium based on Claiborne's criterion.

Specification of DFs is important for two reasons:

1. the DFs represent a set of goals for the development of partitioning processes, and
2. they enable one to examine many of the fuel cycle impacts of P-T while partitioning processes are still being developed.

It is desirable for the specified DFs to represent as closely as possible the conditions expected to be encountered in actual partitioning processes. This will aid in the development of partitioning processes and the analysis of the fuel cycle impacts of P-T.

Two observations should be made concerning the Claiborne DFs. First, for a given reduction in the solidified, high-level waste toxicity index there are many combinations of individual element DFs that would produce the desired toxicity index. Thus, if a plutonium DF of 10,000 could not be attained, then the DF of

^aDecontamination factor is defined as the mass of the element entering a process divided by the mass of the element found in the process effluent.

Table 2.5. Summary of high-level waste decontamination factors

Element or nuclide	Decontamination factor ^a		
	Current technology ^b	Claiborne ^c	Schmidt ^d
U	200	1,000	2,000
Np	10-20 ^e	20	200
Pu	200	10,000	200,000
Am	1	1,000	50,000
Cm	1	1,000	20,000
¹²⁹ I	20-1000 ^f	1,000 ^g	200
⁹⁹ Tc	1	1	50

^aRatio of element mass in spent fuel divided by element mass in high-level waste for typical uranium fuel cycle.

^bRef. 69

^cRef. 67

^dRef. 60

^eNeptunium is not usually recovered in the reprocessing of power reactor fuels. Decontamination factors of 10 to 20 have been attained on a special campaign basis.

^fAssumed; not required to meet high-level waste decontamination criterion.

^gRef. 58

uranium, neptunium, americium, or curium might be increased (within limits) to compensate. The second observation is that the assumed ^{129}I DF of 1000 would not be required to satisfy the criterion of reducing the actinide toxicity index to that of the other long-lived fission products. Claiborne's calculations show that an ^{129}I DF of about 100 would be sufficient to keep the toxicity index of ^{129}I less than that of the actinides.

In summary, a set of partitioning DF goals for high-level waste has been selected to serve as a target for the development of partitioning processes and for calculational investigation of the impact of P-T on the nuclear fuel cycle. However, there are several important aspects of setting DFs which must still be addressed; these are discussed below.

One shortcoming in the specifications of the DFs given in Table 2.5 is that they would apply only to high-level waste. If the same criteria were applied to low- and intermediate-level transuranic contaminated (TRU) wastes, then very little or no partitioning of these wastes would be needed because the actinides and fission products are very dilute in these types of wastes. On the other hand, the total actinide content of the low- and intermediate-level TRU waste streams would, in many cases, be comparable to that of the HLW. Substantial DFs would be required to reduce the total mass of actinides in these wastes to levels similar to that of the HLW. As a result of this paradox, a new criterion for determining DF goals is needed to account for all TRU-contaminated waste streams.

Another consideration is the validity of the "dilution to RCG" concept as a measure of waste toxicity. This question has been discussed at length in the literature.^{64,70} In summary, the consequences of or the risk from an assumed repository release can be calculated by more sophisticated (and complex) methods than "dilution to RCG." These methods tend to give different results than the "dilution to RCG" method, indicating a different relative actinide risk importance or that the actinides are less important than the residual long-lived fission products or both. Ideally, these methods should be used when calculating the waste nuclide decontamination requirements. However, their complexity and site specificity make their use in scoping and feasibility studies prohibitively time-consuming and expensive. Therefore, the "dilution to RCG" method will probably find application in most of the near-term studies, principally because

of its calculational simplicity.

2.2.2.4 Transmutation of Nonactinides

As a result of the elimination process described earlier, ^{129}I and ^{99}Tc are the only two nonactinides that would be candidates for transmutation. Unfortunately, information concerning the transmutation and recycle of these nuclides is limited to the steady-state, desk-calculator results given below.

Based on the ^{129}I and ^{99}Tc parameters given in Table 2.5, the period of irradiation that would be required to transmute 99.9% of a given amount of dilute ^{129}I is 211 years in a PWR and 182 years in an FBR. The corresponding periods for dilute ^{99}Tc are 164 years and 219 years. These times are equivalent to transmutation rates of 3.2%/year in an FBR for ^{99}Tc , assuming continuous irradiation.

A second type of calculation regarding transmutation recycle of ^{129}I and ^{99}Tc is related to the mass buildup of these isotopes at the point where the transmutation plus reprocessing loss rate equals the production rate (i.e., at steady state). One metric tonne of discharged PWR fuel contains about 700 g of ^{99}Tc and 235 g of iodine, of which 185 g are ^{129}I and 50 g are stable ^{127}I . By using the data given in Table 2.5 and a continuous PWR thermal flux level of 3.0×10^{13} neutrons $\text{cm}^{-2} \text{sec}^{-1}$, the steady-state mass of ^{99}Tc during transmutation has been calculated to be a factor of 8.3 greater than that in normal discharged fuel. Thus, during steady-state recycle, there would be $8.3 \times 700 = 5810$ g of ^{99}Tc per MT of heavy metal, which would be equivalent to about 0.6% of the heavy metal mass. The increase factor for iodine would be about 10.6, giving a steady-state recycle mass of $10.6 \times 235 = 2510$ g of iodine per MT of heavy metal, which would be equivalent to about 0.25% of the heavy-metal mass. The steady-state-to-discharge ratios in an FBR would be 16.0 for ^{99}Tc and 13.5 for iodine. The steady-state recycle ^{99}Tc or iodine concentration in FBR fuels would also be somewhat higher than in PWR fuels because of the higher average fuel burnups in the FBR.

In summary, it appears that transmuting fission product iodine, and ^{99}Tc would present no difficulties from a theoretical standpoint. However, several

practical transmutation-related problems must be resolved before iodine and ^{99}Tc transmutation could occur. Among these are:

1. the greatly increased xenon production from iodine transmutation,
2. the mode of recycling the iodine and ^{99}Tc (i.e. homogeneously dispersed in the fuel or as targets, with the attendant degradation of the transmutation rate by self-shielding effects),
3. the chemical form of the recycled iodine and technetium, and
4. the effects of the iodine and ^{99}Tc on the fuel behavior in the reactor, particularly in the case where concentrated iodine-or technetium-compound targets are used.

2.2.3 P-T Benefits

Only one realistic study was made before 1976 to determine the long-term benefits of removing the actinides from high-level waste.⁷¹ The previously mentioned studies of long-term benefits that were based on the toxicity index are not realistic because it assumes that the wastes are ingested directly with no change in composition. However, a more realistic assumption is that the nuclides might be leached from the waste in the repository in the distant future and then be slowly transported through the geosphere to the biosphere. During this transportation process, the chemical and physical interactions with the geosphere and the biological differentiation in the biosphere have the net effect of greatly retarding the release of radioactive isotopes and substantially changing the elemental and isotopic mixture ultimately ingested. The study cited above,⁷¹ which included these effects, concluded that ". . . for the situations investigated the incentives for a special effort to remove any elements, including the transuranics, from high-level waste are vanishingly small. . . ." However, since the objectives of this study did not include consideration and comparison of the near-term risks and costs of removing the actinides from high-level waste to the calculated benefits, it is difficult to state conclusively that there are no incentives for actinide removal until the penalties incurred by the process are assessed.

2.2.4 Other P-T Impacts

Up to this time, no studies had been made of the other varied, but important, impacts of P-T on the nuclear fuel cycle. Examples of these impacts are the effects of the highly neutron-active transplutonium isotopes on fuel fabrication, transportation, and handling; the effects of neptunium, americium, and curium on in-reactor behavior, fabricability, and cladding compatibility of reactor fuels; and the disposition of actinides produced prior to the implementation of P-T.

2.2.5 Incentives

Additionally, no overall study has been made of the feasibility and incentives for implementing the P-T concept. This type of study, in which all short-term and long-term advantages and disadvantages would be included, is necessary if the incentives for P-T are to be realistically and believably evaluated.

2.3 ORNL P-T STUDY

In 1976, the U.S. Energy Research and Development Administration [now the U.S. Department of Energy (DOE)] asked the Oak Ridge National Laboratory (ORNL) to develop a program to establish the technical feasibility and incentives for partitioning elements having waste nuclides and transmuting them to shorter-lived or stable isotopes in power reactors. The program was broadly based, consisting of both experimental and computational activities that would be required to develop a meaningful and defensible evaluation of the P-T concept. In addition to ORNL, several other organizations having specialized experience and experimental facilities also participated in the program. These organizations included:

1. Argonne National Laboratory;
2. Brookhaven National Laboratory;
3. Mound Laboratory;
4. Savannah River Laboratory;
5. Sandia Laboratory;
6. Rocky Flats Plant;
7. Idaho National Engineering Laboratory
8. the Ralph M. Parsons Company;
9. Science Applications, Inc.; and
10. Los Alamos Technical Associates.

The program lasted approximately 3 years. The first seven organizations listed above, plus ORNL, conducted studies on specific aspects of P-T during the first 2 years of the program. The results of these individual studies were used to

develop fuel cycle material and facility descriptions, which were then subjected to risk and cost analyses by the last three organizations (see list above) during the third year of the program. In the final part of the program, all these results were evaluated, leading to an assessment of the feasibility and incentives for P-T and the specification of the research, development, and demonstration (RD&D) requirements needed to implement P-T. The results were then documented in a series of reports⁷²⁻¹⁰¹ to make them widely available.

2.3.1 Partitioning Processes

The ORNL program developed conceptual partitioning flowsheets for both a fuel reprocessing plant (FRP) and a mixed-oxide fuel fabrication plant. The processes used in these flowsheets are described below in summary form.⁹⁶

Partitioning of the wastes involves two generic steps: separation of the actinides from the waste by either leaching or breaking down strong organic-actinide chemical compounds, and recovery of the actinides. The second step is accomplished using the following standardized processing sequence:

1. The tetravalent and hexavalent actinides (uranium, plutonium, and neptunium) are recovered by TBP extraction, stripped from the solvent, and returned to the main purex process.
2. The trivalent actinides (americium and curium) and lanthanides are coextracted from the waste using a bidentate (CPM^b) extractant and stripped from the solvent for subsequent treatment using cation exchange chromatography (CEC). The residual waste is mixed with the liquid HLW for solidification before disposal.
3. The actinides are separated from the lanthanides using CEC. The lanthanide fraction is returned to the main process and mixed with the treated HLLW prior to solidification. The recovered actinides (americium and curium) are returned to the main process for conversion to the oxides.

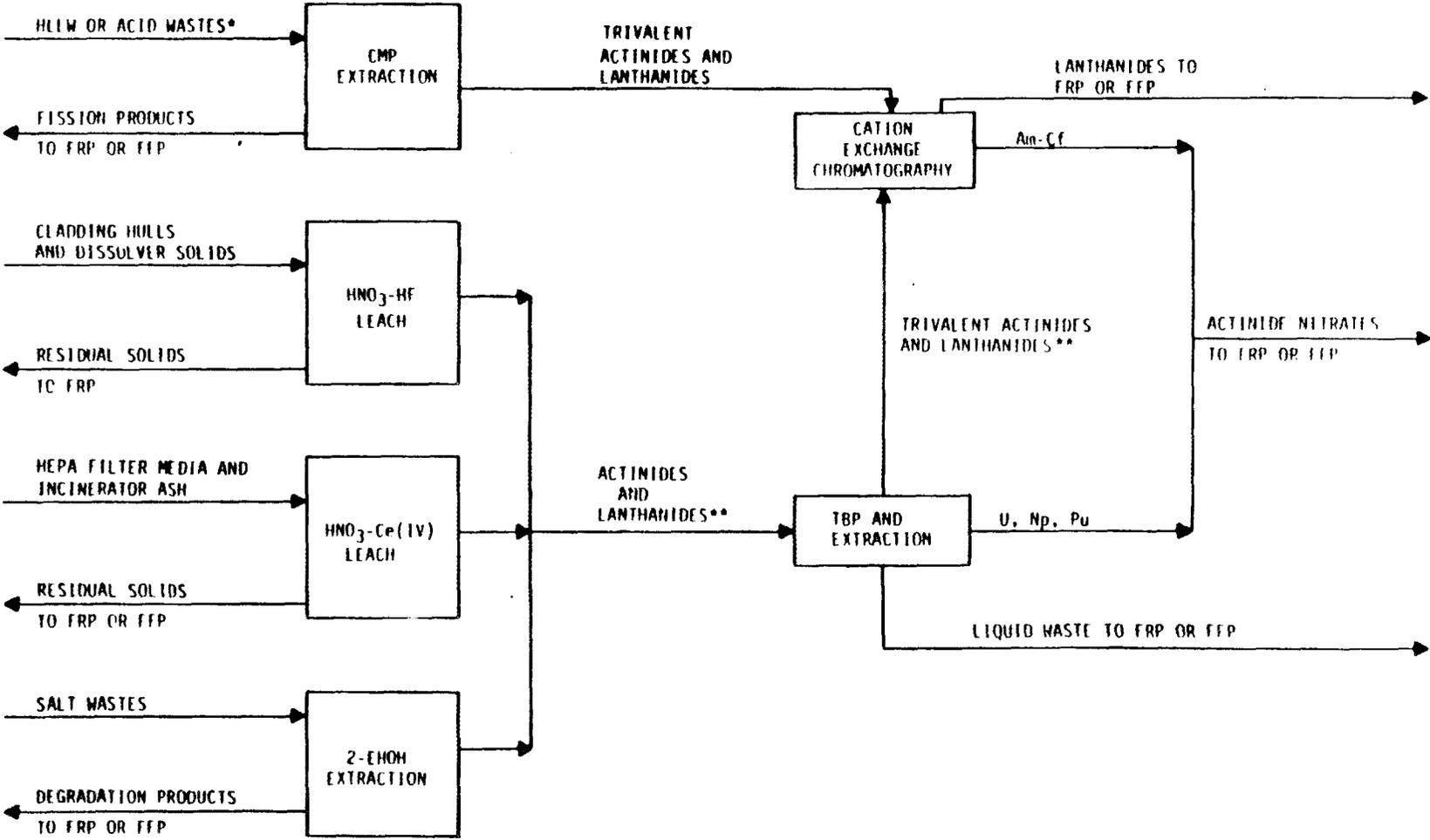
^bCPM = dihexyl-N,N-diethylcarbamylnethylene phosphonate.

This sequence is depicted schematically in the generic partitioning flowsheet shown in Fig. 2.1.

The major wastes from the main purex process are treated as follows:

1. The HLW, which is the raffinate from a TBP first-cycle solvent extraction in the FRP, is fed directly to the CMP extraction process for recovery of the trivalent lanthanides and actinides. These two groups of elements are subsequently separated using CEC.
2. The cladding hulls and dissolver solids, which have been previously leached with nitric acid, are subjected to a final leaching with HNO_3 -HF for removal of additional actinides. The fluoride ion catalyzes the dissolution of previously insoluble actinides.
3. The HEPA filter and incinerator ash wastes from both the FRP and the FFP contain actinides that are also largely insoluble in nitric acid. Leaching the filter media with HNO_3 -HF results in an intractable, gooey mass that cannot be filtered or centrifuged and will result in complete dissolution of the incinerator ash. Leaching with a HNO_3 -Ce(IV) solution has been found to be a suitable alternative. This process allows the physical characteristics of the HEPA media to be retained and only partially dissolves the incinerator ash. The Ce(IV) is produced by the electrolytic oxidation of Ce(III); and when the leaching is complete, oxalic acid is added to the system to convert Ce(IV) to Ce(III) and thus reduce equipment corrosion rates.
4. The salt wastes, principally the Na_2CO_3 solutions from solvent cleanup, contain a variety of actinides, many of which are bound in nonstrippable actinide-organic complexes. These complexes are destroyed and removed by extraction with 2-ethylhexanol (2-EHOH).

The actinides from the latter three wastes are then separated and recovered, first by TBP (for uranium, neptunium, and plutonium) and then by CMP (for trivalent actinides and lanthanides) extraction, followed by CEC (to separate the trivalent actinides and lanthanides).



*RAFFINATES FROM TBP EXTRACTION IN FRP OR FFP
**PREDOMINANTLY STABLE CERIUM AND GADOLINIUM

All of the actinide-depleted wastes are returned to the main process for final treatment (e.g., vitrification, concretion) and packaging for disposal. In general, the increases in process waste volumes are held to a minimum because of the use of chemicals that can be recovered and recycled. The concreted wastes increase significantly in volume (about 50%), and this can be attributed to the wastes produced by the CEC process and the additional solvent cleanup chemicals used in the partitioning. Failed equipment waste increases by 100% at the FRP site and 25% at the FFP site due to the partitioning.

2.3.2 Transmutation

As noted in the previous section, the transmutation studies described herein are restricted to neutron-induced transmutation. Furthermore, because of the relatively small number of studies on fusion reactors and the lack of definition concerning the design of a realistic fusion reactor, these potential transmutation devices are only considered briefly. Finally, as a result of these considerations, and of DOE (then ERDA) guidance, LWRs (specifically PWRs) were taken to be the reference transmutation device. LMFBRs were considered to be a parametric variation.

A review of the transmutation literature was given earlier which covered the major contributions to the literature prior to 1976. Table 2.6 lists many of the published contributions since that time. The table gives the principal investigator(s), the corporate or academic affiliation(s) of the investigators, a brief description of the transmutation studies reported, and a reference to any generally available documentation for the transmutation studies.

Evaluation of the transmutation literature cited in Table 2.6 indicates that, as in the earlier literature, many of the studies are uncoordinated and repeat work which has already been performed. However, there are several interesting aspects to the studies listed in Table 2.6.

1. Relatively sophisticated actinide transmutation calculations (i.e., multigroup, multidimensional) have been performed for thermal reactors, thus giving a more accurate picture of the neutronic behavior of the actinides in these systems.^{102,110,111,114}

Table 2.6. Summary of fission and fusion reactor transmutation studies

Investigators (Organization)	Description	Reference
C. Anderson (AE ATCMENERGI Studsvik, Sweden)	Recycling of actinides containing residues of yttrium and lanthanides in thermal and fast reactors	102
R. L. Engel D. E. Deonigi (Battelle, Richland)	Evaluations of fusion-fission concepts	103
G. A. Harte R. H. Clarke (UK Central Electricity Generating Board)	Incineration of UK reactor wastes in a fast breeder reactor	104
J. J. Prabalos (Combustion Engineering)	Actinide recycling in a 1500-MW(e) carbide LMFBR	105
M. Taube (Fed. Inst. for Reactor Research, Switzerland)	Transmutation of ^{90}Sr and ^{137}Cs in a fast reactor with a thermalized central region	106
R. Gasteiger (Karlsruhe)	Irradiation of $^{241}\text{AmO}_2$ in an aluminum matrix	107
T. H. Pigford J. Choi (U. of California-Berkeley)	Generic actinide transmutation study	108
E. Zamorani (Ispra)	Dose rates from LWR P-T fuel refabrication	109
T. C. Gorrell (SRL)	Survey calculations of candidate irradiation schemes for transmutation of waste actinides in thermal reactors	110-112
G. Oliva G. Palmiotti M. Salvatores L. Tondinelli (CNEN-Cassica)	Comparison of burnup in a Superphenix liquid-metal fast breeder reactor with that of a thermal reactor	113
G. Oliva L. Tondinelli (CNEN-Cassica)	Actinide recycling in LWRs	114
M. L. Williams J. W. McAdoo G. F. Flanagan (ORNL)	Actinide transmutation in an LMFBR	115

Table 2.6 (continued)

D. H. Berwald J. J. Duderstadt (Exxon Res. & Eng.; U. of Michigan)	A laser-fusion-driven actinide waste burner	116
D. J. Murphy W. M. Farr B. D. Ganapol (Sandia Laboratory; U of Arizona)	Actinide transmutation in a dedicated, hard-spectrum reactor	117
T. A. Parish (U. of Texas)	Transmutation of fission products by fusion neutrons	118, 119
A. H. Robinson (Oregon State University) G. W. Shirley (Gulf Atomic) A. W. Prichard (Oregon State University) T. J. Trapp (PNL)	Actinide transmutation in a dedicated, hard-spectrum reactor	120
S. L. Beaman (GE)	Extensive study of actinide transmutation in LMFBRs	121

2. A small sample of ^{241}Am was actually fabricated and irradiated.¹⁰⁷
3. A relatively detailed study of a fast reactor fuelled solely with waste actinides as published.¹¹⁷
4. Seven of the fifteen references are based on studies conducted in western Europe, where there is apparently somewhat more interest in the P-T concept than in the United States.
5. The study of fusion reactors as actinide and fission product transmutation devices has continued.^{103,116,118} Generally, present and previous studies have shown fusion transmutation reactors to be less attractive than had been originally thought, unless the material being transmuted is nearly critical, thus preventing the flux from rapidly decreasing in the blankets.

2.3.3 Conclusions

The conclusions of the ORNL evaluation of P-T are summarized as follows:

2.3.3.1 Feasibility

1. The partitioning of actinides appears to be feasible based on the use of currently identified technology, all of which has been experimentally verified at the laboratory level and much of which has been verified at the hot, production-scale level.
2. Although the partitioning of technetium has not been adequately investigated, there is presently no reason to believe that it is not feasible.
3. Iodine partitioning is feasible using existing, demonstrated technology.
4. The transmutation of actinides appears to be feasible in thermal, fast, and fusion reactors, subject to the acceptability of fuels

containing higher-than-normal concentrations of neptunium, americium, and curium.

5. The transmutation of technetium appears to be feasible, subject to the identification of an acceptable fuel form.
6. The transmutation of iodine is marginally feasible at best because of low transmutation rates, the volatility of iodine compounds, the production of xenon gas as a transmutation product, and the corrosiveness of iodine and its compounds.
7. The transportation of highly neutron-active P-T fuels appears to be feasible at a reasonable cost.

2.3.3.2 Incentives

1. The costs of actinide partitioning are relatively high, \$9.2 million/GW(e)-year, (~1 mill/Kwhr[e]) because of the variety of wastes that must be partitioned.
2. The short-term (contemporary) risks from P-T are substantial if the nonradiological impacts are taken into account, amounting to 0.57 health-effect/GW(e)-year. The short-term radiological risks are small, amounting to 0.003 health-effect/GW(e)-year.
3. The long-term benefits (i.e., risk reduction) of P-T, using very conservative assumptions, are small, amounting to only 0.06 health-effect/GW(e)-year, or about 0.001% of the effects of natural background radiation.
4. There are no incentives for actinide P-T, even if very conservative assumptions are used in the analysis. The cost of the actinide P-T benefits is \$32,400/person-rem if the nonradiological risks are ignored; if the nonradiological risks are included, the short-term risks exceed the long-term benefits integrated over 1 million years.

5. Incentives may exist for technetium P-T if very conservative long-term risk analysis assumptions continue to be used and if partitioning processes can be developed.
6. Incentives may exist for iodine P-T if very conservative long-term risk analysis assumptions continue to be used and a feasible method for transmuting iodine can be identified.
7. Sensitivity analyses indicate that the above conclusions concerning the incentives for P-T are valid for a wide range of input assumptions and parameters.
8. The incentives for P-T are virtually independent of the transmutation device used. Thus the existence of advanced devices would not alter the incentives.

2.3.4 Outcomes

The completed ORNL study formed the basis for subsequent DOE decisions concerning the future of P-T in the U.S. The salient result was the cessation of DOE support for and interest in P-T for many years following.

2.4 P-T STUDIES IN EUROPE CIRCA 1979-1982

During the time when the ORNL P-T study was being undertaken, and for a couple of years following, the European community undertook similar studies of P-T. This work was focussed at the Ispra Center in northern Italy, with primary interest from the Germans, British, and, to some extent, the French.

Both experimental study of partitioning processes and transmutation studies were undertaken. These studies were generally along the same lines as those done previously in the U.S. The Europeans eventually addressed the issue of P-T incentives, although in a much more qualitative manner than in the ORNL study. However, the salient result was the same: they found no incentives for P-T. At

this point, continued study of P-T greatly diminished in Europe, especially at the Ispra Center.

Unfortunately, the results of these studies were very poorly documented and what documentation is available is very difficult to interpret because of varying initial assumptions and language difficulties.

2.5 CURRENT EVENTS

Despite the lack of incentives resulting from previous studies, various aspects of P-T have continued to be studied during the last several years. The French briefly established P-T as national policy, primarily at the instigation of a single senior government official. This was never fully accepted by the French nuclear industry, and was never seriously pursued. This policy is now defunct, and P-T is not being seriously considered in France.

Numerous researchers have continued to evaluate actinide transmutation in a variety of devices. These studies have typically been performed in universities (theses) and by national laboratory staff members, and represent work of those unaware of the vast body of previous work, or continued promotion of ideas that have previously been rejected, respectively. Most of the studies are rudimentary, and repeat previous work.

DOE/DP has continued to support development of the TRUEX process because of the special nature of the defense tank waste (HLW) situation. In particular, because of the enormous volumes of tank waste that would potentially require exhumation and repository disposal, and the dilute nature of these wastes, separating the actinides may well result in significant cost savings that would not otherwise accrue in a commercial system.

Finally, the previous rejection of P-T as an effective means for managing long-lived wastes was primarily based on the lack of technical incentives. That is, the cost was high and the short-term risks outweighed the long-term benefits. However, it was stated at that time that there might nevertheless be incentives for P-T based on specific sociopolitical situations. Specifically, if the 'benefit' of P-T were to make waste management acceptable, and thus permit the

continued use of nuclear power, then the balance of the cost-benefit equation would likely shift to a favorable indication. It appears that this may become the case in Japan, with the situation indeterminate in some other countries. However, in all cases the government positions appear to be along the lines of supporting P-T at a relatively modest level while studiously avoiding any commitments unless forced to this position (i.e., a contingency option if political solutions are not effective).

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Chapter III

COST ANALYSIS FOR DISPOSAL OF WASTES FROM A P-T FUEL CYCLE

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This chapter examines the costs for disposal of spent fuel versus the costs of disposal of waste from a fuel cycle that included P-T of wastes to eliminate long-lived radionuclides. The economics are examined from two perspectives: the currently planned repository system (section 3.1) and other possible disposal systems (section 3.2). A summary of conclusions is presented in section 3.3.

3.1 Cost of HLW/SF Disposal

The Office of Civilian Radioactive Waste Management (OCRWM) of the Department of Energy has responsibility for disposal of spent fuel and high-level wastes in the United States. The original legislation¹ assigned to OCRWM only the responsibility for disposal of civilian wastes. A later decision by the President² expanded the OCRWM responsibility to include disposal of defense wastes. As defined by law, ORCWM has the responsibility to accept the wastes at the power reactor or other waste generator site, transport wastes, process and package wastes, and dispose of such wastes.

The funding for the program is from two sources. For civilian wastes, OCRWM collects a fee [1 mill/kWh(e)] from each utility for spent fuel generated. For defense wastes, Congress appropriates money. There is a legal requirement that the civilian program be fully funded by the monies paid by the utilities. Because of this requirement, OCRWM annually estimates all past and future program costs. Based on these cost estimates, the utility fees on utility spent fuel are adjusted annually. The cost numbers herein³ are based on these OCRWM numbers.

To understand these costs, this discussion will be divided into three sections: (1) engineering basis for cost estimates, (2) current cost estimates, and (3) implications for P-T.

3.1.1 Engineering Basis for Cost Estimates

For costing purposes, OCRWM breaks costs into three categories: (1) development and evaluation costs (D&E), (2) transportation costs, and (3) repository costs.

"The development and evaluation cost category covers all the siting, design, development, testing, regulatory, and institutional activities associated with the repositories, the facility for monitored retrievable storage (MRS), and the transport system. Most of the D&E activities take place before the construction of waste-management facilities and the fabrication of waste packages and transport casks, but some efforts, such as regulatory activities, continue during the facility-construction period.³" The key characteristic of these costs is that they tend to be independent of the quantity of wastes awaiting disposal.

The transportation cost category includes "the costs of fabricating shipping casks and carrying out the actual transport of waste once the waste management system is operational." Transportation costs are generally proportional to the quantities of waste to be handled.

The repository cost category includes both surface and underground facilities, disposal containers, and other related costs. The costs can be broken into capital and operating costs. Many capital costs are semi-independent of the waste quantities handled, while operating costs are primarily dependent upon radioactivity (heat and gamma radiation) of the wastes and only secondarily on the quantities of waste.

The repository capital costs include such items as receiving facilities, shafts, ventilation equipment, and initial underground works. Many of these items are one-of-a-kind items (such as access shafts or tunnels) whose cost is independent of the waste quantity to be handled.

The repository operating costs include the waste packages and the disposal tunnels into which the waste packages are to be placed. These operating costs are primarily dependent on the radioactive decay heat from the wastes and only

secondarily upon the volume of the wastes. The decay heat is from ^{137}Cs and ^{90}Sr , with only minor contributions from transuranic radionuclides and other radionuclides. Spent fuel, high-level waste, and P-T wastes have similar quantities of ^{137}Cs and ^{90}Sr , and similar quantities of decay heat per unit of energy generated in a power reactor. Consequently, from a repository engineering viewpoint, they are very similar wastes. The repository has multiple heat and temperature limits:

1. Waste package temperature must be limited to minimize failure of waste packages.
2. Near-field temperatures in disposal tunnels must be limited to avoid thermal stresses in tunnel rock which could cause structural failure of the tunnels.
3. Total heat output in an area of the repository must be limited to prevent repository failure by repository uplift. As decay heat is generated, the rock in the repository expands and uplifts the land surface above the repository. If there is too much uplift, the geology that isolates the waste may fail and allow water into the repository and cause repository failure.
4. High temperatures for long time periods may degrade the rock, allowing water flow through the repository.

To ensure repository integrity against effects of decay heat, three engineering solutions are used. All of these solutions create a system where operational costs depend primarily on radioactive decay heat rather than waste volumes or other characteristics of the waste. The engineering solutions are:

1. Wastes are packaged in containers with an expected lifetime of 300 to 1000 years. The radioactive decay heat in a repository primarily occurs during the first 300 years with the decay of ^{137}Cs and ^{90}Sr . Waste packages provide an independent barrier

against release of radionuclides during this period of high heat generation when the heat could be a driving force for damaging the performance of the repository.

2. A maximum decay heat output is specified for each waste package. This implies that either waste packages are loaded according to the decay heat of the wastes (not volume loaded) and/or small waste packages are chosen to avoid high heat outputs per package.
3. Waste packages are spaced out in disposal tunnels to minimize heat loading on the rock. The "capacity" of any mined disposal tunnel is determined by the heat given off from the wastes - not the toxicity, lifetime, or volume of the waste.

3.1.2 Current Cost Estimates

The 1987 cost estimates for the waste repository system are shown in Tables 3.1 through 3.5.

Table 3.1 lists key assumptions used by DOE in deriving total system life cycle costs with respect to system size and key engineering characteristics.

Table 3.2 shows estimated costs by major cost category and how their cost estimates have changed with time. All costs herein are in 1986 dollars. Several trends are evident. First is the explosive growth of D&E costs over the five-year history of the program. Second, estimated transport costs have decreased with time due to improved transport cask design, which allows for more spent fuel to be placed in a single cask. Third, the actual cost of the repository has remained relatively constant.

Tables 3.3, 3.4, and 3.5 break down the costs of the three system components: D&E, transportation, and repository.

In late 1987, Congress amended the Nuclear Waste Policy Act.⁴ This was, in part, due to the growth in D&E costs. The old program was based on simultaneously evaluating three possible sites for the first repository. The

Table 3.1. Key assumptions for the TSLCC analysis

Waste Types and Quantities

Spent fuel	106,300 MTU through 2020
DHLW	16,000 canisters (assumed to be equivalent to 800 MTU)
CHLW	300 canisters (from reprocessing 640 at West Valley)

Waste Characteristics

BWR	0-50,000 MWd/MTU
PWR	0-60,000 MWd/MTU

Two Repositories

Startup repository 1	2003 (70,000 MTU capacity)
Startup repository 2	2023 (remainder of waste)

Table 3.2. Total System Cost Estimates for the Reference System by Year of Cost Estimate (Adjusted to 1986 Dollars^a; Billions of Dollars)

Year of Cost Estimate	Cost Category ^a			Total Cost ^b
	D&E	Transportation	Repository	
1983	5.4	4.5	12.2-12.8	22.1-22.7
1984	8.4	2.0-4.3	11.6-14.2	23.0-26.9
1985	8.3	3.5-5.4	13.3-17.9	25.3-31.5
1986	9.2-9.6	1.5-2.6	12.8-21.3	24.2-33.1
1987 ^c	14.5-14.6	2.1-2.2	13.6-14.7	30.2-31.5

a. Cost Deflator: 1985-1986, 2.6%; 1984-1985, 3.3%; 1983-1984, 3.8%; and 1982-1983, 3.9%

b. Range of Costs reflect range of engineering and site assumptions.

c. Costs based on first repository in Nevada. Repository cost cases in earlier years included possible Basalt repository in the state of Washington which would have had higher transport and repository costs.

Table 3.3. Breakdown of D&E Costs
(Billions of Dollars)

First Repository	
Systems	0.337
Waste Package	0.396
Site	1.183
Repository	1.293
Regulatory	0.754
Exploratory Shaft	0.910
Test Facilities	0.082
Land Acquisition	0.034
Project Management	0.642
Subtotal	5.631
Second Repository	
Subtotal	4.711
Transportation and System Integration	
Subtotal	1.080
Socioeconomic Impact Mitigation	
Subtotal	0.66
Government Administration	
Subtotal	2.532
Grand Total	14.614

Table 3.4. Breakdown of Transport Costs
(Tuff/Salt Repository Case, Billions of Dollars)

Shipping	1.119
Inspection	.113
Detention	.055
Security	.296
Capital (Casks, etc.)	.510
Maintenance	<u>.314</u>
Total	2.412

Table 3.5. Breakdown of Repository Case
(Billions of Dollars)

Case (Repository Type)	Tuff/Hard Rock	Tuff/Salt
First Repository	Tuff	Tuff
Construction	1.22	1.22
Operation	4.86	4.67
Closure	<u>0.38</u>	<u>0.38</u>
Subtotal	6.46	6.27
Second Repository	Hard Rock	Salt
Construction	3.15	2.08
Operation	4.61	4.66
Closure	<u>0.46</u>	<u>0.35</u>
Subtotal	8.22	7.09
Total	14.68	13.55

revised program, as required by the amendments, is based on evaluating first the proposed repository site in Nevada. If the Nevada site is suitable for a repository, there should be major savings in D&E costs for the first repository. If the Nevada site is found unsuitable, D&E costs for the first repository would grow since a new national siting program would have to be initiated. Transportation and repository costs should not be greatly affected by this change in the law. Official costs estimates for the changes in the program have not yet been completed.

Earlier studies of the cost impacts of characterizing one disposal site versus three sites⁵ indicate D&E costs can be reduced by 15 to 20%, or 9 to 10% of the total program costs. Preliminary analysis of DOE costs shows similar savings. The relatively small savings reflect, in part, that many D&E costs are independent of the number of sites to be characterized.

In addition to base-case cost studies, OCRWM has conducted multiple sensitivity cost studies. These studies indicate that total costs are insensitive to the quantity of waste for disposal. An 18% reduction in tons of spent fuel to be disposed of reduces total costs by 4.6%. A 25% reduction in tons of spent fuel for disposal reduces total costs by 6.9%.

3.1.3 Cost Implications with Respect to Partitioning-Transmutation

If the wastes from a P-T cycle are sent to a conventional repository, the disposal costs are not expected to be significantly different from those for spent fuel or conventional high-level wastes. There are two reasons for this:

1. Major system costs (D&E, repository capital costs) are nearly independent of the quantities of the waste being handled.
2. Other system costs (transportation and repository operating costs) are primarily proportional to the radioactive decay heat of the waste. Radioactive decay heat is primarily from ¹³⁷Cs and ⁹⁰Sr with only minor contributions from transuranic radionuclides in the waste. Since decay heat per unit of

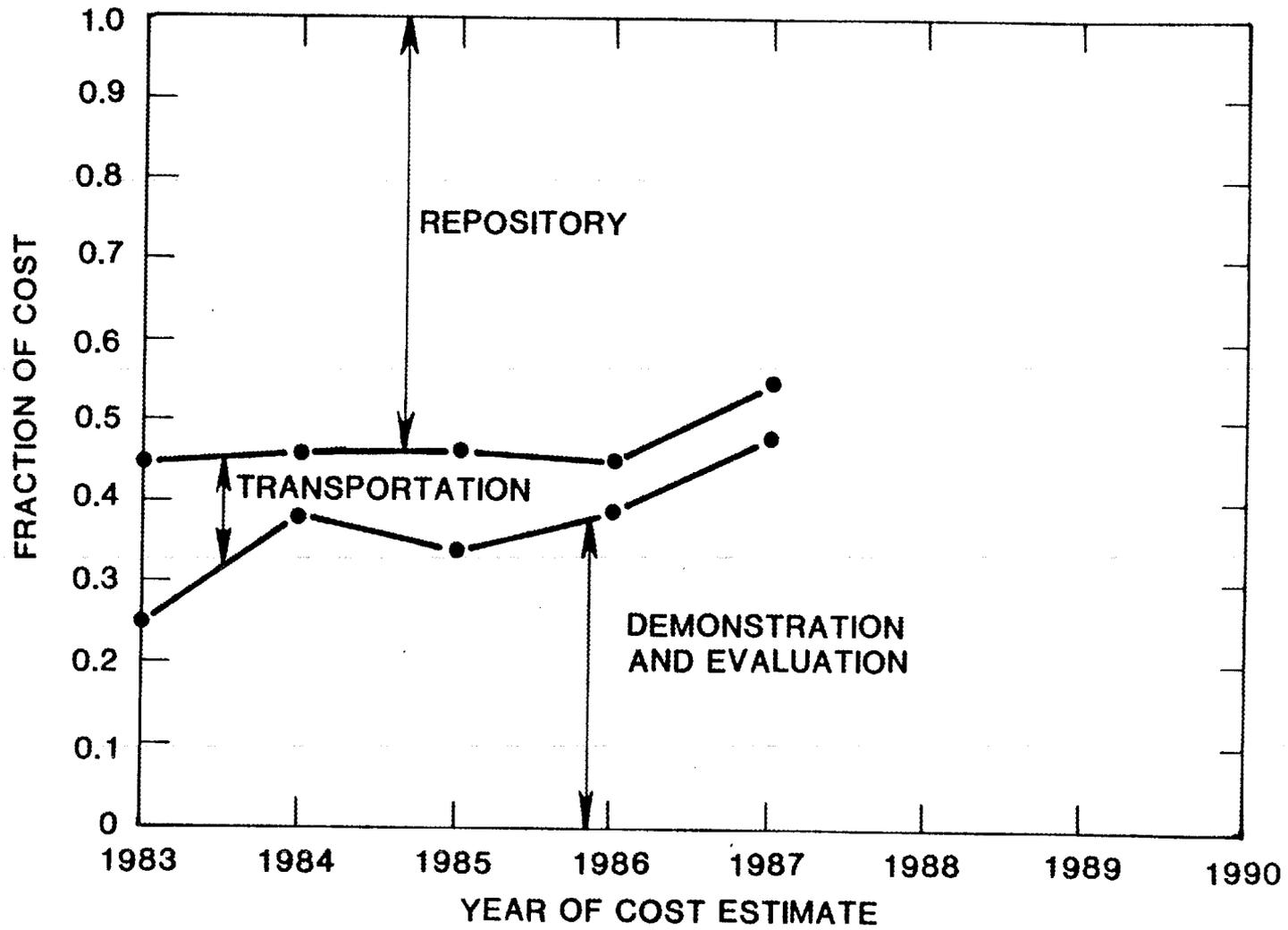
energy generated by the reactor is similar for high-level waste, spent fuel, and P-T wastes, these costs are similar for all three waste forms.

There is one major caveat with these conclusions. Demonstration and evaluation costs (Fig. 3.1) are the dominant costs and are growing rapidly. These costs are primarily to demonstrate to the public through the licensing process that the repository will protect public health and safety. The public concern and controversy over waste disposal derive in part, from the long-lived toxicity of these wastes. [Note: Controversy over low-level (short lived) radioactive wastes suggest the long-term hazard of radioactive waste is not the only public issue]. If P-T can significantly reduce licensing costs and/or alter these public perceptions, then D&E costs would be reduced as well as some repository costs. From a programming perspective, the difficulty is that D&E costs will primarily be incurred early in the program; hence, these costs may be sunk (already incurred) costs before any P-T program or policy would be accepted.

3.2 Other Disposal Systems

If the success of partitioning-transmutation is assured, then less restrictive methods of waste disposal may become possible. One method of greater confinement waste disposal is discussed herein - Modified Geological Disposal (Section 3.2.1). This method assumes that the high $^{137}\text{Cs}/^{90}\text{Sr}$ content of the wastes requires some type of geological disposal, but not with the same level of licensing proof of integrity as required for conventional high-level waste and spent fuel disposal. There have been many studies on Greater Confinement Disposal (GCD) of high-activity waste⁶; however, the levels of radioactivity are much less than would be found in a P-T system with the expected quantities of $^{137}\text{Cs}/^{90}\text{Sr}$.

A secondary issue with alternative waste systems is the issue of schedule (timing). A conventional repository has a very high front end cost but low incremental waste disposal costs. Once a repository becomes operational, there is less economic incentive to develop GCD disposal options. This issue is discussed in Sect. 3.2.2.



Distribution of Total System Life Cycle Costs vs Time.

3.2.1 Costs for a Modified Geologic Disposal

With P-T, the waste toxicity is primarily determined by the ^{137}Cs and ^{90}Sr . This toxicity will vanish within 300 to 1000 years. Since the repository will only need to perform for 1000 years, major simplifications are possible. The primary features of a P/T repository would be as follows:

1. The waste package planned for current repositories would be used for the P-T repository. These waste packages are designed to last approximately 1000 years, and hence provide full containment of the waste until it is relatively nonhazardous.
2. The waste package would be placed in a repository with the purpose of protecting the waste package from external threats. Since the repository is not needed to prevent the release of radionuclides to the environment, repository characterization would be primarily to ensure mine integrity during operations.
3. The minimal requirements for the repository suggest an existing, nonoperational mine could be used. This eliminates the need to build a repository. Repository construction would primarily involve upgrading of shafts and utilities. (Note: The initial Lyons, Kansas, repository cost estimate made in 1970 indicated a repository capital cost of approximately $\$25 \times 10^6$ or $\$65 \times 10^6$ in 1987 dollars. This low cost was primarily because it was assumed an existing mine would be used. There have also been some changes in standards since then.)

Table 3.6 shows the cost estimates for this type of repository starting with current system costs and reducing system costs where appropriate. Detailed descriptions of cost categories are those currently used by the OCRWM program.⁷

The basic conclusion is that disposal costs can be cut in half (or perhaps more). The key uncertainty is public acceptance for the current program, which is clearly driven by institutional issues.

Table 3.6. Cost estimate of simplified repository
(billions of dollars)

Cost Category	Current system	Simplified system	Comments
<u>D&E costs</u>			
First repository			
Systems	0.337	0.115	Proportional cost reduction
Waste package	0.396	0.396	Identical package
Site	1.183	0.394	Use existing mine information
Repository	1.293	0.431	Mine design effort limited
Regulatory	0.754	0.251	One-third costs
Exploratory shift	0.910	0.000	Existing mine, no cost
Test facilities	0.082	0.082	Identical
Land	0.034	0.034	Identical
Management	<u>0.641</u>	<u>0.219</u>	Proportional cost reduction
Subtotal	5.631	1.922	
Second repository	4.711	1.608	Same % reduction as first repository
System integration	1.080	0.369	Proportional cost reduction
Socioeconomic impact	0.66	0.225	Proportional cost reduction
Gov. administration	<u>2.532</u>	<u>0.864</u>	Proportional cost reduction
Total D&E	14.614	4.988	
<u>Transport costs</u>	2.412	2.412	Identical
<u>Repository costs</u>			
First repository			
Construction	1.22	0.610	One-half cost (existing facilities)
Operation	4.86	3.240	Two-third costs (less mining)
Closure	<u>0.38</u>	<u>0.380</u>	Identical
Subtotal	6.46	4.230	
Second Repository			
Construction	3.15	1.575	One-half cost
Operation	4.61	3.073	Two-third cost (less mining)
Closure	<u>0.46</u>	<u>0.46</u>	Identical
Subtotal	8.22	5.108	
Total Repository	14.68	9.338	
<u>GRAND TOTAL</u>	31.71	16.74	

*Proportional cost reduction implies costs reduced in proportion to total costs in category.

3.2.2 Schedule

The basic characteristic of the planned geologic waste disposal system is that it has very high front end costs with low incremental waste disposal costs. Once a repository is built, there is less economic incentive to develop alternative disposal methods since the money has already been spent. Table 3.7 shows planned expenditures by OCRWM through the year 2039. The two peaks in expenditure correspond to the two opening dates (2003 and 2023) of the two repositories. Recently, it was announced that the first repository opening will be delayed to 2010. The new schedule of expenditures has not yet been published. It is expected, however, that the growth and decrease of expenditures for any repository will follow a pattern similar to that shown. A repository closes about 25 years after initial operation.

The practical implication for P-T is that if a repository program is successful, most of the repository costs will be sunk costs by the time the repository is opened. The economic incentive is much less for P/T if a repository system is already operating.

3.3 Conclusions

The following economic conclusions can be drawn:

1. The cost of a repository is insensitive to the quantities of waste to be disposed of. Repository costs are sensitive to the heat generation rates of the waste; however, spent fuel, high-level waste, and P-T wastes have similar quantities of the primary high-heat generating isotopes - ^{137}Cs and ^{90}Sr . If wastes from a P-T fuel cycle are treated as conventional HLW, there will be no significant savings in waste management costs.
2. Disposal costs are primarily driven by licensing and repository performance issues. These, in turn, are being driven by public concerns about radioactive waste disposal.

Table 3.7. Total-system costs in multi-year increments*
(Millions of 1986 dollars)

Years	D&E costs	Transportation	First repository	Second repository	Total
1983-84	525	0	0	0	525
1985-89	2481	0	0	0	2481
1990-94	3299	0	0	0	3299
1995-99	1157	6	386	0	1549
2000-04	1144	98	990	0	2232
2005-09	1050	364	880	0	2294
2010-2014	2672	361	973	34	4040
2015-2019	729	311	936	1293	3269
2020-2024	547	398	844	2251	4040
2025-2029	125	424	619	1504	2672
2030-2034	125	238	100	1413	1876
2035-2039	105	98	100	637	940

*For authorized system with the EIA upper reference case with the first repository in tuff and the second repository in generic hard rock.

P-T may impact these costs but the uncertainty of any such cost analysis is high.

3. In theory, costs for disposal of P-T wastes could be half or less of conventional HLW if regulatory authorities reduce disposal requirements for these shorter-lived wastes and this is accepted by the public.
4. The economic incentives for a P-T fuel cycle are much less after startup of the first repository. In theory, a P-T cycle could eliminate the need for a second repository.

3.4 References for Chapter III

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Chapter IV

LEGAL AND REGULATORY ISSUES FOR EVALUATION OF POTENTIAL
FOR ACTINIDE PARTITIONING AND TRANSMUTATION

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1. Introduction

This chapter discusses a number of legal and regulatory issues of importance to an evaluation of the benefits of partitioning and transmutation of actinide radioelements in an integral fast liquid-metal reactor (LMR), the actinides having been produced by burning of uranium fuel in a light-water-cooled nuclear power reactor and by self-generated fuel recycle in an LMR system. As discussed elsewhere in this report, actinide transmutation in an LMR presumably would reduce the concentrations of long-lived transuranic (TRU) radionuclides in the residual wastes to levels much less than those that occur in the original spent fuel from the usual uranium fuel cycle.

Two sets of waste streams would be generated by use of an LMR system: (1) wastes from reprocessing of the original uranium spent fuel and (2) wastes from the LMR system itself. Throughout this chapter, the phrase "wastes from an LMR" is used to refer to both sets of waste streams.

Spent fuel from the usual uranium fuel cycle contains such high concentrations of long-lived, alpha-emitting TRU radionuclides that disposal in a deep geologic repository (or some other disposal system with equivalent waste-isolation capabilities) generally is regarded as necessary for long-term protection of public health. If the concentrations of TRU radionuclides in wastes from an LMR were sufficiently low (i.e., if the wastes consisted primarily of shorter-lived fission products, the most important of which would be ^{90}Sr and ^{137}Cs in wastes that have been aged for a few years), then disposal systems considerably less confining than a geologic repository might be acceptable. The potential benefits of acceptable alternatives to a

geologic repository for disposal of wastes from an LMR could include (1) a need for less stringent technical requirements for the disposal system, (2) increased confidence in demonstrations of compliance with technical requirements and with general environmental radiation standards, due to the shorter time period over which the waste would remain hazardous and isolation from man's exposure environment would be required, and (3) a significant reduction in the costs of waste disposal.

In this discussion, we assume that actinide transmutation in an LMR is used only for materials obtained from reprocessing of spent fuel from commercial nuclear power reactors. In this case, the U.S. Nuclear Regulatory Commission (NRC) will have licensing authority over all aspects of an LMR fuel cycle, and particularly over all radioactive wastes regardless of how they are classified or which types of disposal systems are used.

In our view, the key legal and regulatory issues to be considered in evaluating the potential benefits of partitioning and transmutation of actinides in an LMR may be stated as follows.

- [1] How would wastes from an LMR be classified for purposes of disposal? In particular, would the wastes be classified as high-level radioactive waste (HLW)?
- [2] Depending upon the classification of wastes from an LMR, what types of disposal systems would be required in order to ensure long-term protection of public health, and what technical requirements might be applied to these systems? In particular, could less costly alternatives to deep geologic repositories be acceptable?
- [3] If alternatives to deep geologic repositories could be acceptable for disposal of wastes from an LMR, is the legal and regulatory framework for developing these alternatives currently in place? If not, what additional laws and regulations might be needed?

The discussions in this chapter are presented in four parts. First, we discuss the three issues outlined above in light of current laws and regulations regarding waste classification and disposal. Second, we

discuss the potential impacts on development of an LMR system of current laws and regulations regarding (1) reprocessing of spent fuel from commercial power reactors and (2) the fee assessed on electricity generated by commercial reactors to support activities related to radioactive waste disposal in geologic repositories. Third, we discuss potential impacts on disposal of wastes from an LMR of current plans for disposal of reprocessing wastes generated by the atomic energy defense activities of the U.S. Department of Energy (DOE). Although we assume that the DOE's defense wastes would be excluded from an LMR system, current plans for their disposal could have important impacts on the potential benefits of partitioning and transmutation of actinides in commercial spent fuel. Finally, the last two sections present (1) some concluding remarks on the legal and regulatory issues of importance to classification and disposal of wastes from an LMR, including our views on difficulties which must be overcome for the proposed use of an LMR system to prove feasible, and (2) our recommendations for actions that should be taken by the DOE.

2. Classification and Disposal of Wastes from an LMR

In our view, the most important legal and regulatory issues affecting the potential benefits of partitioning and transmutation of actinides in an LMR are the questions of whether or not (1) the resulting wastes would be classified as HLW and (2) disposal in a deep geologic repository would be required. In the following paragraphs, we review the definitions of HLW and other waste classes, with particular emphasis on the NRC's current views regarding wastes that would be classified as HLW. We also review the current relationships between waste classification and acceptable disposal systems. The historical development of definitions of HLW and current definitions of other waste classes are discussed in detail elsewhere.¹⁻³

2.1 Waste Classification and Requirements for Disposal

High-Level and Transuranic Wastes. The term "high-level radioactive waste" traditionally has been applied to waste from a particular source, i.e., radioactive waste from chemical reprocessing of spent nuclear fuel. It also has long been recognized that reprocessing wastes contain high concentrations of (1) shorter-lived radionuclides (principally fission products), which produce high levels of decay heat and external radiation, and (2) long-lived, alpha-emitting TRU radionuclides. Again, it is primarily the high concentrations of long-lived TRU radionuclides which necessitate disposal systems for HLW that provide a high degree of long-term isolation from man's exposure environment. HLW was described in terms of its source, rather than its properties, because fuel reprocessing was the only significant source of waste with these characteristics.

In 1970, the first regulatory definition of HLW was promulgated in 10 CFR Part 50, Appendix F.⁴ Specifically, HLW was defined as:

"....those aqueous wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels."

There are two noteworthy aspects of this definition. First, although HLW refers to the highly concentrated waste which contains virtually all fission products and TRU radionuclides (except plutonium) in irradiated reactor fuel, the term "concentrated" is not quantified. Thus, it is implicit in the definition that normal burnups of uranium fuel in either commercial power reactors or defense production reactors result in sufficient concentrations of fission products and TRU radionuclides in the primary reprocessing wastes for these wastes to be classified as HLW.

Second, the definition of HLW does not include (1) radioactive hulls and other irradiated and contaminated fuel structural hardware or incidental wastes resulting from reprocessing plant operations (e.g., ion exchange beds or sludges).⁵ The NRC also has indicated that "incidental" wastes generated in the further treatment of HLW (e.g., decontaminated salts containing substantially lower concentrations of ⁹⁰Sr, ¹³⁷Cs, and Pu than first-cycle solvent extraction wastes) would be excluded from the

Appendix F definition.²

The first statutory definition of HLW appears in the Marine Protection, Research, and Sanctuaries Act of 1972 (Public Law 92-532). This Act adopted the definition in 10 CFR Part 50, Appendix F, but broadened it to include unprocessed spent fuel as well. The NRC later adopted this position when it declared spent nuclear fuel to be a form of HLW and, further, when it found TRU-contaminated wastes not to be HLW.^{6,7}

Another statutory definition of HLW of more restricted applicability appears in the West Valley Demonstration Project Act of 1980 (Public Law 96-368). Here, HLW was defined as:

"...waste which was produced by the reprocessing at the [West Valley] Center of spent nuclear fuel. Such term includes both liquid wastes which are produced directly in reprocessing, dry solid material derived from such liquid waste and such other material as the Commission designates as high level radioactive waste for purposes of protecting the public health and safety."

The NRC has not yet designated any "other material" as HLW under the West Valley Act. Rather, the NRC has interpreted this term in a manner consistent with the definition in 10 CFR Part 50, Appendix F; i.e., HLW is the liquid wastes in storage at West Valley and the dry solid materials derived from solidification of these liquid wastes.

The NRC's current definition of HLW is contained in 10 CFR Part 60.⁸ Here, HLW is defined as:

"...(1) irradiated reactor fuel, (2) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted."

Thus, the NRC has retained the qualitative definition of HLW in previous laws and regulations, and spent fuel is still included in HLW.

The NRC's 10 CFR Part 60 governs licensing of DOE activities at deep geologic repositories. However, the NRC has emphasized that 10 CFR Part 60 does not require (1) that any radioactive materials, whether they are

classified as HLW or not, be stored or disposed of in a geologic repository or (2) that radioactive materials be classified as HLW in order to be eligible for disposal in a geologic repository.²

The NRC's 10 CFR Part 60 also contains technical criteria for the performance of engineered barriers and the surrounding environment in a geologic repository system. These criteria include:⁸

- substantially complete containment of waste within waste packages for 300-1,000 years;
- a limit on release rate of any radionuclide from the engineered barrier system following the containment period of (1) 10^{-5} per year of the inventory of that radionuclide at 1,000 years following permanent closure of the repository or (2) 10^{-5} per year of the inventory of all radionuclides placed in the disposal facility that remains after 1,000 years of decay; and
- a pre-waste-emplacment ground-water travel time along the fastest path of likely radionuclide travel from the edge of the disturbed zone (i.e., the region beyond the excavation within which mechanical or thermal disturbances may significantly affect repository performance) to the accessible environment (e.g., any part of the lithosphere more than 5 km from the outer boundary of the original location of wastes in the disposal system) of at least 1,000 years.

On a case-by-case basis, however, the NRC may approve or specify alternative criteria for the containment period, radionuclide release rate, or pre-waste-emplacment ground-water travel time.⁸ In this regard, we note that the criteria for release rate and ground-water travel time are intended primarily to ensure adequate long-term isolation of the long-lived TRU radionuclides which occur in high concentrations in the usual spent fuel and HLW. Thus, the NRC might approve a relaxation of these requirements for disposal in geologic repositories if the waste contains much lower concentrations of TRU radionuclides.

The most recent statutory definition of HLW is contained in the Nuclear Waste Policy Act (NWPA) of 1982 (Public Law 97-425). In the NWPA, HLW is defined in two parts as:

- "(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and
- (B) other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation."

The definition of HLW in Clause (A) follows the traditional source-based definitions in 10 CFR Part 50, Appendix F, and the Marine Sanctuaries Act, and the definition again is only qualitative; i.e., the phrases "highly radioactive material" and "fission products in sufficient concentrations" are not quantified. However, in contrast to the definition in 10 CFR Part 60, the NWPA does not classify spent fuel as HLW.

The definition of HLW in Clause (B) of the NWPA represents a significant departure from previous statutory and regulatory definitions in that it calls for development of a generally applicable definition, i.e., one that is not based on the source of the waste. However, as in Clause (A), the phrases "highly radioactive material" and "requires permanent isolation" are not quantified. The NRC's response to the definition in Clause (B) is considered later in this chapter in the discussions of ongoing developments in waste classification.

As in the case of the NRC's 10 CFR Part 60, the NWPA does not require that spent fuel or HLW be disposed of in a geologic repository. Indeed, the NWPA directs the DOE to continue investigations into alternative technologies for permanent disposal of these wastes. On the other hand, the NWPA does not specifically authorize the DOE to construct or operate alternative disposal facilities. Thus, new legislative authorization might be needed in order to dispose of spent fuel or HLW by means other than emplacement in a deep geologic repository.²

In 40 CFR Part 191, the U.S. Environmental Protection Agency (EPA) has developed general environmental radiation standards for disposal of spent nuclear fuel, HLW, and TRU waste.⁹ As in the case of the NWPA and

the NRC's 10 CFR Part 60, the EPA standards do not require disposal of these wastes in a geologic repository. We note, however, that a geologic repository was the only disposal system assumed by the EPA in performing the technical analyses used to support development of the standards.¹⁰⁻¹²

The EPA's 40 CFR Part 191 has adopted the definition of HLW in the NWPA. Then, TRU waste is defined as "...waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) high-level radioactive waste; (2) wastes that the [DOE] has determined, with the concurrence of the [EPA], do not need the degree of isolation required by this Part; or (3) wastes that the [NRC] has approved for disposal on a case-by-case basis in accordance with 10 CFR [Part] 61."

Most TRU wastes currently are generated by the DOE's defense activities,¹³ and the DOE's wastes are intended for disposal at the Waste Isolation Pilot Plant (WIPP). However, the WIPP facility is not permitted to accept for permanent disposal any waste classified as HLW.¹⁴

Low-Level Waste. In 10 CFR Part 61, the NRC has established technical criteria for three classes of radioactive waste that are generally acceptable for near-surface land disposal.¹⁵ Class-C wastes contain the highest radionuclide concentrations; e.g., the Class-C concentration limit for long-lived, alpha-emitting TRU radionuclides is 100 nCi/g. Then, so-called greater-than-Class-C wastes generally would require disposal using technologies more confining than near-surface land disposal, unless an exception is authorized by the NRC.¹⁵

Although near-surface land disposal generally is associated with low-level radioactive waste (LLW), the NRC's 10 CFR Part 61 does not define LLW. Thus, some wastes with concentrations of radionuclides greater than the Class-C limits that are generally acceptable for near-surface land disposal may be classified as LLW.

LLW currently is defined in the Low-Level Radioactive Waste Policy Amendments Act (LLWRPAA) of 1985 (Public Law 99-240) as material that is not HLW, spent fuel, or byproduct material (e.g., uranium mill tailings). Thus, LLW is defined only by exclusion, and there is no statutory or regulatory limit on the concentrations of radionuclides in LLW. According to the definition in the LLWRPAA, TRU waste, as defined in the EPA's 40 CFR Part 191,⁹ also would be a form of greater-than-Class-C LLW.

The LLRWPA assigns to the DOE the responsibility for disposal of greater-than-Class-C LLW, including all such waste generated in the commercial sector. The DOE has indicated that it will manage and store greater-than-Class-C LLW pending resolution of several issues affecting development of acceptable methods for disposal.¹⁶ Some of the needed regulatory actions identified by the DOE include: (1) promulgation by the NRC of licensing guidance for disposal facilities for greater-than-Class-C LLW; (2) promulgation by the EPA of a general environmental radiation standard for disposal of non-TRU greater-than-Class-C LLW (the EPA's 40 CFR Part 191 applies to disposal of TRU waste⁹); (3) a decision by the NRC whether or not to proceed with developing a generally applicable definition of HLW in response to Clause (B) of the NWPA, since such a definition could change the present definition of greater-than-Class-C LLW; and (4) if the decision is to develop a generally applicable definition of HLW, promulgation of the definition by the NRC.

2.2 Ongoing Developments in Waste Classification and Disposal

In 1987, the NRC published an advance notice of proposed rulemaking (ANPR) amending 10 CFR Part 60, which indicated the NRC's intent to develop a quantitative and generally applicable definition of HLW in response to Clause (B) of the NWPA.² The ANPR suggested that the generally applicable definition would be expressed in terms of minimum concentrations of radionuclides that would constitute HLW, and that these concentrations would be based on an analysis of risks from waste management and disposal. In particular, the generally applicable definition would quantify the phrases "highly radioactive" and "requires permanent isolation" that appear in the Clause (B) definition.

One important issue on which the NRC requested comment in the ANPR was whether the generally applicable definition of HLW should also encompass and quantify the traditional source-based definition in Clause (A) of the NWPA (i.e., quantify the phrase "fission products in sufficient concentrations"), or whether the phrase "other highly radioactive material" in Clause (B) should apply only to materials other than reprocessing wastes (i.e., to wastes presently classified as

greater-than-Class-C LLW). In the latter interpretation, which the NRC indicated it preferred,² the definition in Clause (A) would continue to apply to all wastes previously considered to be HLW according to the source-based definitions in 10 CFR Part 50, Appendix F, and the Marine Sanctuaries Act.

Following publication of the NRC's ANPR on revising the definition of HLW in 10 CFR Part 60, a proposal for a quantitative, generally applicable, and risk-based classification system for HLW and other radioactive wastes was published by Oak Ridge National Laboratory (ORNL) under DOE sponsorship.³ The ORNL study concluded that a reasonable waste classification system could be developed in which (1) the generally applicable definition of HLW that addresses Clause (B) of the NWPA also encompasses and quantifies the traditional source-based definition in Clause (A) and (2) all radioactive wastes are identified uniquely on the basis of the concentrations of radionuclides, without regard to the source of the waste. Furthermore, the waste classification system proposed in the ORNL study requires only near-surface land disposal and deep geologic repositories as acceptable disposal systems. This is a desirable result, since these are the only disposal alternatives recognized in current law for which general environmental radiation standards⁹ and technical criteria^{8,15} have been developed.

However, in spite of the ANPR on revising the definition of HLW² and the encouraging results from the ORNL waste classification study,³ the NRC has since indicated, in a proposed rulemaking amending 10 CFR Part 61, its intent to abandon efforts to develop a generally applicable definition of HLW in response to Clause (B) of the NWPA.¹⁷ In essence, it is the NRC's view that the Clause (B) definition would not apply to reprocessing wastes as defined in Clause (A) of the NWPA.^{2,17} The NRC then judged that there is no compelling need to develop a new definition of HLW, given the current institutional setup for radioactive waste management, the small volumes of greater-than-Class-C LLW that exist now or likely will be generated in the future, and the considerable efforts that would be required for the NRC (1) to define wastes that "require permanent isolation," i.e., to quantify on the basis of a risk analysis the minimum concentrations of radionuclides that require disposal in deep geologic repositories for long-term protection of public health, and (2) to develop

technical criteria for intermediate disposal facilities, which would be intended for disposal of greater-than-Class-C wastes that do not require disposal in a geologic repository.

Thus, the NRC has indicated its intention to maintain the existing definitions of HLW and LLW. That is, HLW would continue to be defined on the basis of its source as spent fuel or the primary wastes from fuel reprocessing (incidental wastes produced in reprocessing would continue to be excluded from the definition¹⁷), and LLW would be any radioactive waste other than spent fuel, primary reprocessing wastes, or byproduct material. In particular, greater-than-Class-C waste would continue to be classified as LLW.

The important proposed amendment to 10 CFR Part 61 is the requirement that greater-than-Class-C LLW be placed in a deep geologic repository, unless disposal elsewhere has been approved by the NRC.¹⁷ This proposal would address some of the DOE's concerns regarding regulatory requirements for disposal of these wastes¹⁶ discussed previously.

2.3 Summary of Current Requirements and Needed Regulatory Actions

The following paragraphs summarize the current statutory and regulatory requirements for waste classification and disposal and the needs for further laws and regulations to address classification and disposal of wastes from an LMR. Some of these discussions necessarily represent our opinions.

Waste Classification. If the language in definitions of HLW in current law and regulations were interpreted literally, then one would conclude that wastes from an LMR must be classified as HLW, because these wastes would include the primary wastes from reprocessing of spent nuclear fuel. However, it is important to recall that the types of reprocessing wastes (and spent fuel) that have been classified as HLW have certain properties that are essential to this classification, particularly the presence of high concentrations of fission products and long-lived, alpha-emitting TRU radionuclides. Thus, if wastes from an LMR would have much lower concentrations of these radionuclides than the original spent fuel, then the NRC might consider the former not to be HLW. An example

precedent for such a finding is the NRC's current position that incidental wastes from reprocessing operations are not classified as HLW, because they contain much lower concentrations of fission products and TRU radionuclides than the primary reprocessing wastes.

Spent fuel from commercial reactors typically contains concentrations of the important long-lived, alpha-emitting TRU radionuclides ^{237}Np , ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Am , and ^{243}Am about two-to-five orders of magnitude greater than the Class-C limit for near-surface land disposal of 100 nCi/g specified in the NRC's 10 CFR Part 61.^{3,15,18,19} On the basis of discussions in the NRC's ANPR on revising the definition of HLW,² it can be inferred that wastes from an LMR still would need to be managed as HLW if the concentrations of TRU radionuclides were greater than 100 nCi/g. This inference presumes that the concentrations of the principal fission products ^{90}Sr and ^{137}Cs also would exceed their Class-C limits,¹⁵ which is highly likely due to the high concentrations of these radionuclides in the original spent fuel^{3,15,18,19} and the apparent lack of a method for significant transmutation of fission products in an LMR system. Thus, we would surmise that in order for the NRC to judge that wastes from an LMR are not HLW, a very high percentage of TRU radionuclides would need to be removed from the original spent fuel and transmuted in an LMR. If the resulting concentrations of TRU radionuclides in wastes from an LMR were below the Class-C limit of 100 nCi/g, then the wastes presumably could be classified as greater-than-Class-C LLW on the basis of current waste definitions.

Requirements for Waste Disposal. Regardless of whether wastes from an LMR would be classified by the NRC as HLW or greater-than-Class-C LLW according to current definitions, current law and regulations do not specify that certain disposal systems must be used for particular classes of waste. In particular, neither the NWPA nor the NRC and EPA standards^{8,9} require that waste be placed in a deep geologic repository if it is classified as HLW.² Furthermore, the NRC's proposed amendments to 10 CFR Part 61 would not require, without exception, that all greater-than-Class-C LLW be placed in a geologic repository.¹⁷

On the other hand, near-surface land disposal and deep geologic repositories are the only disposal systems which have been authorized by law and for which general environmental radiation standards and technical

criteria have been developed. Thus, under current law and regulations, a geologic repository is the only authorized disposal system for wastes classified as HLW. Furthermore, the NRC's proposed amendments to 10 CFR Part 61 indicate that a geologic repository is the intended disposal system for greater-than-Class-C LLW.¹⁷

Needed Laws and Regulations. If we assume that wastes from an LMR would be classified as either HLW or greater-than-Class-C LLW, then additional laws and regulations would be required to permit disposal using systems other than a deep geologic repository. Acceptable alternatives could have waste-isolation capabilities equivalent to those of a repository or intermediate between those of a repository and systems for near-surface land disposal. Again, intermediate disposal facilities presumably would be considerably less costly than a geologic repository.

If wastes from an LMR were classified as HLW, then new legislative authorization probably would be needed in order to develop disposal systems other than a geologic repository,² because the NWPA does not specifically authorize construction or operation of alternative disposal facilities for HLW. Although the general environmental radiation standards for disposal promulgated by the EPA⁹ would apply to alternative disposal facilities for HLW, the existence of these standards is not necessarily advantageous for development of alternative disposal systems for wastes from an LMR, due to two factors. First, as mentioned previously, the EPA standards were developed with the assumption that geologic repositories would be used for disposal of HLW, but the long-term containment requirements in Section 191.13 may not be appropriate for intermediate disposal facilities and, furthermore, are so stringent that they may not be reasonably achievable by such facilities. Second, the First Circuit Court recently vacated the individual protection and ground-water protection requirements in Sections 191.15 and 191.16, respectively, and remanded the standards to the EPA for further rulemaking proceedings.²⁰ The EPA has not yet published a proposal for modifying the standards consistent with the Court's opinion, so the final form of standards for disposal of HLW is uncertain. In addition, regardless of how the EPA standards are revised, the NRC would need to develop a new set of technical criteria by which disposal in alternative facilities would be licensed, since the criteria in 10 CFR Part 60 apply only to geologic

repositories.⁸ For intermediate disposal facilities, these criteria presumably would include limits on concentrations of radionuclides that are acceptable for disposal.²

If wastes from an LMR were classified as greater-than-Class-C LLW, rather than HLW, then additional legislative authorization would not be needed to develop alternatives for disposal, because the LLWRPAA specifically requires that the NRC (1) identify disposal methods for LLW other than shallow-land burial, which presumably would include intermediate disposal facilities for greater-than-Class-C wastes, and (2) establish technical criteria by which such facilities would be licensed. Thus, there would be an immediate advantage if wastes from an LMR were not classified as HLW. In this case, however, a general environmental radiation standard, which would be the responsibility of the EPA, has not been developed; and, again, the NRC has not developed the required technical criteria for licensing of disposal facilities other than geologic repositories⁸ and facilities for near-surface land disposal.¹⁵ Both types of regulations would be needed before an intermediate disposal facility could be developed for greater-than-Class-C wastes from an LMR. Furthermore, the NRC has indicated that it will not promulgate the required technical criteria until the DOE demonstrates a compelling need for such a facility.^{2,17}

We would also caution that wastes from an LMR still might require disposal in a geologic repository even if (1) the wastes contain sufficiently low concentrations of long-lived TRU radionuclides that they would be classified by the NRC as greater-than-Class-C LLW and (2) the necessary regulations for developing intermediate disposal facilities were promulgated by the EPA and the NRC. In the ORNL waste classification study,³ a crude analysis was performed to estimate maximum concentrations of radionuclides that would be acceptable for intermediate-depth burial (i.e., minimum concentrations that would require a deep geologic repository or equivalent). The analysis suggests that the concentrations of the shorter-lived fission products ^{90}Sr and ^{137}Cs , as well as the longer-lived ^{99}Tc and ^{126}Sn , could be sufficiently high in the original spent fuel from commercial reactors that the wastes from an LMR would be unacceptable for intermediate disposal unless significant transmutation of these radionuclides occurred in the LMR system. Although these results do

not represent a definitive analysis,³ they indicate that concentrations of fission products as well as long-lived TRU radionuclides will be of concern in determining acceptable alternatives for disposal of wastes from an LMR.

Finally, we believe that development by the NRC of a quantitative, generally applicable, and risk-based waste classification system in response to the definition of HLW in Clause (B) of the NWPA which also encompasses the traditional source-based definition in Clause (A), e.g., as proposed in the ORNL study,³ would be of benefit in developing reasonable and defensible proposals for disposal of wastes from an LMR, primarily because (1) such wastes were not envisioned in developing the present system for waste classification and (2) a generally applicable waste classification system would encourage increased flexibility in developing waste management and disposal systems while still protecting public health. However, we also acknowledge that a revised waste classification system is not necessary for developing alternatives to a geologic repository for disposal of wastes from an LMR, due to the provisions in current law and regulations that permit such alternatives for existing waste classes.

3. Fuel Reprocessing and the Nuclear Waste Fund

This section briefly discusses current law and regulations regarding (1) reprocessing of spent fuel from commercial reactors and (2) the Nuclear Waste Fund, which was established by the NWPA to support activities related to disposal of commercial spent fuel and HLW in geologic repositories. In both cases, changes in current law and regulations probably may be needed in developing an LMR system.

3.1 Fuel Reprocessing

An essential requirement for the proposed use of an LMR system is the capability for reprocessing of the large amounts of spent fuel that routinely are being generated and stored at commercial power reactors. At

the present time, commercial spent fuel is not being reprocessed, due primarily to economic disincentives arising from (1) the current Federal policy that such reprocessing should be financed by the private sector and (2) lack of a market for the plutonium obtained from reprocessing.

It should be emphasized, however, that there are presently no legal barriers to reprocessing of commercial spent fuel. Indeed, the NWPA addresses disposal in geologic repositories of HLW derived from reprocessing of spent fuel from commercial power reactors. On the other hand, it seems reasonable to assume that new legislative authorization will be needed to develop an LMR system, including facilities for reprocessing of commercial spent fuel, particularly if we assume that initial development and testing of prototype systems will be the responsibility of the DOE.

The EPA's general environmental radiation standards for the uranium fuel cycle in 40 CFR Part 190 would apply to facilities for reprocessing of commercial spent fuel,²¹ and such facilities would be licensed by the NRC according to procedures specified in 10 CFR Part 50.²² It also should be anticipated that the NRC will develop detailed technical requirements for the construction and operation of reprocessing facilities which would be similar to the current technical requirements for operating commercial reactors in 10 CFR Part 50, Appendix A.²³

3.2 *Nuclear Waste Fund*

Section 302 of the NWPA has established a Nuclear Waste Fund primarily for the purpose of offsetting expenditures related to disposal of commercial spent fuel and HLW in geologic repositories. The Waste Fund is supported by assessing a fee of 1 mil per kilowatt-hour on electricity generated by commercial nuclear power reactors.

If an LMR system could be developed which would obviate the need for geologic repositories for disposal of the primary wastes arising from burning of uranium fuel in commercial power reactors, then it still may be reasonable to maintain a fund similar to that specified in the NWPA to support activities related to disposal of wastes from an LMR. However, since the cost of disposal of these wastes presumably would be

significantly less than the cost associated with present plans for disposal of commercial spent fuel and HLW in a geologic repository, it also seems reasonable that the Congress would reexamine the question of an appropriate fee on electricity generated by commercial light-water reactors and LMRs to support activities related to waste disposal.

4. Effect of Defense HLW on Disposal of Wastes from an LMR

Defense HLW (i.e., the primary reprocessing wastes from the DOE's production reactors) is being stored or produced at a number of DOE sites.¹³ Current and projected volumes of defense HLW are considerably larger than those for commercial spent fuel,¹³ but the concentrations of both fission products and long-lived, alpha-emitting TRU radionuclides in defense HLW are considerably less than the corresponding concentrations in commercial spent fuel.^{18,19} Although we have assumed that defense HLW will be excluded from an LMR system, current plans for disposal of defense HLW could greatly influence the cost-effectiveness of alternatives to a deep geologic repository for disposal of wastes from an LMR.

In addition to establishing a geologic repository program for disposal of commercial spent fuel and HLW, the NWSA directed the President to evaluate the use of one or more of these repositories for disposal of defense HLW, as opposed to the alternative of developing separate disposal facilities. (We note again that the DOE's WIPP facility for disposal of defense TRU waste cannot be used for permanent disposal of defense HLW.¹⁴) The evaluation was to take into account factors relating to cost efficiency, health and safety, regulation, transportation, public acceptability, and national security.

On the basis of a study performed by the DOE,²⁴ the President recommended that defense HLW be co-disposed in the same repository with commercial spent fuel and HLW. This decision was based primarily on considerations of cost efficiency, since all other factors mentioned above were judged to be of little importance to the choice.

Development of an LMR system for partitioning and transmutation of actinide elements in commercial spent fuel probably will be cost-effective only if the need for a geologic repository is obviated and a considerably

less costly disposal system can be used. Thus, development of an intermediate disposal facility for wastes from an LMR probably can be justified only if a similar alternative to a geologic repository could be used for disposal of defense HLW. On economic grounds, it probably makes little sense to develop an alternative disposal system for wastes from an LMR, even if it is considerably less costly, while maintaining the present repository program for disposal of defense HLW only.

Therefore, in conjunction with the necessary investigations into the feasibility of alternatives to a geologic repository for disposal of wastes from an LMR, it would seem highly desirable to conduct similar investigations for disposal of defense HLW. A crude analysis of the acceptability of intermediate-depth burial for defense HLW in borosilicate glass from the Savannah River Plant was presented in the ORNL waste classification study.³ The analysis was not encouraging for the proposed use of an LMR system, because the results suggested that the concentrations of both fission products (i.e., ^{126}Sn and ^{137}Cs) and long-lived, alpha-emitting TRU radionuclides (i.e., ^{238}Pu , ^{239}Pu , ^{240}Pu , and ^{241}Am) in defense HLW could be sufficiently high that disposal in a geologic repository would be required for protection of public health. However, this conclusion would need to be sustained by a more rigorous analysis which would take into account the variety of defense HLW at all DOE sites¹³ and information related to the long-term performance of particular types of intermediate disposal systems at specific sites.³

5. Conclusions

In this chapter, we have discussed legal and regulatory issues related to classification and disposal of wastes from an LMR system. Two principal conclusions may be drawn from this discussion.

- [1] HLW currently is defined only in terms of its source as the primary wastes from reprocessing of spent nuclear fuel. However, there are no legal or regulatory barriers to reclassifying the primary wastes from an LMR as non-HLW (i.e., as greater-than-Class-C LLW), provided the concentrations of long-lived, alpha-emitting TRU radionuclides

are less than the Class-C limit of 100 nCi/g that is generally acceptable for near-surface land disposal.

- [2] Regardless of how wastes from an LMR would be classified, there are no legal or regulatory barriers to seeking alternatives to a deep geologic repository for disposal of such wastes, including systems with waste-isolation capabilities intermediate between those for near-surface land disposal and a geologic repository.

It is also reasonable to conclude that, under current law and regulations, the classification of wastes from an LMR would be largely irrelevant to a determination of acceptable alternatives to disposal in a geologic repository, because definitions of particular waste classes are not associated with requirements for use of specific disposal systems.

Although there are currently no legal or regulatory barriers to classification of wastes from an LMR as non-HLW or to disposal of these wastes in intermediate facilities, we have emphasized that there are institutional barriers, particularly within the NRC, to fundamental changes in current practices regarding waste classification and disposal. In addition, there are two important technical considerations related to waste disposal which are not encouraging with regard to the feasibility of the proposed use of an LMR system.

- [1] Even if the concentrations of long-lived, alpha-emitting TRU radionuclides are reduced to levels less than the Class-C limit of 100 nCi/g that is generally acceptable for near-surface land disposal, wastes from an LMR may contain sufficient concentrations of fission products that disposal in a geologic repository still would be required for protection of public health.
- [2] The DOE's defense HLW, which is assumed to be excluded from an LMR system, may contain sufficient concentrations of both fission products and long-lived, alpha-emitting TRU radionuclides that disposal in a geologic repository would be required for protection of public health. In this case, the economic incentive for developing less costly alternatives for disposal of wastes from an

LMR probably would be negated.

If either of these conditions were borne out by rigorous technical analysis, then we believe that there would be little justification for the proposed use of an LMR system in regard to the potential benefits arising from disposal in facilities other than a deep geologic repository.

We also discussed changes in current law and regulations that would be needed to permit disposal of wastes from an LMR in an intermediate disposal facility, rather than a deep geologic repository. At the present time, all wastes classified as HLW are intended (but not required) for disposal in a geologic repository. Furthermore, proposed NRC regulations¹⁷ indicate the same intention for greater-than-Class-C LLW, regardless of the concentrations of TRU radionuclides. Thus, unless all wastes from an LMR system (including wastes from reprocessing of the original spent fuel) contain concentrations of TRU radionuclides and fission products less than their Class-C limits, in which case the wastes would be generally acceptable for near-surface land disposal,¹⁵ we believe that the DOE will need to make a compelling case on both technical and economic grounds for the proposed use of an LMR system and disposal of the resulting wastes in an intermediate facility if the Congress, EPA, and NRC are to be persuaded to promulgate the necessary laws and regulations. For example, recent rulemakings of the NRC^{2,17} indicate that regulations for the licensing of new waste management systems will not be developed unless the DOE demonstrates a clear need and benefit.

Technical and economic considerations aside, we also believe that public perceptions should not be ignored in evaluating the feasibility of the proposed use of an LMR system. The nuances of the NWPA and 10 CFR Part 60 notwithstanding, there is a strong public perception that commercial spent fuel is HLW (and therefore very hazardous) and that HLW must be placed in a geologic repository. Thus, it should be anticipated that efforts to change current waste management and disposal practices for any kind of spent fuel or primary wastes resulting from its reprocessing, particularly proposals to use disposal systems considerably less confining than a geologic repository, may be met with considerable public opposition, and that the NRC will be sensitive to adverse public opinion in promulgating regulations and rendering licensing decisions.

6. Recommendations for the DOE

We conclude this chapter by discussing recommendations for actions that should be taken by the DOE in regard to the proposed use of an LMR system for transmutation of actinide radioelements. We focus on recommendations related to disposal of wastes from an LMR; again, these wastes include those arising from reprocessing of the original uranium spent fuel from light-water reactors.

We reiterate the general recommendation that the DOE will need to be aggressive in promoting any benefits of the proposed use of an LMR system in regard to radioactive waste disposal if the required changes in current law and regulations are to be considered by the Congress, EPA, and NRC. Disposal of wastes from an LMR in facilities other than a deep geologic repository, particularly intermediate disposal facilities, would represent a significant change in the current institutional setup for management of commercial radioactive wastes, because near-surface land disposal (for LLW in concentrations less than the Class-C limits) and deep geologic repositories (for spent fuel, primary reprocessing wastes, and greater-than-Class-C LLW) are the only disposal technologies currently recognized in law and regulations. Thus, on the basis of defensible technical and economic analyses, the DOE must demonstrate clearly the benefits of alternative waste management systems.

We then offer the following specific recommendations in regard to actions that should be taken by the DOE.

First, expected isotopic compositions of wastes from an LMR, including the concentrations of fission products as well as long-lived, alpha-emitting TRU radionuclides, must be estimated. If the radionuclide concentrations are not significantly different from the concentrations in primary wastes from conventional reprocessing of commercial spent fuel, then there would be no benefit from the proposed use of an LMR because disposal in a deep geologic repository undoubtedly would be required.

In the unlikely event that the concentrations of fission products and long-lived, alpha-emitting TRU radionuclides in wastes from an LMR are less than the Class-C limits specified in the NRC's 10 CFR Part 61,¹⁵ the DOE could petition the NRC for concurrence that the wastes would be generally acceptable for near-surface land disposal, based strictly on the

composition of the wastes rather than their source. A favorable finding by the NRC would result in the greatest reductions in costs of waste disposal and the least effort and risk on the part of the DOE.

Second, on the basis of the reasonable assumption that neither of the two outcomes described above regarding radionuclide concentrations in wastes from an LMR will be obtained, an analysis should be undertaken to estimate maximum concentrations of radionuclides, including both fission products and long-lived, alpha-emitting TRU radionuclides, that would be acceptable for intermediate disposal. Such an analysis would define minimum concentrations of radionuclides that would require disposal in a deep geologic repository (or other disposal system with equivalent waste-isolation capabilities).² A crude analysis of this type was presented in the ORNL waste classification study,³ but a more rigorous analysis is needed. In particular, expected waste forms for wastes from an LMR and reasonable requirements on the performance of other engineered barriers for the intermediate disposal system would need to be taken into account in the analysis. If such an analysis strongly suggests that wastes from an LMR would require disposal in a geologic repository, then there would again be no benefit from the proposed use of an LMR in regard to disposal.

It is important to include fission products in this analysis because, as indicated in the ORNL study,³ the wastes might be unacceptable for intermediate disposal on account of high concentrations of fission products, even if the concentrations of long-lived, alpha-emitting TRU radionuclides are less than the Class-C limit of 100 nCi/g that is generally acceptable for near-surface land disposal.¹⁵ The ORNL study also indicates that it is important to include both the shorter-lived (i.e., ⁹⁰Sr and ¹³⁷Cs) and the longer-lived (e.g., ⁹⁹Tc, ¹²⁶Sn, and ¹²⁹I) fission products in the analysis.

The analysis for intermediate disposal described above normally would be performed by the NRC in developing technical criteria by which such facilities would be licensed. However, since it is likely that the DOE will need to petition the NRC to develop the necessary technical criteria, an analysis that favorably supports the DOE's petition for development of alternative disposal facilities for wastes from an LMR probably would be needed to persuade the NRC to proceed with a rulemaking.

Third, on the basis of the analysis described in the second recommendation, a determination should be made concerning the potential acceptability of intermediate disposal for the DOE's defense HLW. If a geologic repository clearly would be required for disposal of defense HLW, then we believe there would be little incentive to develop intermediate disposal facilities for wastes from an LMR.

Fourth, assuming a favorable outcome regarding the acceptability of intermediate disposal for wastes from an LMR and for defense HLW, discussions should be undertaken with the NRC regarding a rulemaking on classification of radioactive wastes on the basis of radionuclide concentrations, regardless of their source. As emphasized previously in this chapter, development of a new waste classification system which could permit primary wastes from fuel reprocessing to be classified as non-HLW is not necessary for a finding by the NRC on the acceptability of intermediate disposal, since current law and regulations do not require that deep geologic repositories be used for disposal of wastes presently classified as HLW. However, the possibility of reclassifying wastes from an LMR and defense reprocessing wastes as non-HLW would encourage flexibility in developing waste management systems, and could increase public acceptance of intermediate disposal for these wastes.

Finally, again assuming a favorable outcome regarding the acceptability of intermediate disposal for wastes from an LMR and for primary defense reprocessing wastes, discussions should be undertaken with the EPA regarding a rulemaking on general environmental radiation standards for intermediate disposal, regardless of whether or not the NRC would classify these wastes as HLW. If these wastes were classified as non-HLW, then the required EPA standards do not exist and would need to be developed. However, even if these wastes were classified as HLW (because of their source) and the present standards in the EPA's 40 CFR Part 191 would apply,⁹ the EPA might be persuaded to develop new standards for intermediate disposal, particularly if the existing (and very stringent) containment requirements were judged not to be reasonably achievable or appropriate for intermediate disposal but alternative (and less stringent) standards would ensure protection of public health.

7. References for Chapter IV

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