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An Evaluation of the Concept of Transuranic Burning Using Liquid Metal Reactors

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An Evaluation of the Concept of Transuranic Burning Using Liquid Metal Reactors

This evaluation investigates the potential benefits of separating the transuranic elements from spent reactor fuel before it is disposed of in geologic repositories. It addresses the question: Would the benefits to radioactive waste disposal justify both processing the spent fuel and deploying liquid metal reactors (LMRs) to transmute the separated transuranics?

INTEREST CATEGORY

Light water reactor fuel

KEYWORDS

Nuclear power
Nuclear fuels

BACKGROUND During 1990, the transuranic-burning concept was identified within the nuclear industry as a potential method of simplifying the disposal of existing spent fuel from light water reactor (LWR) power plants. In this concept, transuranic elements would be separated from spent reactor fuel for subsequent transmutation in liquid metal reactors. To support informed responses to utility inquiries, EPRI undertook an evaluation of the transuranic-burning concept.

OBJECTIVE To answer the question: Would the benefits to radioactive waste disposal justify processing of existing spent LWR fuel and deploying LMRs to consume the separated transuranics?

APPROACH The project team gathered the available information on the transuranic-burning concept. They found adequate information on the processes for separating and transmuting the transuranics, but little information on the waste packages that would result from the separation process and on how the disposal of the waste would differ from that of unprocessed spent fuel. Also unavailable was an estimate, independent of the LMR program, of the cost of processing spent LWR fuel. Accordingly, contractors were engaged to fill these information gaps (for details of this research see EPRI reports NP-7262, NP-7263, and NP-7264). On the basis of its research, EPRI was able to define the advantages and disadvantages of the transuranic-burning concept and to draw conclusions. An advisory panel of senior representatives of the nuclear power industry reviewed the findings.

RESULTS Adoption of a process-before-diposal policy for current spent fuel would accrue minimal benefits. It would not significantly lessen the accumulation of uranium mill tailings and the national inventory of transuranics or significantly facilitate the licensing of a geologic repository. The policy would likely incur a large cost penalty, encounter major institutional difficulties, multiply licensing difficulties, and amplify political and public opposition to the nuclear power program as a whole. The conclusion is that spent LWR fuel should not be processed before it becomes necessary to support an economically justified LMR deployment program.

However, should LMR deployment become economically justified, the plutonium fraction of spent LWR fuel is projected to be substantially less expensive than enriched uranium as a fissile material for startup of LMRs. At that time, the LMR would fulfill its role as a reactor system that would protect the nation from

diminishing energy resources. For this reason, development tasks aimed at defining and developing the most cost-effective LMR and its associated fuel cycle remain highly desirable.

EPRI PERSPECTIVE This evaluation encourages R&D in the areas of spent-fuel processing and LMRs, for the purpose of resource conservation but not as a means of radioactive waste simplification. Related EPRI work on the transuranic-burning concept, a survey of foreign research on the topic, has been published as EPRI report NP-7265.

PROJECT
RP3030
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Research Project 3030

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ABSTRACT

The evaluation investigates the potential benefits to radioactive waste disposal of separating the transuranic elements from spent reactor fuel before the spent fuel is disposed of in geologic repositories. The evaluation addresses the question whether the benefits to radioactive waste disposal would justify processing the fuel to separate the transuranics, plus a liquid metal reactor (LMR) deployment program to transmute the separated transuranics.

The evaluation concludes that adoption of a process-before-disposal policy for all the spent fuel from the light water reactors (LWRs) would accrue only modest benefits with respect to the accumulation of uranium mill tailings, the national inventory of transuranics and the licensing of a geologic repository. It is likely that this process-before-disposal policy would incur a large cost penalty, encounter major institutional difficulties, multiply licensing hurdles, and amplify political and public opposition to the overall nuclear power program.

However, plutonium from spent LWR fuel is projected to be substantially more economic than enriched uranium, as fissile material for startup of LMRs when LMR deployment becomes economically justified. At that time, the LMR would fulfill its role as a reactor system that would protect the nation from diminishing energy resources. Development tasks towards defining and developing the most cost-effective LMR and associated fuel cycle remain very important.

FOREWORD

During 1990, the concept of transuranic burning using liquid metal reactors (LMRs) was identified within the nuclear industry as a potential method of simplifying the disposal of the current spent fuel from the light water reactor (LWR) power plants. Accordingly, to support informed responses to utility inquiries, a brief Electric Power Research Institute (EPRI) evaluation of this potential application of transuranic burning has been conducted.

The transuranic burning concept has also been evaluated in the context of it being a potentially attractive feature of the LMR fuel cycle when LMRs are deployed as economically justified power producers. Deployment of LMRs, with their extremely efficient use of uranium, has long been projected as the response to the long-term possibility of demand induced escalation of the price of uranium.

The basic ingredients of the concept of transuranic burning using LMRs are separation of the bulk of all the transuranic elements from the spent fuel, followed by transmutation of the separated transuranics in the fast neutron flux of LMRs. The desired result is a major reduction in the extremely long-term radioactivity of the high-level waste.

This evaluation draws upon and references previous work by other organizations. Adequate information to support the evaluation was judged to be available regarding the processes for separation and transmutation of the transuranics, but little information was available on the waste packages that would result from the transuranic separation process and on how disposal of the waste packages would differ from that of unprocessed spent fuel. Also unavailable was an estimate, independent of the LMR development program, of the cost of processing spent LWR fuel.

Accordingly, contractors were engaged to fill these information gaps. General Electric (GE) prepared quantitative definitions of the waste packages that are projected to result from the processing of spent fuel. Rogers & Associates (RA) made a projection of the impacts of the quantified waste packages on the disposal facilities required and on the resulting disposal costs. S. M. Stoller (SMS) made an independent assessment of spent LWR fuel processing costs. Rockwell International (RI) summarized current foreign transuranic burning development programs. The GE, RA, SMS and RI inputs are documented in EPRI reports NP-7262, NP-7263, NP-7264 and NP-7265, respectively.

The format of the EPRI evaluation described in this report is to identify the potential applications of transuranic burning and the alternative processes that could be drawn upon. Separate chapters then summarize the inputs on projected process waste packages and on potential waste disposal impacts and the integration of the economic assessment inputs. The merits of the potential transuranic burning applications are then addressed and conclusions drawn. The report is completed by a summary of foreign programs and an identification of appropriate follow-on work. A summary precedes the above sequence.

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CONTENTS

Section 1

EXECUTIVE SUMMARY

1.1 THE CONCEPT

After a few hundred years, the transuranic elements in spent reactor fuel dominate its long-term radioactivity. Quantitatively, plutonium is the dominant transuranic, but the smaller quantity of "minor" transuranics (neptunium, americium and curium) contribute comparable radioactivity. In the transuranic burning concept, the bulk of the plutonium and the minor transuranics would be separated from the fuel. The remaining spent fuel process waste would then contain only a very small residual fraction of all the transuranics and would thereby have its extremely long-term (i.e., greater than 1000 year) radioactivity level reduced by orders of magnitude. The spent fuel waste would still contain the fission products and the activation species, as well as the residual fraction of transuranics not separable from the waste.

The separated transuranics would be used as startup fuel in liquid metal reactors (LMRs), which would fission the transuranics much more effectively than would light water reactors (LWRs).

1.2 POTENTIAL APPLICATIONS

The earliest potential application of the transuranic burning concept which has been suggested would be to the current spent fuel from the nation's commercial LWRs. The basic questions for this evaluation are thus: What would be the benefits to the high-level waste (HLW) disposal program, and would they justify spent LWR fuel processing and an early LMR deployment program?

Also addressed are supplementary questions relevant to the timeframe when LMRs may be deployed on their economic merit: Would plutonium recovered from spent LWR fuel be economically superior to enriched uranium, as fissile material for starting up LMRs? Would there be a net benefit in separating as high a percentage of all the transuranics as the processing technology would allow, when spent fuel is processed as part of an economically justified LMR deployment program?

1.3 ALTERNATIVE PROCESSES

The version of the LMR that would diverge least from prior LMR experience and would be usable in the transuranic burning concept is one in which the minor transuranics are uniformly dispersed in the new LMR fuel. The plutonium and minor transuranics would be in the same ratio as they are in the spent fuel prior to processing. The LMR fuel could be in the oxide form already developed, or in the metal form currently being developed by Argonne National Laboratory.

An aqueous separation process is usually visualized for the processing of spent LMR oxide fuel, and a pyrochemical process for LMR metal fuel. Both basic processes have been recommended by their advocates for the potential processing of the spent oxide fuel from LWRs. The different effects of the alternative processes are addressed in the evaluation.

The basic aqueous plutonium and uranium extraction process known as PUREX is a well established process applied in several foreign commercial power generation programs and in the U.S. defense program. In defense applications, the minor transuranics remain in the HLW, with the fission products. In the transuranic burning concept, PUREX would also separate the bulk of the neptunium, with the bulk of the uranium and plutonium. Also, the defense program has recently developed a similar process known as TRUEX (transuranic extraction) which, in the transuranic burning concept, would be used downstream of the PUREX step, to separate the bulk of the americium and curium and some of the residual plutonium and neptunium.

A review of the status of the aqueous technology indicates that a modest development program would be necessary to verify the process characteristics and determine the costs of separation of the bulk of the uranium and plutonium from spent power plant fuel. This is all the separation that would be necessary to support oxide-fueled LMRs deployed purely on their economic merit. To support separation of the americium and curium, the necessary development program would contain some additional elements.

The central feature of the pyrochemical process being developed for spent LMR metal fuel is an electrorefiner in which first the bulk of the uranium, then the plutonium and americium, and finally the neptunium and curium would deposit on anodes. The pyrochemical process is at an early stage of development for application to the LMR fuel cycle, and will need completion of a large development program to support commercial application.

In the pyrochemical process visualized for spent LWR oxide fuel, the refiner would be preceded by process steps to reduce the oxide to metal and to recover the uranium. These functions would be performed in molten reduction and transfer salts, contacting the fuel with selected molten alloys to extract the uranium and the transuranics. This process is largely undeveloped and would offer several developmental challenges.

1.4 IMPACTS ON WASTE DISPOSAL

1.4.1 Waste Packages and Disposal Thereof

The main waste stream that would remain in the aqueous process after the separation of the bulk of the transuranics would be concentrated and immobilized in glass blocks by a vitrification process already developed and being applied to waste at the Savannah River site. The vitrified packages would contain the fission products, including the main heat producers, cesium and strontium. A smaller number of unvitrified packages would contain the fragments of cladding from the fuel, and a smaller number still would contain the gases that would have been released and collected during the process.

There would be two main HLW streams from the pyrochemical process for spent LMR fuel, a salt waste containing most of the fission products and a metal waste containing the cladding fragments and the residual transuranics. The salt and metal waste streams would be immobilized in ceramic and copper matrices, respectively, implicitly requiring a significant development effort to characterize suitable waste forms.

The wastes from pyrochemical processing of spent LWR fuel would be similar to those from pyrochemical processing of spent LMR fuel, but divided more because of the use of three salt processes in series (reducing, transferring, refining). The clad fragments would be separated from the fuel early in the process and would have their own waste packages, unlike LMR clad fragments which would separate from the fuel in the refiner and would be included in the refiner metal waste.

The waste packages that would be created from these waste streams are characterized in the report, quantifying the number of packages and their sizes, internal chemistry, isotope contents and heat outputs. Then follows a comparison of the waste packages with disposal criteria in the Code of Federal Regulations.

The comparison indicates that the waste types would not qualify for near-surface, instead of geologic disposal, except for fuel assembly fittings. Even if continuing development of the processing technologies achieves a tenfold improvement in transuranic separation efficiencies over those currently projected, none of these waste packages would be downgraded thereby from geologic to near-surface disposal. The waste packages would still be precluded from near-surface disposal because of their enclosed concentrations of residual transuranics, extremely long-life fission

products, extremely long-life activation species, and medium-life, high-activity fission products.

However, processing the spent fuel and removal of large fractions of the transuranics would reduce the waste heat output at the time of disposal (by about 20% for spent LWR fuel), and thereby increase the GW-years of power generation that a geologic repository of a given size could support.

1.4.2 Compliance With Waste Disposal Standard

Waste disposal standards and criteria for licensing an HLW repository are formulated by EPA and NRC. Many of these standards and criteria are currently under question, and many are yet to be formulated. Consequently, this evaluation did not search for conclusive statements regarding the ease or difficulty in demonstrating compliance for unprocessed spent fuel, with the standards governing allowable releases of radioactive isotopes. Nonetheless, based on current data and EPA standards, it may transpire that the task of demonstrating compliance with the standard would be eased somewhat by the vitrified or equivalently immobilized waste forms that would result from aqueous processing of the spent fuel. Even then, other potential options, such as an engineered barrier would influence the acceptable cost impact of the fuel processing scenario.

1.5 ECONOMIC PROJECTIONS

1.5.1 Current Spent LWR Fuel

Processing all the spent fuel from the LWRs and deploying LMRs, instead of some of the future's LWRs, to transmute the separated transuranics, would require a large LMR deployment program (about 30 GW) during the first quarter of the next century. This scenario is estimated to incur an annual cost penalty rising to between $0.5B and $2B per year ('90 $) by the end of that quarter century. Although the plant lifelong cost of processing spent LMR fuel and refabricating it would be substantially less than the equivalent LWR plant lifelong cost of procuring uranium, enriching it and fabricating fuel assemblies, this LMR fuel cycle cost advantage would not be enough to offset the high cost of processing the spent LWR fuel to extract the transuranics to be used in the LMRs. To limit the size of the LMR deployment program required to clear the backlog of spent LWR fuel, it would be necessary to design each LMR to accept a far greater quantity of transuranics than would be economically optimum.

1.5.2 Supplementary Cost Assessments

The processing costs projected in this evaluation indicate an economic incentive of greater than 2 mil/kWh in busbar cost to use spent LWR plutonium rather than enriched uranium as the fissile material to start up LMRs, when LMR deployment becomes economically justified. Separating the minor transuranics from spent fuel when it is processed to recover the plutonium would not incur a net cost increase to the total scenario, when all the impacts on processing and waste disposal costs are taken into account.

1.6 NONTECHNICAL/ECONOMIC CONSIDERATIONS

Bringing into being the large LMR deployment program that would be required to implement a process-before-disposal policy for the current spent LWR fuel would require statutory action or financial incentives large enough to overcome the economic disadvantage that would attend the LMRs when selecting the energy sources for new power plants. Similar government initiatives would be required to bring into being the associated LWR and LMR spent fuel processing facilities. The burden of resolving this institutional issue would constitute a deterrent to adoption of a process-before-disposal policy.

Bringing into being spent fuel processing would also require a major licensing effort, and would have to overcome political and public opposition to its introduction. These hurdles would be complicated by the need to demonstrate acceptable risk with respect to diversion of strategic materials. Although these steps must be taken when deployment of LMRs becomes economically appropriate, pursuing licensing and political and public acceptance without an economic justification would be particularly difficult.

1.7 CONCLUSIONS

A modest development program would be needed for aqueous processing of spent LWR fuel and spent LMR oxide fuel.

A large development program would be needed for pyrochemical processing of spent LMR metal fuel. Additional development tasks would be needed to apply the pyrochemical process to spent LWR fuel.

Transuranic burning would not alleviate the need for an HLW disposal facility. The presence of long half-life fission and activation products and residual transuranics would still cause the processing waste to be classified as high-level. However, a reduction in the waste heat output, resulting from the removal of the transuranics from the spent fuel would potentially increase the storage capacity of a repository.

Adoption of a process-before-disposal policy for the current spent fuel would not be economic.

Development tasks are appropriate to establish the capability to introduce the transuranic burning concept as a refinement of the overall fuel cycle when LMRs are deployed on their economic merit. Development tasks towards defining and developing the most cost-effective LMR and associated fuel cycle remain very important, on a schedule consistent with their expected roles in meeting the nation's future energy requirements.

Section 2

POTENTIAL APPLICATIONS

2.1 GENERIC PROCESS INVOLVED

The radioactivity of spent reactor fuel is dominated by two groups of elements, fission products created from the fissioned nuclei, and transuranics created by capture of one or more neutrons. Initially, the radioactivities of the two groups are roughly equal, but most of the fission products decay more quickly, leaving the transuranics to dominate the extremely long-term radioactivity, although not necessarily to dominate the extremely long-term health risk to the public. As a point of reference only, after 200 to 300 years the fission product radioactivity drops well below that of the original uranium ore used to make the fuel, whereas the transuranic radioactivity remains higher than that of the uranium ore for over a million years and contributes to the challenge to provide adequate protection against release of radioactive material to the environment.

As transuranics fall within the broader category of actinides, the concept of separating and destroying these radioactive transuranics has commonly been termed "actinide burning." In this report, because it is frequently necessary to use collective nouns that define whether uranium is included ("actinides") or excluded ("transuranics") for the point being made, the more specific term, "transuranic burning" is used. Quantitatively, plutonium is the dominant transuranic (about 1% of the heavy metal content of typical current spent LWR fuel), but the smaller quantities of neptunium, americium and curium (in total equal to about 10% of the plutonium weight) contribute comparable radioactivity.

Separation of the plutonium from spent fuel is already routine in several foreign commercial reactor programs and in the U.S. defense program. In the transuranic burning concept, the other or "minor" transuranics would also be separated, so that the remaining spent fuel waste package would contain only a very small residual fraction of all the transuranics and would thereby have its extremely long-term radioactivity reduced by several orders of magnitude. In the concept evaluated in this report, the separated transuranics would be incorporated into fresh fuel and fissioned in a reactor, either directly or after neutron capture and conversion to a fissionable isotope. The cross-sections of the minor transuranics in the fast neutron flux of an LMR are comparable to those of uranium and plutonium. Consequently, even if mixed with larger quantities of uranium in the fabrication of new LMR fuel,

the minor transuranics, as well as the plutonium, would capture an adequate fraction of the neutrons and would fission.

Early in the evaluation came an awareness that the final disposition for or against transuranic burning would depend as much on the visualized application as on the generic process. Accordingly, this evaluation addresses the three potential transuranic burning applications identified below. Earlier evaluations of transuranic burning in different contexts are summarized in reference 2-1.

2.2 APPLICATION TO SPENT LMR FUEL

LMRs have always been perceived as the successors to LWRs when the most accessible, high-grade uranium ore has been consumed and the resulting uranium cost increase makes the busbar cost of LWRs decisively higher than that of LMRs. Because of its high fissile isotope breeding characteristic, the LMR would require very much less uranium for each kilowatt-hour (kWh) of electricity generated.

This benefit would be realizable only if the spent LMR fuel were processed to extract and return the bulk of the plutonium to the reactor. Therefore, as LMR deployment would implicitly involve spent LMR fuel processing to recover the plutonium and, as noted above, the LMR can fission minor transuranics as well as plutonium, there may be an incentive to separate the minor transuranics as well as the plutonium from the spent fuel and return them to the LMR for destruction, thereby substantially reducing the extremely long-term radioactivity of the spent LMR fuel process waste.

2.3 APPLICATION TO SPENT LWR FUEL POTENTIALLY NEEDED BY LMRS

Although LMRs can maintain an adequate fissile content once started up, they require startup fissile material from outside sources. The only two reliable sources of enough fissile material to support a substantial U.S. LMR deployment program are enrichment of uranium and recovery of plutonium from spent LWR fuel. Potentially unwanted defense plutonium and offshore plutonium are in limited quantities and/or are insufficiently reliable to be the basis for planning a substantial utility LMR deployment program.

The process for enriching uranium is well established, and the cost thereof is known. Unfortunately, use of enriched uranium would involve consumption of uranium ore (some 20 to 30% of that consumed by LWRs per kWh of electricity generated), thereby somewhat diluting the basic advantage of LMRs.

Use of plutonium from spent LWR fuel would eliminate the need for any uranium ore as a source of fissile material, and enough fertile uranium to meet the needs of a large LMR deployment program would be obtainable from the stocks of depleted uranium from the enrichment plants. Although one process for recovering plutonium from spent LWR fuel has been established by the U.S. defense program

and an alternative process is under detailed evaluation, the cost in a commercial context has not been demonstrated. The economic advantage compared with enriched uranium is therefore currently uncertain. A prognosis on the relative economics of LWR plutonium and enriched uranium is attempted in this evaluation.

If LWR plutonium should prove to be the preferred option, then, as LMRs can fission minor transuranics as well as plutonium, there may be an incentive to separate the minor transuranics as well as the plutonium from the spent LWR fuel needed to support the LMR program, thereby substantially reducing the extremely long-term radioactivity of the waste from the processing of that spent LWR fuel.

2.4 APPLICATION TO CURRENT SPENT LWR FUEL

The central objective of this potential application of transuranic burning would be to process all the spent LWR fuel, not just that needed to support a future economically justified LMR deployment program, separate all the transuranics and transmute them in LMRs, in order to achieve a substantial reduction in the extremely long-term radioactivity of the process waste compared with that of unprocessed spent fuel. The basic questions for this evaluation are thus: What would be the benefits to the HLW disposal program, and would they justify processing of current spent LWR fuel and an LMR deployment program to consume the separated transuranics?

2.5 REFERENCES

2-1 C. W. Forsberg, A. G. Croff, and D. C. Kocher. Historical Perspective, Economic Analysis and Regulatory Analysis of the Impacts of Waste Partitioning - Transmutation on the Disposal of Radioactive Wastes. Oak Ridge National Laboratory, 1990. ORNL/TM-11650.

Section 3

ALTERNATIVE PROCESSES

This chapter summarizes the alternative processes, both for the separation of the transuranics from the spent fuel and for the subsequent fissioning in LMRs.

3.1 FISSIONING PROCESSES

3.1.1 Near-Conventional LMR

The version of the LMR that would diverge least from prior LMR experience and would be usable for all three potential transuranic burning applications identified in chapter 2 would be one in which the minor transuranics would be uniformly dispersed in the new LMR fuel, in the same ratio to the plutonium content as they were in the spent fuel prior to processing.

Whether the startup fissile material were enriched uranium, or plutonium from spent LWR fuel, or surplus plutonium from the defense program, from foreign sources or from other LMRs, each bringing a different fraction of minor transuranics, each minor transuranic would tend towards an asymptotic concentration, as the rate of elimination (by fission or neutron capture) approached the rate of creation (by neutron capture). The time required essentially to reach the asymptote would vary with the transuranic, but would be well within the life of the LMR, as illustrated by figure 3-1 provided by GE for a typical LMR started up with plutonium from spent LWR fuel. This figure illustrates how the LMR would destroy all those minor transuranics that are in excess of the asymptotic fraction in the fuel quantity required to continue power generation. At the end of the LMR's life, the remaining transuranics would be in the amount necessary to start up a replacement LMR of the same capacity.

As the amount of plutonium created by an LWR during its plant life is about the amount needed to start up an LMR of the same electrical output, deploying an LMR that would, after startup, be exactly self-sufficient with respect to fissile material (no makeup, no surplus), instead of deploying another LWR, would, by the end of the LMR's plant life, reduce by a factor of about two the quantity of plutonium that would otherwise have been created by the two reactors deployed in series. It would also reduce by a factor of about six the quantity of minor transuranics.

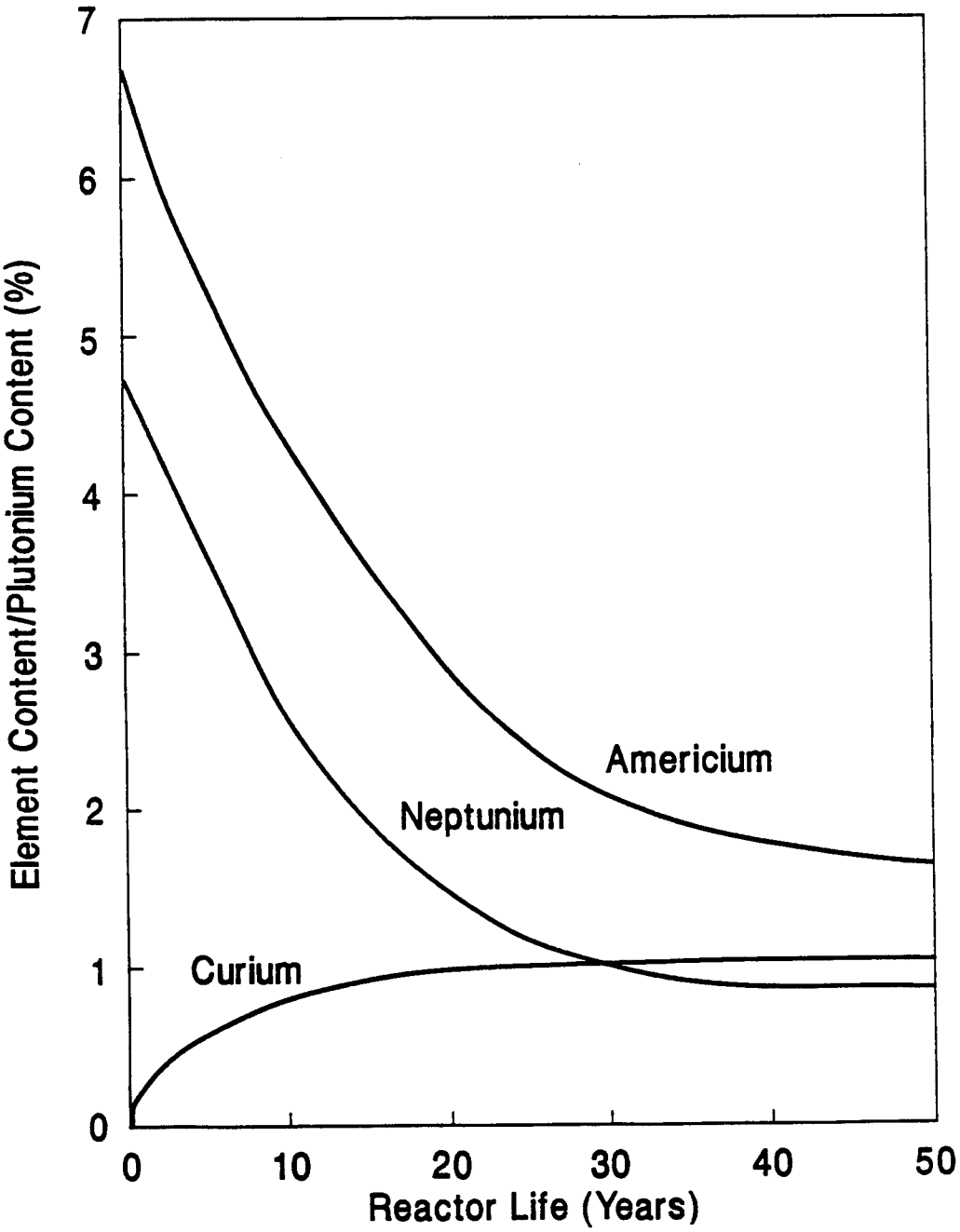

Figure 3-1. Change of Minor Transuranic Content in LMR Fuel (From Initial Charge of LWR Bred Transuranics)

For a separation process decontamination factor of 10^3 (i.e., 99.9% of the transuranics recovered), the transuranics going to waste during the LMR's plant life would be about 1% of the average quantity in existence during the LMR's plant life. If a ramp down in deployed LMR capacity were eventually required, the undisposed inventory of transuranics could also be ramped down by reducing the fissile breeding ratio.

Although the LMR's minor transuranic content would be higher than in a conventional LMR to which only the plutonium would be sent, the transuranic content and a possibly higher content of lanthanide fellow-travelers are judged to be insufficient to change the general steady-state and off-normal nuclear/thermal behavior of the LMR materially.

Of significance may be the impact of these higher minor transuranic and lanthanide contents on the metallurgical behavior of the LMR fuel pins, at least if the fuel is in metal form. Metal fuel behavioral characteristics that may limit fuel burnup and/or reactor outlet temperature are known to vary with the plutonium content. Whether the fuel behavior also varies with the small minor transuranic content and lanthanide content and whether the behavior would be improved or degraded by the increased minor transuranic and lanthanide contents and result in significant changes to plant and fuel design parameters are not known and would have to be determined experimentally.

3.1.2 Minor Transuranics LMR

The quantitatively dominant transuranic, plutonium, also has an adequate cross-section for fissioning in the thermal flux spectrum of an LWR, thereby introducing the possibility, for the applications of transuranic burning to spent LWR fuel, of sending to and fissioning in LMRs only the minor transuranics . This alternative would be responsive to a possible objective to minimize the number of LMRs needed.

Reference 3-1 describes an RI LMR concept which would be fueled only with minor transuranics from spent LWR fuel and is calculated to consume about 5% of the minor transuranics per year. This consumption would be compensated by the addition of more LWR minor transuranics during the processing of the spent LMR fuel. For startup alone, a 1200-MWe deployment would take up all the minor transuranics created by the nation's LWRs by the year 2005

This unconventional fuel content would have some plant and fuel design parameter repercussions. For example, the metallurgical behavior of the fuel could differ substantially from that of conventional LMR fuel and could significantly impact the limiting fuel burnup and reactor outlet temperature. In addition, a higher source term and higher decay heat than in a conventional LMR would have to be accommodated by the plant design.

LMR concepts between the above two extremes, near-conventional LMR and minor transuranics LMR, are possible. Both Argonne National Laboratory (ANL) and Westinghouse Advance Energy Systems [WAES(3-2)] have analyzed the nuclear performance of LMR concepts in which various proportions of plutonium are mixed with the minor transuranics.

3.1.3 LMR Fuel Forms

The two most developed fuel forms for LMRs are oxide and metal. The oxide form has been extensively developed in all four major LMR development centers (Japan, USA, USSR and Western Europe). The metallurgical behavior has been characterized in depth and has been improved to the point whereby the fuel design burnup is determined as much by nuclear and thermal-hydraulic optimization considerations as by fuel pin metallurgical limitations. Both reference 3-3 and WAESD analyses performed for EPRI indicate that peak burnups in excess of 200 MWd/kg are likely to be the feasible optimum.

The metal form is being developed in an aggressive program at ANL along with a pyrochemical procedure for processing spent LMR metal fuel. Pyrochemical processing, followed by metal fuel refabrication, is projected by its advocates to be significantly less expensive than aqueous processing followed by oxide fuel refabrication. Data from GE projects levelized fuel cycle costs 0.5 mil/kWh lower for an LMR with metal fuel and pyrochemical processing than for an LMR with oxide fuel and aqueous processing, the advantage being attributable to a simpler fuel refabrication process for metal fuel. However, the current status of pyrochemical technology does not permit a projected cost reduction to be accepted with confidence.

In addition, until the metal fuel technology development program has progressed a few more years, there will remain some expectation that the metallurgical behavior of metal fuel may limit the fuel burnup and/or the reactor outlet temperature to values lower than those cost-effective with oxide fuel. Such potential limitations would have a cost impact that would counteract the above potential cost advantage of the pyrochemical process. Relevant behavioral characteristics that are being explored in depth are the swelling of the metal fuel and the metallurgical interaction between the constituents of the metal alloy and those of the clad.

In short, a convincing projection as to which fuel form will prove preferable for LMRs cannot yet be made, so the effects of both possibilities are addressed in this evaluation of the transuranic burning concept.

3.2 SEPARATION PROCESSES

As indicated above, LMR oxide fuel is associated with an aqueous separation process, and LMR metal fuel is associated with a pyrochemical separation process. Both basic processes have recently been recommended by their advocates for the potential processing of oxide spent fuel from LWRs. In addition, both basic processes contain steps for which variations are available. The following discussion attempts to define enough alternative process variations to cover the field and omit process variations which appear unlikely to affect the conclusions of this evaluation. It is recognized that continuing work in this area may reveal more cost-effective process variations than visualized in this evaluation.

3.2.1 Aqueous Actinide Separation Process

The plutonium and uranium extraction process known as PUREX is a well established process applied in several foreign commercial power generation programs and in the U.S. defense program, with process variations from location to location. The basic element of the PUREX variations is a multistage mass transfer counterflow contacting device in which a paraffin hydrocarbon mixture containing tributyl phosphate (TBP) pulls the plutonium and uranium from an acid solution of the fuel. Most of the mass transfer contacting devices in the world, including those at the Hanford site are in the form of tall columns. The main alternative, including that at the Savannah River site is a compact but more complex centrifugal contactor.

For defense applications, the degree of multistaging and of scrubbing between each stage has been determined by the purity required of the product, plutonium. For the separation of plutonium and uranium from spent LMR fuel for returning to the LMR driver fuel refabrication line, the LMR is so tolerant of impurities that less scrubbing and multistaging would be required and there would be no need to prevent coseparation of neptunium with the plutonium. For the separation of plutonium from spent LWR fuel to use as startup fissile material for LMRs, there would be an economic incentive to deliver a byproduct stream of uranium as clean as possible for reuse in enrichment plants, as is already routinely done in at least the UK (3-4), in which case a higher degree of scrubbing of the uranium stream would still be included. Similarly, the stream of partitioned uranium from the processing of spent LMR blanket assemblies would be well scrubbed to permit reuse in a contact-handling blanket fabrication line.

There are several process steps both before and after the plutonium and uranium separation step. Some of the steps can be accomplished in a variety of ways. Based on information provided by GE, Oak Ridge National Laboratory [ORNL (3-5)], and Westinghouse Hanford Company [WHC(3-6)] the options adopted for this evaluation are as follows. First, the spent fuel assemblies would be mechanically disassembled so that only the fuel pins would need to be processed. Then, the pins would be sheared to expose the fuel to the acid solution, for which nitric acid is preferred. The plutonium and uranium and most (about 90%) of the neptunium

would then be separated from the rest of the dissolved fuel constituents using centrifugal contactors.

The remaining dissolved fuel constituents would, after further nitric acid treatment to dissolve any residual solids, be passed through a TRUEX (transuranics extraction) process. The separation element of TRUEX is very similar to that of PUREX, the basic difference being that another solvent, known by the acronym CMPO is mixed with the TBP and pulls the americium and curium and residual plutonium, uranium and neptunium from the nitric acid solution (3-7). The process has recently been developed in connection with defense waste streams from which the bulk of the plutonium and uranium had been removed earlier by PUREX.

The actinides separated in the above process steps would be stripped from the hydrocarbon solvent using very dilute nitric acid to reverse the relative solubilities in the hydrocarbon and acid solvents. For the separation of actinides from spent LWR fuel so that the transuranics could be used as startup fissile material for LMRs, the ratio of uranium to plutonium and neptunium in the solvent stream would be more than an order of magnitude too high for LMR use, so the valency of the plutonium and neptunium would be changed so that they would strip from the solvent first. Partial uranium/plutonium partitioning would also be needed during the processing of spent LMR blanket assemblies to achieve the plutonium/uranium mix required for LMR driver fuel refabrication. For the separation of actinides from spent LMR driver fuel for returning to the LMR, this partitioning would not be necessary.

Both for the separation of the actinides from spent LMR oxide fuel to return them to the LMR and for the separation of transuranics from spent LWR fuel to use as startup fissile material for oxide fueled LMRs, an additional step would be necessary for the separated stream containing the minor transuranics, americium and curium. At this point in the process, these trivalent transuranics would still be accompanied by the lanthanide fission products. To reduce the neutronic burden of the lanthanides on the LMR, these transuranics would be separated from the bulk of the lanthanides by a process which has not yet been selected, developed and demonstrated.

For the separation of actinides from spent LWR fuel to use as startup fissile material for metal-fueled LMRs, the americium and curium, still accompanied by the lanthanides could be delivered to the LMR fuel facility, packaged separately from the uranium, plutonium and neptunium. The LMR metal fuel facility would contain a step that would achieve adequate transuranics/lanthanides separation in the processing of the spent LMR fuel and would, therefore, be able to accept lanthanides with the americium and curium from spent LWR fuel.

At this point in the process, the separated actinides would be in dilute nitric acid solutions. They would be converted to oxide by established methods, the preferred method varying with the actinide. For the separation of transuranics from spent

LWR fuel to use as startup fissile material for metal-fueled LMRs, there would be an additional conversion to produce the metal form.

Only a modest development program would be necessary to support separation of the bulk of the uranium, plutonium and neptunium from spent power plant fuel. Such development would include demonstration of a high -efficiency iodine trap and of cryogenic collection of noble gases, which are anticipated to be required features for commercial fuel process facilities, and selection and demonstration of a reduction to metal process if the LMR were metal-fueled. In addition, to permit reenrichment of the bulk uranium separated from spent LWR fuel, there would be a need to select and demonstrate the process steps to decontaminate the uranium adequately, and to select and demonstrate the reenrichment flowsheet.

To support the additional separation of the minor transuranics, the necessary development program would include establishing the transuranic separation efficiency achievable on the PUREX process raffinate, demonstrating the degree to which the process equipment could be decontaminated of transuranic-bearing solids, and selection, development and demonstration of a minor transuranics/ lanthanides partitioning process if the LMR were oxide-fueled. Of the above, only the minor transuranics/ lathanides partitioning process development task is judged to carry significant doubt regarding the acceptability of the resulting performance and cost.

3.2.2 Pyrochemical Actinide Separation from Spent LMR Fuel

Pyrochemical processing of spent LMR fuel would be associated with selection of the metal fuel form for the LMR deployment program. Pyrochemical processing of oxide fuel, if oxide fuel were selected for LMRs, is judged not to be a sufficiently likely eventuality for consideration in this evaluation.

Based on information provided by ANL and GE, the spent LMR metal fuel pyrochemical process adopted for this evaluation is as follows. First, the fuel assemblies would be mechanically disassembled so that only the fuel pins would need to be processed. Then the pins would be sheared and placed in an anodic perforated basket to expose the fuel to a chloride electrolyte which would be supported by a molten cadmium pool at about 500°C and would contain a solid uranium cathode.

The movement of the main elements in the chopped spent fuel pins would be as follows. Most of the uranium would deposit on the uranium cathode. The bulk of the transuranics, plus zirconium from the metal alloy fuel form, plus the noble metal fission products would go into solution in the liquid cadmium pool. The rest of the actinides would only transfer as far as the salt to restore the equilibrium level following processing of the preceding batch of fuel. The electropositive fission products, including the cesium, strontium and lanthanides, would convert to

chlorides in the salt. The ferritic stainless steel clad fragments would remain in the basket and would retain some fuel contamination.

After separating most of the uranium, the electrolyte would be adjusted so that the transuranics would convert to chlorides in the salt, and the uranium cathode would be replaced by a small liquid cadmium pool cathode containing lithium. This combination would achieve preferential reduction and deposition of the transuranics (initially plutonium and americium, followed by neptunium and curium) over the lanthanides and residual uranium, although unavoidable but acceptable minor fractions of these elements would reduce and deposit with the transuranics.

The separated actinides would be melted to drive off adhering salt and cadmium and then combined together and with zirconium to recreate the LMR metal alloy fuel mix.

At this point in the process, some of the transuranics would still be in the electrorefiner, both in the salt and in the main liquid cadmium pool. After a batch of spent fuel had been processed, some of the salt, contaminated mainly with the electropositive fission products, would be tapped off for replacement by clean salt. The contaminated salt would be passed through a multistage extractor in which the salt would be contacted with a cadmium/uranium solution which would exchange uranium for most of the transuranics, plus an unavoidable but acceptable fraction of the lanthanides. The resulting cadmium/heavy metal/lanthanide solution would then be drained off, retorted to drive off the cadmium and returned to the electrorefiner.

The salt waste would then be contacted with a cadmium/lithium solution which would exchange some of the lithium for the residual actinides and lanthanides. This metal solution would then be drained off and combined with the main liquid cadmium pool cleanup waste stream, which would contain the other unseparated transuranics, plus the zirconium and noble metals. The extremely long-life isotopic contents of the salt waste would then be insufficient to necessitate extremely long-term integrity of the salt waste form.

This pyrochemical process is at an early stage of development and therefore would need completion of a large development program to support commercial application. The development program would include establishing the decontamination level achievable for the clad fragments, the refiner metal waste and the refabrication process scrap, establishing the refiner separation rate, demonstrating the salt waste clean-up process and waste salt fraction and demonstrating process equipment maintenance procedures. At this stage in the development program, the establishment of the refiner separation rate is judged to carry the most doubt regarding the acceptability of the resulting process cost implications.

3.2.3 Pyrochemical Actinide Separation From Spent LWR Fuel

Based on information provided by ANL, the spent LWR pyrochemical process adopted for this evaluation is as follows. First the fuel assemblies would be disassembled so that only the fuel pins would need to be processed. Then the zirconium clad would be removed from the fuel by a process that is yet to be defined and demonstrated. The fuel would then be dissolved in a chloride salt and would be treated with calcium and contacted with a copper/magnesium alloy at about 800°C. The calcium would reduce the oxide fuel, and the copper/magnesium alloy would pull the actinides, lanthanides and noble metals.

The salt, containing the alkaline fission products and the calcium oxide, would then be replaced by a different chloride salt, which would act as a transfer salt as it is moved back and forth between the copper/magnesium/actinide/lanthanide/noble metal alloy and a separate magnesium/cadmium alloy. The magnesium would exchange preferentially with the transuranics and most of the lanthanides, and the cadmium/residual magnesium/transuranic/lanthanide alloy would be drained off and the magnesium and cadmium boiled off and distilled for reuse. The transuranics would then be separated from most of the lanthanides in a refiner similar to that for pyrochemical processing of spent LMR fuel as described above.

An injection of fresh magnesium/cadmium into the salt transfer process step would then pull off the uranium. A fraction of the separated uranium would be delivered to the LMR fuel facility to become the quantity of LMR startup uranium associated with the quantity of transuranics separated as above. As with the aqueous process, the bulk of the uranium would potentially be reusable in enrichment plants. For the separation of transuranics from spent LWR fuel to use as startup fissile material for oxide-fueled LMRs, there would be an additional step to oxidize the metallic transuranics.

This pyrochemical process for spent LWR fuel is currently substantially less established than that for spent LMR fuel. The development tasks that would carry the greatest uncertainty regarding the acceptability of the resulting performance and cost are judged to be selection, development and demonstration of the zirconium clad removal process, verification of equipment materials and demonstration of the reduction process, and verification of equipment materials and demonstration of the salt transport process. Other development tasks would include demonstration of transuranic-free reduction and transport salt wastes, demonstration of an economically acceptable copper waste fraction, selection and demonstration of a uranium cleanup process, selection and demonstration of an actinide oxidation process if the LMR is oxide-fueled, plus some of the development tasks identified above for pyrochemical processing of spent LMR fuel and selection and demonstration of a clad fragments decontamination process if a high overall transuranic recovery efficiency is required.

3.3 REFERENCES

3-1 Nuclear Waste Management With Actinide Conversion. Rockwell International, 1989. AI-DOE-13568.

3-2 L. M. Gundy, C. A. Porter and R. A. Doncals. Actinide Burning in a Small Liquid Metal Reactor. Westinghouse Advanced Energy Systems, 1990. WAES-TR-90-0013.

3-3 Review of Nuclear Fuel Cycle Costs for the PWR and Fast Reactor, BNF, CEGB and UKAEA, 1987. FRJC/P(87)4.

3-4 "British Reprocessing." Nuclear Engineering International, October 1990.

3-5 J. C. Mailer et al. Evaluation of Conceptual Flowsheets for Incorporating LWR Fuel Materials in an Advanced Nuclear Fuel Cycle. Oak Ridge National Laboratory, 1990. ORNL/TM-11466.

3-6 J. A. Rawlins and J. J. Holmes. CURE: Clean Use of Reactor Energy. Westinghouse Hanford Company, 1990. WHC-EP-0268.

3-7 W. W. Schultz and E. P. Horowitz. "The TRUEX Process and the Management of Liquid TRU Waste." Separation Science and Technology, 1988.

Section 4

PROJECTED WASTE PACKAGES

This chapter comprises summarized results from GE's quantitative definition of the waste packages that are projected to result from the processing of spent fuel. Detailed results plus descriptions of the quantification method and of the assumptions can be found in companion report NP-7262.

4.1 WASTE PACKAGES FROM AQUEOUS PROCESSING OF SPENT LWR FUEL

The main stream that would remain after the separation of the actinides would be concentrated and vitrified by a process already developed and being applied to waste from the Savannah River site operations and also to waste from French and British commercial spent fuel processing. The vitrified waste would be enclosed in two, an inner and an outer, stainless steel containers.

The main waste package that is calculated to result from a PUREX-only separation process (i.e., proceeding only as far as extracting the bulk of the plutonium for LMR startup) is summarized quantitatively in table 4-1, along with the radioactive waste packages that would result from the parallel streams associated with the aqueous process. The table is based on the companion report NP-7262 anticipation that replacement process equipment would be cleanable to the degree necessary to permit subsequent disposal as LLW. The number of packages identified for each waste type in the table is the number of such packages calculated to result from the processing of a quantity of spent LWR fuel which has generated 10^{11} kWh of electricity (equal, for example, to that produced every eighteen months by 10 GW of reactors operating at 75% capacity factor). The same kWh basis is applied to the quantitative definition of the waste packages that would result from the alternative separation processes addressed later in this chapter. An equal basis permits an equitable comparison between the impacts on the disposal cost. The number of waste packages is also a function of the size of each container. The container size defined in table 4-1 is a currently licensed waste disposal container.

Table 4-1

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LWR FUEL PUREX - ONLY

Waste Type	Raffinate	Cladding	Noble Gases	Other Gases
Number of pkgs[2]	79	46	10	6
o.d./length (cm)	66/320	66/320	66/320	66/320
Weight (Te)	3.1	3.6	2.7	1.2
Main chemistry	Glass Fission products	Zirconium Stainless steel	Noble gases	Mol. sieves Iodine
Key isotopes[3] (Element/KCi)	Cs-Ba/800 Sr-Y/600 AE[4] /20 241Pu/0.4 Tc/0.007	63Ni/7 241Pu/0.7 AE[4]/0.03 Nb/0.01		C/0.05 I/0.002
Package activity (KCi)[5]	2,000	40	200	20
Package heat (W)[5]	5,000	300	300	1

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Alpha emitters.
[5]10 years after removal of fuel from core.

Based on experience to-date, table 4-1 assumes that the PUREX process would remove 99.9% of the plutonium from the main waste stream, and that 90% of the neptunium would coseparate with the plutonium. The residual plutonium and neptunium and all the americium and curium would remain in the waste stream and be included in the vitrified waste package. Table 4-1 also assumes that 0.1% of the fuel, and therefore, 0.1% of all the transuranics would remain on the clad fragments as contamination.

A significant parameter in the quantification of the waste packages is the fuel burnup. Technological advancements have recently increased the burnup achievable at some LWR plants and further increases may be achieved. To limit the number of variables in this quantification of waste packages, a single figure of 33 MWd/kg average burnup, with delivery to the disposal sites of the process waste packages ten years after removal of the fuel from the reactor are assumed. Later in this report, the impacts on the evaluation's conclusions, of the increases in burnup and of the reality that current fuel will experience at least thirty years cooling before disposal, or processing and disposal, are addressed.

If the separation process included the additional steps necessary to separate the americium and curium and residual plutonium and neptunium, i.e., the TRUEX and minor transuranics/lanthanides partitioning steps, the calculated waste packages would be those summarized in table 4-2. An equal separation efficiency of 99.99% for all the transuranics is assumed to result, i.e., a tenfold greater recovery than that used in table 4-1 for the separation of plutonium by the PUREX-only process. Use of such a high separation efficiency contributes to determining whether there would result a sufficient improvement to waste disposal to justify pushing the separation technology development towards achieving very high performance. Table 4-2 also assumes that the clad fragments would be subjected to additional nitric acid cleansing so that the transuranics reporting to waste via the clad fragments would be comparable to those via the vitrified waste.

Table 4-2 shows the technetium in its own waste package, based on the expectation that, as the objective of removing the transuranics would be to reduce the health risk to the public from those extremely long-life isotopes, the opportunity would be taken to separate and custom immobilize the technetium, the extremely long-life fission product often projected as making the biggest contribution, of all the isotopes in the spent fuel, to the extremely long-term risk to the public. The incremental process for separating the technetium would be selected from those described in reference 4-1 and would need to be demonstrated.

A backup disposition for the separated technetium would be to transmute it in target assemblies which contain material which would reduce the fast neutron spectrum of the LMR to an epithermal spectrum local to the target assembly. The spectrum shift would accelerate the rate at which the technetium would capture neutrons and transmute to a stable isotope.

Table 4-2

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LWR FUEL WITH THE TRUEX ADDITION

Waste Type	Raffinate	Cladding	Noble Gases	Other Gases	Technetium
Number of pkgs[2]	72	46	10	6	3
o.d./length (cm)	66/320	66/320	66/320	66/320	66/320
Weight (Te)	3.1	3.6	2.7	1.3	3.1
Main chemistry	Glass Fission products	Zirconium Stainless steel	Noble gases	Mol. sieves Iodine	Ceramic Technetium
Key isotopes[3] (Element/KCi)	Cs-Ba/900 Sr-Y/700 241Pu/0.04 AE[4] /0.004	63Ni/7 241Pu/0.07 Nb/0.01 AE[4]/0.003		C/0.05 I/0.002	Tc/2
Package activity (KCi)[5]	2,000	40	200	20	2
Package heat (W)[5]	5,000	300	300	1	1

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} KWH (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Alpha emitters.
[5]10 years after removal of fuel from core.

4.2 WASTE PACKAGES FROM AQUEOUS PROCESSING OF SPENT LMR FUEL

Aqueous processing of spent LMR fuel would be associated with selection of the oxide fuel form for the LMR deployment program. Aqueous processing of metal fuel, if metal fuel is selected for LMRs, is judged to be too unlikely an eventuality for consideration in this evaluation.

The quantified waste packages that are calculated to result from a PUREX-only process are summarized in table 4-3 and those from inclusion of the TRUEX step in table 4-4. The burnup specified for the quantification of the LMR waste packages is 150 MWd/kg average (225 MWd/kg peak), and, for consistency with the LWR waste packages, delivery of the waste packages to the disposal sites ten years after removal of the fuel from the reactor core.

Unlike the LWR, the LMR's spent fuel isotopic content would vary during the plant life. The most exacting spent fuel, with respect to waste package disposal would be the first discharge from an LMR started up on plutonium and minor transuranics from spent LWR fuel. Thereafter, the total concentration of the key alpha emitters would decrease as the reactor core approached equilibrium conditions. Thus, a fuel facility serving several LMRs would produce waste averaged streams that have alpha emitter concentrations somewhat higher than for core equilibrium conditions. In addition, the transuranic content would vary with the enrichment level, and therefore with the reactor capacity. To limit the number of variations addressed in this evaluation, these two variables are balanced by assuming equilibrium fuel discharge from the small, 155-MWe LMR currently being developed in the Department of Energy's (DOE) LMR development program.

4.3 WASTE PACKAGES FROM PYROCHEMICAL PROCESSING OF SPENT LMR FUEL

The chapter 3 summary description of the pyrochemical separation process for spent LMR fuel identified two main waste streams, a salt waste containing the medium-life, heat-producing isotopes, cesium and strontium, plus the extremely long-life fission product, iodine, and a metal waste containing the bulk of the lanthanides, the noble fission products, the zirconium from the metal alloy fuel form and the residual transuranics, to which would be added the transuranic contaminated, steel clad fragments and transuranic waste from the downstream metal fuel refabrication steps.

The pyrochemical process is at an earlier stage of development than the aqueous process, and the separation capability, which would determine the actinide content of the metal waste stream, cannot yet be defined accurately. For this evaluation, it is judged that a transuranic separation efficiency of 99% is a reasonably assured performance comparable to the separation efficiency of 99.9% identified above for the PUREX-only aqueous process. The technetium would be trapped in the metal waste package; however, the metal waste package would contain no significant heat producers.

Table 4-3

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LMR FUEL PUREX-ONLY

Waste Type	Fittings	Raffinate	Cladding	Noble Gases	Other Gases
Number of pkgs[2]	53	47	36	6	6
o.d./length (cm)	66/320	66/320	66/320	66/320	66/320
Weight (Te)	3.6	3.1	3.6	2.7	1.3
Main chemistry	Stainless	Glass Fission products	Stainless	Noble gases	Mol. sieves Iodine
Key isotopes[3] (Element/KCi)		Cs-Ba/1000 Sr-Y/400 AE[4]/100 241Pu/1 Tc/0.1	241Pu/1 AE[4] /0.4		C/0.05 I/0.002
Package activity (KCi)[5]	1	2000	3	100	20
Package heat (W)[5]	0	8000	10	200	1

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Alpha emitters.
[5]10 years after removal of fuel from core.

Table 4-4

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LMR FUEL WITH THE TRUEX ADDITION

Waste Type	Fittings	Raffinate	Cladding	Noble Gases	Other Gases	Technetium
Number of pkgs[2]	53	41	36	6	6	1
o.d./length (cm)	66/320	66/320	66/320	66/320	66/320	66/320
Weight (Te)	3.6	3.1	3.6	2.7	1.3	3.1
Main chemistry	Stainless	Glass Fission prod.	Stainless	Noble gases	Mol. sieves Iodine	Ceramic Technetium
Key isotopes[3] (Element/KCi)		Cs-Ba/1000 Sr-Y/400 241Pu/0.1 AE[4] /0.04	241Pu/0.1 AE[4] /0.04		C/0.05 I/0.002	Tc/3
Package activity (KCi)[5]	1	2000	2	100	20	3
Package heat (W)[5]	0	5000	1	200	1	2

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Alpha emitters.
[5]10 years after removal of fuel from core.

The salt waste stream and the metal waste stream would be immobilized in ceramic and copper matrices, respectively, implicitly requiring a significant development effort to achieve licensed waste forms. The two main waste packages that are calculated to result from a separation process that would achieve the above separation efficiency are summarized quantitatively in table 4-5 along with the radioactive waste packages that would result from the parallel streams. It is assumed that if the metal fuel form is to prove superior to the oxide fuel form for LMRs, the metal fuel form will have proved capable of achieving equal burnup, so the same burnup is specified for the quantification of the waste packages' contents.

4.4 WASTE PACKAGES FROM PYROCHEMICAL PROCESSING OF SPENT LWR FUEL

As for the processing of spent LMR fuel, there would be a salt waste stream, in this case a reduction salt, containing the medium-life, heat-producing isotopes, cesium and strontium. In this case, the iodine would be separate. The alloy contacting of the downstream transport salt is projected to be of such high performance, with respect to the separation of transuranics, that the transport salt waste stream would contain no isotopes that would violate LLW criteria. As for pyrochemical processing of spent LMR fuel, the technetium would be trapped in the transport metal waste, which would be free of major heat producers. The clad fragments would be packaged separately. There would also be smaller salt and metal waste volumes from the transuranics/lanthanides refiner. The metal waste would contain the small fraction of the transuranics that defy separation.

The waste packages that are calculated to result from the above process are defined quantitatively in table 4-6 along with the radioactive waste packages that would result from the parallel streams. Table 4-6 uses the same transuranic separation efficiency (99%) used above for the pyrochemical processing of spent LMR fuel.

4.5 REFERENCES

4-1 J. A. Rawlins and J. J. Holmes. CURE: Clean Use of Reactor Energy. Westinghouse Hanford Company, 1990. WHC-EP-0268.

Table 4-5

PROJECTED WASTE PACKAGES[1] FROM PYROCHEMICAL PROCESSING OF SPENT LMR FUEL

Waste Type	Refiner Salt	Metals	Fittings	Noble Gases	Tritium
Number of pkgs[2]	166	83	54	6	0.6
o.d./length(cm)	66/320	66/320	66/320	66/320	66/320
Weight (Te)	1.8	5.5	3.6	2.7	1.3
Main chemistry	Alk metals Chlorides Alk earths Chlorides Zeolite Halides	Copper Cadmium Crucibles + bskts Zirconium Stainless steel Lanthanides	Stainless steel	Noble gases	Mol. sieves Hydrogen
Key isotopes[3] (KCi)	Cs-Ba/300 Sr-Y/100 I/0.1	241Pu/7 AE[4] /2 Tc/0.05			
Package activity (KCi)[5]	400	80	3	200	600
Package heat (W)[5]	1000	200	1	200	20

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Alpha emitters.
[5]10 years after removal of fuel from core.

Table 4-6

PROJECTED WASTE PACKAGES[1] FROM PYROCHEMICAL PROCESSING OF SPENT LWR FUEL

Waste Type	Reduction Salt	Cladding	Transport Metal	Refiner Salt	Transport Salt	Refiner Metal	Noble Gases	Other Gases
Number of pkgs[2]	127	46	38	19	18	12	9	6
o.d./length (cm)	66/320	66/320	66/320	66/320	66/320	66/320	66/320	66/320
Weight (Te)	1.4	3.7	7.5	2.4	1.7	6.2	2.7	1.3
Main chemistry	Zeolite Alkali earths Alkali metals Calcium Haloids	Zirconium Stainless	Copper	Chlorides Zeolite	Chlorides Zeolite Lanthanides	Copper Cadmium Lanthanides	Noble gases	Mol. sieves Iodine
Key isotopes[3] (Element/KCi)	Cs-Ba/600 Sr-Y/400	63Ni/7 241Pu/7 AE[4] /0.5 Nb/0.01	Tc/0.1	Cs-Ba/40 Sr-Y/30		241Pu/30 AE[4]/2 Tc/0.005		C/0.05 I/0.002
Package activity (KCi)[5]	900	50	20	60	20	500	200	20
Package heat (W)[5]	3000	400	80	200	60	2000	300	1

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).
[3]For comparing with LLW acceptance criteria.
[4]Apha emitters.
[5]10 years after removal of fuel from core.

Section 5

POTENTIAL IMPACTS ON RADIOACTIVE WASTE DISPOSAL

This chapter comprises summarized results from the RA determination of the potential impacts of the quantified waste packages on the disposal facilities required, plus brief reviews of the potential impacts on compliance with release regulations for geologic repositories and on the health risk to the public. Detailed results from the RA impacts determination, plus a description of the determination method and of its assumptions can be found in companion report NP-7263.

5.1 IMPACTS ON DISPOSAL FACILITIES REQUIRED

5.1.1 With Currently Authorized Waste Disposal Facilities

The only types of radioactive waste disposal facilities currently authorized by the Nuclear Regulatory Commission (NRC) are near-surface disposal facilities for LLW and geologic repositories for HLW and for other radioactive wastes that exceed NRC's LLW acceptance criteria. Tables 5-1 through 5-6 reidentify the waste packages quantified in chapter 4 and, for each waste package, identify the type of facility (near-surface or geologic) required for its disposal.

A salient observation from tables 5-1 through 5-6 is that the breaking down of the spent LWR fuel into different waste types, as would occur in the processing, would lead to few of the waste types qualifying for near-surface, instead of geologic disposal, other than the LLW packages resulting from secondary process streams and process equipment replacement. A significant exception in the case of spent LMR fuel would be the fuel assembly end fittings and shrouds, which would be mechanically removed at the beginning of the process sequence and would be packaged separately and disposed of in a near-surface facility.

A second observation from tables 5-1 through 5-6 is that, even if continuing development of the processing technologies achieves a tenfold improvement in transuranic separation efficiencies over those used in the quantification of the waste packages, none of the waste packages would be downgraded from geologic to near-surface disposal. This observation applies to all the alternative processes addressed; the PUREX-only process for spent LWR and LMR fuel, the PUREX plus TRUEX process for spent LWR and LMR fuel, the pyrochemical process for spent LMR fuel, and the different pyrochemical process for spent LWR fuel.

Table 5-1

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LWR FUEL PUREX - ONLY

Waste Type	Raffinate	Cladding	Noble Gases	Other Gases
Number of pkgs[2]	164	28	10	6
o.d./length (cm)	46/530	66/530	66/320	66/320
Main chemistry	Glass Fission products	Zirconium Stainless steel	Noble gases	Mol. sieves Iodine
Disposal	Geologic	Geologic	Geologic	Geologic

[1]Excluding LLW from secondary process streams and process equipment replacement.

[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

[redacted]

Table 5-2

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LWR FUEL WITH THE TRUEX ADDITION

Waste Type	Raffinate	Cladding	Noble Gases	Other Gases	Technetium
Number of pkgs[2]	145	28	10	6	3
o.d./length (cm)	46/530	66/530	66/320	66/320	66/320
Main chemistry	Glass Fission products	Zirconium Stainless steel	Noble gases	Mol. sieves Iodine	Ceramic Technetium
Disposal	Geologic	Geologic	Geologic	Geologic	Geologic

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

Table 5-3

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LMR FUEL PUREX-ONLY

Waste Type	Fittings	Raffinate	Cladding	Noble Gases	Other Gases
Number of pkgs[2]	32	156	22	6	6
o.d./length (cm)	66/530	46/530	66/530	66/320	66/320
Main chemistry	Stainless	Glass Fission products	Stainless	Noble gases	Mol. sieves Iodine
Disposal	Near-surface	Geologic	Geologic	Geologic	Geologic

[1]Excluding LLW from secondary process streams and process equipment replacement.

[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

Table 5-4

PROJECTED WASTE PACKAGES[1] FROM AQUEOUS PROCESSING OF SPENT LMR FUEL WITH THE TRUEX ADDITION

Waste Type	Fittings	Raffinate	Cladding	Noble Gases	Other Gases	Technetium
Number of pkgs[2]	32	75	22	6	6	1
o.d./length (cm)	66/530	46/320	66/530	66/320	66/320	66/320
Main Chemistry	Stainless	Glass Fission products	Stainless	Noble gases	Mol. sieves Iodine	Ceramic Technetium
Disposal	Near-surface	Geologic	Geologic	Geologic	Geologic	Geologic

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2]Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

Table 5-5

PROJECTED WASTE PACKAGES[1] FROM PYROCHEMICAL PROCESSING OF SPENT LMR FUEL

Waste Type	Refiner Salt	Metals	Fittings	Noble Gases	Tritium
Number of pkgs[2]	99	50	32	6	0.6
o.d./length(cm)	66/530	66/530	66/530	66/320	66/320
Main chemistry	Alk metal Chlorides Alk earth Chlorides Zeolite Halides	Copper Cadmium Crucibles + bskts Zirconium Stainless steel Lanthanides	Stainless steel	Noble gases	Mol. sieves Hydrogen
Disposal	Geologic	Geologic	Near-surface	Geologic	Near-surface

[1]Excluding LLW from secondary process streams and process equipment replacement.

[2] Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

Table 5-6

PROJECTED WASTE PACKAGES[1] FROM PYROCHEMICAL PROCESSING OF SPENT LWR FUEL

Waste Type	Reduction Salt	Cladding	Transport Metal	Refiner Salt	Transport Salt	Refiner Metal	Noble Gases	Other Gases
Number of pkgs[2]	171	28	23	11	11	7	9	6
o.d./length (cm)	46/530	66/530	66/530	66/530	66/530	66/530	66/320	66/320
Main chemistry	Zeolite Alkali earths Alkali metals Calcium Haloids	Zirconium Stainless	Copper	Chlorides Zeolite	Chlorides Zeolite Lanthanides	Copper Cadmium Lanthanides	Noble gases	Mol. sieves Iodine
Disposal	Geologic	Geologic	Geologic	Geologic	Near-surface	Geologic	Geologic	Geologic

[1]Excluding LLW from secondary process streams and process equipment replacement.
[2] Per 10^{11} kWh (e.g., produced every 18 months by 10 GW at 75% capacity factor).

However, processing of the spent fuel and removal of large fractions of the transuranics would have one impact that would increase the GW-years of power generation that a geologic repository could support, and thereby could reduce the disposal costs if advantage were taken of this opportunity, although it should be noted that the current plan for the Yucca Mountain repository does not utilize the site's full potential anyway. The impact would be a waste heat output reduction due to removing large fractions of the transuranics. The magnitudes of the heat output reductions and of volume reductions are indicated in table 5-7 for the aqueous processes and in table 5-8 for the pyrochemical processes.

In addition, as the bulk of the extremely long-term heat producers would have been removed, the process wastes' heat output would decay more quickly than that of unprocessed spent fuel. This would result in a lower peak repository temperature and thereby remove one of the constraints on the acceptable initial heat loading of the repository. On the other hand, the more rapid heat output decay would reduce one beneficial effect, the maintenance of a high enough repository temperature to keep the waste packages dry for a very long time.

The waste packages' dimensions and associated numbers of packages in tables 5-1 through 5-6 differ from those in tables 4-1 through 4-6 as a result of the waste package disposal assessment. First, the heat outputs of some of the waste packages in tables 4-1 through 4-6, particularly the vitrified waste packages from the aqueous process, exceed those considered acceptable based on Yucca Mountain repository program design experience to-date and/or exceed the heat output considered acceptable from a consideration of package centerline temperature and dependent waste form integrity. Accordingly, the diameter of some of the packages is decreased and the associated number of packages increased from those identified in chapter 4.

Second, there is no apparent reason why the package lengths should be less than that of the unprocessed spent LWR fuel package. Accordingly, the length of the numerically dominant waste packages from all the alternative processes is increased, and the associated number of packages decreased, from those identified in chapter 4, thereby avoiding unnecessarily high number-of-package-dependent contributions to the estimated disposal costs.

The net potential cost impacts of the above effects on types of waste disposal facility required and on the geologic repository waste volumes and heat outputs are incorporated into the chapter 6 integration of the economic assessment inputs.

Table 5-7

EFFECTS OF AQUEOUS PROCESSING ON GEOLOGIC REPOSITORY WASTE VOLUMES AND HEAT OUTPUTS
(Expressed as Appropriate Percentages of Those of Unprocessed Spent LWR Fuel)

	Volume	Heat Output*
PUREX-only for spent LWR fuel	33%	90%
PUREX + TRUEX for spent LWR fuel	33%	80%
PUREX-only for spent LMR fuel	22%	75%
PUREX + TRUEX for spent LMR fuel	22%	43%

*10 years after removal from reactor.

Table 5-8

EFFECTS OF PYROCHEMICAL PROCESSING ON GEOLOGIC REPOSITORY WASTE VOLUMES AND HEAT OUTPUTS
(Expressed as Appropriate Percentages of Those of Unprocessed Spent LWR Fuel)

	Volume	Heat Output*
For spent LWR fuel	67%	80%
For spent LMR fuel	67%	43%

*10 years after removal from reactor.

5.1.2 With Potential Future Waste Disposal Authorizations

The National Waste Policy Act of 1982 encourages investigation of alternatives to the currently authorized near-surface and geologic methods of waste disposal. If a substantial program of spent LWR fuel processing plus LMR deployment, based upon pyrochemical processing of the spent LWR and/or spent LMR fuel were undertaken, there would arise an economic incentive to authorize prolonged interim surface storage and/or greater confinement disposal (GCD per the concept postulated in reference 5-1), as well as near-surface and geologic facilities. This would occur because a substantial fraction of the waste packages from the pyrochemical processes (the packages that contain the cesium and the strontium) would either meet postulated GCD acceptance criteria or would decay to below them in about 50 years and to below LLW acceptance criteria in two to three times as long. The geologic repository waste volumes and heat outputs of table 5-8 would thereby be reduced substantially.

There has been insufficient prior debate on the acceptability of interim storage for periods up to 150 years, or of the GCD concept for a judgment to be formed in this evaluation. In any event, two cautions are appropriate. One is to note that the waste packages that might be downgraded from geologic to GCD or near-surface disposal are the salt waste packages for which chapter 4 identified a substantial waste form licensing challenge. The other caution is to observe that if prolonged interim storage were deemed acceptable in the interests of reducing subsequent disposal cost, then it would also be acceptable to store unprocessed spent LWR fuel for a similar period and thereby reduce the heat output from the unprocessed spent fuel instead, increase the geologic repository site's technical capacity and reduce the disposal cost. This would reduce the net disposal cost reduction that could be credited to the pyrochemical process' capability to downgrade some of the waste packages from geologic disposal to a less expensive alternative.

The equivalent interim storage periods that would be required for the vitrified waste packages from the aqueous process to be downgraded from geologic disposal would exceed 200 years and are deemed too long to merit further consideration.

A less ambitious alternative would be interim storage of the major heat-producing waste packages (those that contain the cesium and the strontium) for a period not long enough to avoid subsequent geologic disposal, but enough to accrue a major reduction in heat output, increase the geologic repository site's technical capacity and reduce the disposal cost. Here, similar to the above case, interim storage would reduce the heat output of unprocessed spent LWR fuel by as much as it would reduce the heat output of the process waste packages. The heat output reduction achieved by processing would be that due to removal of the transuranics, as already recognized in the preceding subsection of this chapter. By the time of disposal, the spent LWR fuel waste heat output reduction achievable by interim storage would be several times that achievable by processing.

5.2 IMPACTS ON COMPLIANCE WITH RELEASE REGULATIONS

Code of Federal Regulations, 40CFR191, Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, limits the probable cumulative release of specific extremely long-life radioactive isotopes, by expected mechanisms such as leaching, during the first 10,000 years after a geologic repository is closed. Higher projected releases by some less probable release mechanisms are allowed.

Addressing, with respect to leaching, the relevant isotopes in decreasing order of atomic weight, starting with the most significant of the minor transuranics with respect to compliance with the standard, less than 10^{-3} of the initial americium-241 content in typical spent LWR fuel is permitted to be released during the first 10,000 years. Thus, removal of somewhat more than 99.9% of the americium by spent fuel processing, so that less than 10^{-3} of the americium would report to the repository, would approach the intent of the standard. However, a fractional dissolution rate of less than 10^{-10} per year for a repository in unsaturated tuff is suggested, as recently as 1990 (5-2). This indicates that in 10,000 years, less than 10^{-6} of the initial americium in unprocessed spent fuel would be projected to have dissolved, even if all the containers and enclosed canisters were to have failed early. Thus, a margin of 10^3 would be projected to accrue from just this one step in the release sequence.

In addition, for the Yucca Mountain site in particular, a ground water travel time to the accessible environment in excess of 100,000 years is projected (5-3) and may exceed 10^6 years (5-2). Thus, the groundwater travel time alone is projected to preclude violation of the standard. Further, a projected travel time of the americium orders of magnitude longer than that of the groundwater, due to retardation by the tuff, may be derived from reference 5-3.

Yet further margin would accrue from the fact that the half-life of americium-241 is only 433 years, so that release by a dissolution and travel sequence that would take longer than only a few thousand years would become moot anyway.

Americium-243 does not have such a short half-life, but has an initial activity level only 1% that of the 241 isotope.

Repository engineering and licensing is still at an early stage, and until the nation has engineered and licensed a geologic repository, some of the parameters used in the projections of release rates can be expected to change substantially, as the analyses address such complexities as colloids, e.g., whether they will be generated and thereby increase the dissolution rate, and, if so, whether they will then be subjected to more effective filtering than noncolloids (5-2). The release projections can also be expected to vary substantially with each repository site. However, the several and very large margins indicated by the above references would allow very

large parametric changes without jeopardizing compliance with the standard, with respect to americium, and by extension to the minor transuranics in general. On present data, removal of most of the minor transuranics for the purpose of precluding unacceptable leaching would appear to be superfluous. This conclusion is strengthened by the expectation that the rate at which the minor transuranics would be dissolved would be controlled by solubility and water flow rate over the waste (5-4), and that for the inventory of minor transuranics to become controlling a massive reduction in that inventory would be required, a reduction substantially greater than that deemed credible with the separation processes described in chapter 3.

Turning next to the quantitatively dominant transuranic, plutonium, although the allowable release fractions for the 239 and 240 isotopes are an order of magnitude less than for americium, a margin of 10^2 would still be projected solely from the dissolution rate, and the huge groundwater transport time (plus retardation factor) margin would still apply, plus the likelihood that reducing the inventory would not affect the dissolution rate anyway.

Both the cesium-135 and the iodine contents of typical spent LWR fuel are only a third their 10,000 year allowable release limits anyway. This factor, plus the projected groundwater travel time, indicate very large margins for these isotopes too, despite having higher dissolution rates and, for iodine, poor retardation.

Technetium is the element that appears closest to offering a challenge. Although its content in typical spent LWR fuel is only a little higher (about 30%) than the 10,000-year allowable release limit, a projected fractional dissolution rate greater than 10^{-4} per year appears to necessitate reliance on the groundwater travel time being about 10,000 years or more in order to achieve compliance with the standard, at least for an unsaturated tuff location. The projected fractional dissolution rate for technetium in a repository in a saturated rock location is much slower (5-5).

Processing the spent fuel, at least by aqueous technology, would allow the technetium to be enclosed in the vitrified raffinate waste package, or in its own custom immobilized ceramic package. A glass or ceramic deterioration rate of around 10^{-5} per year (5-6) would then provide a backup to the groundwater travel time for assuring compliance with the standard at an unsaturated tuff location. Thus, for the one isotope, technetium, at an unsaturated tuff location, aqueous processing of the spent fuel could ease somewhat the task of demonstrating that the leaching rate would not violate the standard.

Even for technetium, the benefit from spent fuel processing would be a back-up margin rather than a necessity. If, in the unlikely event that continuing work in repository engineering and licensing should determine that such a margin is necessary, then, as adopting processing (to obtain the margin) would constitute a major programmatic and perhaps expensive change, the feasibility and costs of alternatives to spent-fuel processing for achieving the margin would have to be

considered (such as an engineered barrier for the unprocessed spent fuel, or a reconsideration of the allowable release for technetium. It follows that fuel processing would not be the preferred response to this single, postulated need (to provide improved retention of the technetium) unless the net cost impact of the total scenario that involves fuel processing would be less than the cost of the alternatives.

In addition, intuition suggests that there would be something suspect in making a major programmatic change solely because of an inability, for a single isotope at an unsaturated tuff location, to comply with regulations, regulations that were established without a requirement to prescribe a risk level equivalent to risks accepted in other essential industries. In this regard, it should be noted that release of all the technetium to the accessible environment would violate the standard by only 30%.

Carbon is not addressed in this review because of the current reconsideration of the appropriateness of the specified release limit. Also not addressed are the criteria of 10CFR60, 113, which are intended to contribute to the implementation of the above standard. If compliance with the standard becomes demonstrated, but compliance with the implementing criteria would require a major and expensive programmatic change, then the appropriate response would appear to be to consider whether the criteria do implement the standard appropriately.

Until repository engineering and licensing has produced more data, a projection of the possible contribution of spent fuel processing to the task of demonstrating that the less probable release mechanisms, such as intermittent inadvertent intrusion and volcanoes, will not violate the appropriate application of the standard will be more tenuous than that for leaching. In the absence of data to permit specific conclusions, the generalized conclusion embracing all release mechanisms is that under some circumstances, processing of spent fuel could create additional useful margin and could therefore ease somewhat the task of demonstrating compliance with the standard, but that repository engineering and licensing to-date has not suggested that such additional margin would in fact make much difference to the licensing effort. If such additional margin did prove to be highly desirable or even necessary, alternatives to spent fuel processing for achieving additional margin exist, as noted above, and would serve to put a cap on the acceptable cost impact of the fuel processing scenario.

5.3 IMPACTS ON HEALTH RISK

Compliance with the standard would imply that the residual health risk to the public would be lower than some risk level predetermined to be acceptable. However, there remains the possibility that a means of lowering the release and therefore the risk further could be justified if the cost involved were low enough. This reasoning is implicit in the 10CFR50 criterion of $1000/person-rem specified for determining whether additional nuclear plant effluent controls are justified.

This possibility was addressed in reference 5-7 for a particular geologic repository located in salt. As might be expected from the discussion earlier in this chapter, technetium was found to dominate the risk. The million-year risk from the technetium was estimated to be about 25,000 person-rem/GW-year. Applying the $1000/person-rem criterion yields an encouragement of about 3 mil/kWh to remove the technetium risk. However, reference 5-7 records that the estimate was a bounding case appropriate for that estimate's purpose and identifies the very conservative assumptions involved, implying a margin of several orders of magnitude. The inferred conclusion is that, as disposal of unprocessed spent LWR fuel is projected to cost about 1 mil/kWh, removing the technetium risk from that salt location would only be justified if the fractional increase in the disposal cost were undetectable.

However, such an analysis would vary markedly from location to location, so no general conclusion can be drawn. For example, no population health risk analyses for unsaturated tuff sites are found in the literature and the Yucca Mountain program has not yet performed a risk analysis. Reference 5-8 did report a risk analysis relevant to an unsaturated tuff site, but based on a different criterion, individual risk rather than population risk, created specifically for the analysis. However, reference 5-8 noted the wide range of uncertainty in the assumed parameters, some of which have since been superceded by substantially different values, and the analysis addressed HLW not unprocessed spent fuel.

If continuing repository engineering and licensing should indicate that a significant increase in disposal cost would be justified by the above rationale, then at least three other general considerations would enter the decision-making process. One would address the extent to which the above cost equivalence of the risk reduction should be discounted to reflect the time difference between the expenditure and the benefit. Even if only a very small discount rate (to reflect a compromise between recognizing the logic of applying a financially based discount rate and yet not wishing to apply this sound logic to the value of a long-term health benefit, the compromise being heavily biased towards the latter), the cost equivalent of the risk reduction would become vanishingly small because of the length of time involved.

The second general consideration is one identified earlier in this chapter in a different context; that there may be feasible alternatives to spent fuel processing for reducing the technetium risk, and that the spent fuel processing option would not be preferred unless its net cost impact were less than that of the alternatives.

The third general consideration is that the reduction in repository risk could not be considered in isolation; the risk impact of the total scenario would have to be addressed to verify that the scenario would not increase the near-term risk. Even if there were reluctance to recognize the discounting appropriate for the cost equivalence of a long-term risk benefit, it seems reasonable to conclude that a

long-term risk reduction would have to be a large multiple of any associated near-term risk increase if such a risk-shifting scenario were to be justified.

However, reference 5-9 addresses a spent fuel processing plus LMR deployment scenario and projects that spent fuel processing in the particular scenario addressed would make only a minor contribution to the near-term risk impact of the total scenario. The dominant contributor is projected to be a near-term risk reduction, obtained through not having to mine uranium for the LWRs that would be replaced by the LMRs that would consume the separated transuranics. The projected risk reduction includes a reduction in the risk from uranium mill tailings. Uranium mining is projected to contribute about 1000 person-rem/GW-year, when the radiological equivalent of nonradiologic contributions to the risk are also included. The estimate of this risk is not subject to the large uncertainties involved in estimating long-term risks, and its cost equivalence would not be subject to discounting. Based on the $1000/person-rem criterion, the cost equivalence of this uranium mining risk is, nevertheless, only about 0.1 mil/kWh.

5.4 REFERENCES

5-1 D. C. Kocker and A. G. Croff. "A Proposed Classification System for High-Level and Other Radioactive Wastes." Radioactive Waste Management and the Nuclear Fuel Cycle, 1988.

5-2 T. H. Pigford. "Actinide Burning and Waste Disposal." MIT International Conference on the Next Generation of Nuclear Power Technology, 1990.

5-3 U.S. Department of Energy. Site Characterization Plan: Yucca Mountain Site, Nevada Research and Development Area, Nevada, 1988. DOE/RW 0199.

5-4 M. J. Apted, W. J. O'Connell, K. H. Le, A. T. MacIntyre, T.-S. Ueng, T. H. Pigford, and W. W.-L. Lee. Preliminary Calculations of Release Rates of Tc-99, CS-135, and Np-237 From Spent Fuel in a Tuff Repository." WG-2 5/90, PNL/LLNL/UCB/LBL, 1990.

5-5 Swedish Nuclear Fuel Supply Co. Final Storage of Spent Nuclear Fuel-KBS-3. 1983.

5-6 M. Sadeghi, W. W. L. Lee, T. H. Pigford, and P. L. Chambre. Prediction of Release Rates for a Waste Repository at Yucca Mountain. Lawrence Berkeley Laboratory, 1990. LBL-27767.

5-7 A. G. Croff, J. O. Blomeke, and B. C. Finney. Actinide Partitioning - Transmutation Program. Final Report, Overall Assessment. Oak Ridge National Laboratory, 1980. ORNL-5566.

5-8 A Study of the Isolation System for Geologic Disposal of Radioactive Wastes. Waste Isolation System Panel, National Research Council, 1983.

5-9 J. A. Rawlins and J. J. Holmes. CURE: Clean Use of Reactor Energy. Westinghouse Hanford Company, 1990. WHC-EP-0268.

Section 6

INTEGRATION OF ECONOMIC ASSESSMENT INPUTS

Chapter 2 posed the following four questions to be addressed in the evaluation:

- Would plutonium from spent LWR fuel be economically superior to enriched uranium for LMR startup?

- If so, would there be a net benefit in maximizing the recovery of all the transuranics from the spent LWR fuel that would be processed to recover the bulk of the plutonium to start up economically justified LMRs?

- Would there be a net benefit in maximizing the recovery of all the transuranics from spent LMR fuel when it is processed to recover the bulk of the plutonium?

- Would the benefits to HLW disposal justify the processing of current spent LWR fuel, with or without maximizing of the transuranic separation efficiency, and an LMR deployment program to consume the separated transuranics?

This chapter assesses the economic impacts involved in each question, addressing them in the order in which they are presented above. The economic impacts assessed are those that would be experienced by the nation as a whole, with no attempt to identify how the impacts should or would be shared between the institutions involved.

The assessed economic impacts are expressed in January 1990$, regardless of the time of being incurred. The impacts are assessed ignoring inflation. 8% interest on industrial debts and 12% equity returns are assumed, both constant $.

6.1 CHOICE OF LMR STARTUP FISSILE MATERIAL

6.1.1 Assessment Format, Inputs and Assumptions

The sequence of this economic assessment is first to define two scenarios to be compared; one based on enriched uranium, the other based on plutonium. Then, the cost assessment inputs and assumptions are introduced and the cost comparison performed. Finally, the more significant elements of the scenarios and the more

significant cost assessment inputs and assumptions are reviewed to see how credible changes to the scenario, inputs and assumptions would modify the conclusion from the comparison.

One of the two scenarios is an oxide-fueled LMR started up with enriched uranium, with enough additional enriched uranium to refuel the reactor until the spent LMR fuel passing through the aqueous separation and refabrication processes yields enough plutonium to make the LMR self-sustaining for fissile material.

The other scenario starts the LMR up with plutonium recovered from some of the spent LWR fuel, using an aqueous process that is sufficient to extract the bulk of the uranium and plutonium, as described in chapter 3, but that contains no additional steps to recover the residual plutonium and the minor transuranics. The spent fuel processing facility would be industrially owned and financed on a project basis, as described in companion report NP-7264. To maximize the fissile product per ton of spent LWR fuel processed, high burnup spent LWR fuel (50 MWd/kg) would be drawn upon and would be processed after as short a cooling pond storage period as practicable (nominally three years) to minimize the decay of the fissile 241 isotope that would occur by the time the LMR started up. The spent LWR fuel separation process waste packages and disposal facilities would be those projected in table 5-1.

The cost-incurring elements unique to the enriched uranium scenario and the associated cost assessment inputs and sources are as follows:

- Uranium ore purchased in the timeframe that LMRs may be deployed on their economic merit, $30/lb (6-1).

- Conversion of the ore to hexafluoride, $9.3/kg (6-1).

- Enrichment, $95/SWU [(6-1), as updated by correspondence from one of its authors and reflecting the author's identification of a small premium for high enrichment levels].

- Transport and disposal of that quantity of unprocessed spent LWR fuel that would be processed in the plutonium startup scenario, 0.92 mil/kWh (companion report NP-7263).

The cost-incurring elements that would be unique to the plutonium scenario are as follows:

- Transport of spent fuel from LWRs to a spent LWR fuel processing facility, $8/tonne of initial heavy metal (IHM) (6-2).

- Spent LWR fuel processing and waste packaging, $435/kg (IHM) (companion report NP-7264, after removal of TRUEX and minor transuranics/lanthanides separation costs).

- Transport of the separated actinides to the LMR fuel facility, $700/kg (Pu) (6-2).

- Waste packages transport and disposal, 0.8 mil/kWh (companion report NP-7263).

Processing of the spent LWR fuel would also accrue an added value through the recovery of slightly enriched uranium, reusable as feed to an LWR fuel enrichment process. Reference 6-3 indicates that over half the uranium recovered from the spent fuel of the UK's commercial Magnox reactor program is already back in the UK's commercial reactors, thereby implying an economic incentive for such reuse. However, reference 6-3 also identifies high radiation levels from the recovered uranium, primarily due to the uranium-232 isotope. To give some recognition to the probability that handling this hot uranium would have a cost impact, the recovered uranium in this cost comparison is assumed to have only 75% the value of natural uranium.

In addition, the recovered uranium would comprise about 0.4% as the 236 isotope, some of which would travel with the 235 isotope and, having a poor fission/capture cross-section ratio, would require additional 235 enrichment to compensate. The analysis of reference 6-4 indicates that the effective value of the 236-bearing recovered uranium would be a function of the ratio of contemporaneous ore and enrichment services costs and would vary between 75% and 100% of natural uranium's value as ore cost rose. As an increased ore cost is a prerequisite of economically justified LMR deployment, the assumed value of the uranium is not reduced in this cost comparison to allow for the effect of the 236 isotope.

Companion report NP-7264 assessed spent fuel processing costs assuming that the processing facility would be to a mature design, i.e., for which there had been predecessors which had borne the first-few-of-a-kind engineering and licensing costs. It is anticipated that if and when LMRs are deployed, it will be because consumption of the most accessible, highest-grade uranium ore will have escalated the cost of the ore beyond the point at which continued deployment of LWRs remains economic. Thereafter, LMRs would take a substantial fraction of the total nuclear deployment program, which itself would have to be a substantial program, otherwise this consumption of uranium ore and escalation of its price would not have happened. Thus, LMR deployment, when economically justified, is anticipated to be substantial. The original deployment of LWRs could be considered to be an example of a substantial deployment program, resulting in 6 to 7 GW being brought on line per year. An LMR deployment program of this magnitude would require 3 to 4 of the spent LWR fuel processing facilities assessed in companion report NP-7264. Three to four falls in-between the intended meanings of first-of-a-kind and mature. To reflect some first few-of-a-kind costs spread over the first few processing plants, 15% is added to the $435/kg (IHM) derived in companion report NP-3274 and noted above, to yield an adjusted cost of $500/kg (IHM). This 15% would represent the average over three facilities, for which the first-of-a-kind costs

would be 25%, 15%, and 5%, in that sequence, and is applied to the operating as well as the capital costs.

6.1.2 Resulting Assessment

In order to sum and compare the above cost contributors, it is necessary to convert them to the same units. As the purpose of both scenarios would be to provide fissile material to start up LMRs, the common unit selected is the impact on the levelized fuel cycle cost of the served LMRs, in mil/kWh. Table 6-1 records parameters assumed in making the conversion. The resulting cost comparison between the two scenarios is as follows:

U-235 Scenario

• Uranium ore purchase	3.2 mil/kWh
• Conversion of ore to hexafluoride	0.3 mil/kWh
• Enrichment	2.4 mil/kWh
• Unprocessed spent LWR fuel transport and disposal	3.9 mil/kWh
TOTAL	9.8 mil/kWh

Plutonium Scenario

• Spent LWR fuel transport	0.1 mil/kWh
• Spent LWR fuel processing and waste packaging	3.8 mil/kWh
• Transport of separated actinides	0.1 mil/kWh
• Waste packages transport and disposal	3.5 mil/kWh
• Value of recovered uranium	-0.4 mil/kWh
TOTAL	7.1 mil/kWh

A comment in passing before drawing a conclusion from the above comparison is to observe that the costs of work elements on spent LWR fuel (e.g., processing, disposal), thereby initially expressed in parameters related to the spent LWR fuel (e.g., $/tonne, $/kWh of LWR electricity), make surprisingly large contributions to the LMR's levelized fuel cycle cost. This relationship is primarily due to the fact that a typical LMR requires the lifetime's output of spent fuel from an LWR of the same capacity in order to recover enough plutonium to start up. For example, the above assessment shows that a cost of 0.8 mil/kWh (LWR electricity) for transport and disposal of the waste packages from the processing of spent LWR fuel, when adjusted to recognize the duration between costs and return in this comparison, then converted to the cost per tonne of processed fuel, then to the cost per gram of recovered fissile plutonium, then to the cost of the required inventory of fissile plutonium to start up the LMR, then to the impact on the LMR's levelized fuel cycle cost, equates to 3.5 mil/kWh (LMR electricity).

Table 6-1

PARAMETERS FOR CONVERTING COST INPUTS TO LEVELIZED LMR FUEL CYCLE COST UNITS

LWR net plant efficiency.	32%
Fissile plutonium content of 50 MWd/kg spent LWR fuel six years after removal from its reactors (to represent 3 years of cooling pond storage, doubled through LMR startup to allow for fuel processing and fabrication and LMR loading and commissioning).	0.83% (6-5)
Constant $ cost of money to utilities.	6% (6-1)
Utility ownership of uranium ore before use.	5 years
U-235 enrichment for an LMR of the same capacity as the passive advanced LWR (600 MW).	19%
LMR levelized fuel cycle cost increment per $ increment in the price of a gram of U-235.	0.1 mil/kWh (GE LMR data, adjusted to reflect 600-MW capacity, 38% net plant efficiency and 75% plant capacity factor.)
LMR levelized fuel cycle cost increment per $ increment in the price of a gram of fissile plutonium.	0.06 mil/kWh (as above)
Mean time between centroid of repository expenditures and receipt of waste.	8 years

The above comparison indicates a strong economic incentive (>2 mil/kWh) to use spent LWR fuel plutonium rather than enriched uranium for starting up LMRs. The two main reasons for this result are first that it costs more to obtain a gram of adequately concentrated fissile material by mining and enrichment than by spent fuel processing, and second that it takes more grams of uranium-235 than fissile plutonium to start up an LMR. This latter factor is discussed later in this subsection.

The question arises whether any of the above cost contributions could vary enough to eliminate the net indicated incentive. In view of the large magnitude of the incentive, only the biggest cost contributions are addressed below.

The biggest contribution is the 3.9 mil/kWh from the transport and disposal of unprocessed spent LWR fuel. However, this contribution is almost balanced by the 3.5 mil/kWh on the other side of the comparison, from the transport and disposal of waste packages from the processing of spent LWR fuel. Most of the potential causes for varying either one of these two contributions would also vary the other, pro rata, and the possible absolute variation in the small differential could only be small. In this respect, it may be noted that to keep the number of variables addressed in this evaluation to a manageable level, the spent LWR fuel waste packages were quantified and the unprocessed spent fuel and waste packages disposal costs assessed for a single burnup of 33 MWd/kg. The unprocessed spent fuel and waste packages for the 50 MWd/kg fuel on which this particular cost comparison is based would have smaller volumes and thence slightly lower disposal costs than indicated in the above comparison. However, this small over-statement appears on both sides of the comparison and therefore cancels.

However, it is worth noting that, consistent with the heat output and volume reductions (10% and 67%, respectively) identified in subsection 5.1 of this report, processing of the spent LWR fuel is projected to offer a modest reduction (about 13%) in the waste disposal cost, provided advantage is taken of this opportunity in contrast to the current plan for the Yucca Mountain repository not to use the site's full technical capability. The incremental cost reduction that may accrue from one aspect of the heat output reduction described in subsection 5.1 is not quantified and included in this comparison, because the quantification effort is not justified. The aspect not quantified is that of the faster heat output decay that would occur in the repository due to the absence of the transuranics.

The only other variable that deserves mention is the ratio of about 1.7:1 (implied in the table 6-1 cost conversion parameters) for the quantity of fissile uranium required to start up an LMR and sustain it until self-sufficient, compared with the equivalent quantity of fissile plutonium. This ratio is derived from LMR core calculations addressing required enrichment and breeding rate and drawing upon neutronic calculational technology that is too well established to consider that the ratio could really be as low as 1.2:1, as it would need to be to eliminate the economic incentive for plutonium.

The second biggest contribution is the 3.8 mil/kWh from the spent LWR fuel processing and waste packaging. This processing cost would have to be 70% higher than indicated if it were to eliminate the economic incentive to use plutonium. Review of companion report NP-7264 does not lead to such an expectation; rather, the review draws attention to the fact that two of the most quantitatively significant assumptions leading to the assessed cost are at the high cost end of the possible range. One is the choice of a 30/70, debt/equity ratio, and the other is the choice of manufacturing industry rather than government ownership of the facility. Companion report NP-7264 indicates that the reduced cost of money to the government compared with that to industry could almost halve the processing cost. However, government ownership would inevitably be accompanied by an administrative burden that would consume much of the savings.

A doubt arises because of prices of $700-750/kg reported for contracts recently placed with the French processing company, i.e., more than 40% higher than derived for this cost comparison. However, an attempt to convert the French prices into likely domestic ones encounters terminal difficulties, including choosing a currency conversion rate that does not exaggerate the US/French cost ratio, determining how costs relate to reported prices, adjusting for the larger plant capacity that would be needed in the United States and that formed the basis of the companion report NP-7264 assessment, understanding and adjusting for US/French differences in the annualizing of capital costs, and adjusting for the different first-of-a-kind cost effects incurred by the sequence of constructing a very small facility, followed by an extension of the facility in parallel with construction of a second facility.

On the whole, the assessed cost used in this comparison is judged to be about the mid-point of the likely cost range, and elimination of the economic incentive to use plutonium because of a 70% higher processing cost appears very unlikely.

Companion report NP-2764 indicates that adoption of the pyrochemical process for recovering the plutonium from spent LWR fuel would raise the processing cost substantially, possibly enough to undermine the above conclusion in favor of plutonium. However, it is reasonable to assume that if the pyrochemical alternative does prove to be significantly more expensive than the aqueous process, it would not be adopted anyway, so this challenge to the conclusion of the comparison is considered moot.

The next biggest contribution is the 3.2 mil/kWh from the purchase of uranium ore. The ore would have to be almost free if it were to eliminate the economic incentive for plutonium, which would not be consistent with the visualization of LMR deployment. Rather, it may be expected that LMR deployment would be triggered by the uranium ore cost rising substantially above, not below, the $30/lb input to this comparison.

In conclusion, the overall projection is for an economic incentive greater than 2 mil/kWh to use spent LWR fuel plutonium, with a sensitivity review indicating that the incentive is likely to be higher still rather than lower.

6.2 MAXIMIZING RECOVERY OF TRANSURANICS FROM SPENT LWR FUEL

One of the two scenarios for this comparison is the same as one in the preceding comparison, an LMR initially fueled with plutonium recovered from high burnup spent LWR fuel by the basic aqueous process (PUREX), in an industrially owned facility. The waste packages and required disposal facilities would be those projected in table 5-1.

The other scenario would add the TRUEX, minor transuranics/lanthanides partitioning and technetium separation steps, and some additional multistaged cleansing of the clad fragments, as described in subsection 3.2.1 of this report. The waste packages would be those projected in table 5-2, for which the projected disposal locations would be unchanged by the much reduced transuranic content, as noted in subsection 5.1.

The estimated cost increments and decrements that would be caused by these processing additions are all small. Using the same or equivalent cost assessment inputs from the same sources as in the preceding comparison, the following specific results are obtained:

- The estimated spent fuel process cost increment due to adding the above process steps would equate to less than 0.3 mil/kWh onto the levelized fuel cycle cost of the LMRs that would consume the separated transuranics.

- This increment would be balanced by an estimated reduction in waste packages disposal cost, due to the 10% reduction in waste packages heat output that would accrue from removal of the minor transuranics, as noted in subsection 5.1.

- There would be a very small additional cost decrement due to the extracted minor transuranics constituting fissile material and, therefore, having some monetary value, but equivalent to less than 0.1 mil/kWh and therefore negligible.

- Assumed also to be negligible are the impacts on core nuclear design and on the fuel metallurgical life, and therefore on the dependent costs, due to the fact that the initial LMR fuel would contain an increased, but still small minor transuranic content (about 1%). As the LMR fuel fabrication process would probably be a remote-handled operation even without the minor transuranics being included in the fissile material input, the fuel fabrication cost also would not be impacted materially by including them.

The overall projection, therefore, is that including minor transuranic separation would not increase the overall cost of the scenario.

6.3 MAXIMIZING THE RECOVERY OF TRANSURANICS FROM SPENT LMR FUEL

This comparison and its results are very similar to its LWR equivalent above. Both scenarios in this comparison would include an oxide-fueled LMR supported by an industrially owned centralized aqueous spent LMR fuel processing and refabrication facility. One scenario would include the basic PUREX process for recovering the bulk of the uranium and plutonium and would produce the waste packages projected in table 5-3. The other would have the additional TRUEX, minor transuranics/lanthanides partitioning and technetium separation steps and some additional multistaged cleansing of the clad fragments. The waste packages would be those projected in table 5-4, for which the projected disposal locations would be unchanged by the much reduced transuranic content, as noted in subsection 5.1.

The estimated spent fuel process cost increment due to adding the above process steps would contribute less than 0.3 mil/kWh to the levelized fuel cycle cost, which would be more than offset by an estimated reduction in waste packages disposal cost, due to the 40% reduction in waste packages heat output that would accrue from removal of the minor transuranics, as noted in subsection 5.1.

The one comparison variation that merits a mention is that if metal fuel plus pyrochemical processing is adopted for the LMR, the separation of the minor transuranics would incur even less incremental cost than in the aqueous process described above.

The overall projection, therefore, is that including minor transuranic separation in the processing of spent LMR fuel would not increase the overall cost.

6.4 APPLICATION TO CURRENT SPENT LWR FUEL

6.4.1 Scenarios, Inputs and Assumptions

One scenario in this comparison consists of current and future unprocessed spent fuel from existing LWRs being deposited in geologic repositories, accompanied by spent fuel from future advanced LWRs. In the alternative scenario, the current and future spent LWR fuel would be processed in an industrially owned aqueous facility to separate both the plutonium and the minor transuranics. The waste packages and required disposal facilities would be those projected in table 5-2. The separated transuranics would be used to start up oxide-fueled LMRs, which would thereby take up deployment slots otherwise intended for some of the future advanced LWRs. The spent LMR fuel would be processed and refabricated in an centralized aqueous processing facility to separate both the plutonium and the minor

transuranics. The waste packages and required disposal facilities would be those projected in table 5-4.

This comparison is initially confined to fuel cycle costs and is then expanded by a discussion of the other contributors to the total busbar costs. The fuel cycle cost-incurring elements unique to the no processing scenario would be as follows:

- Transport and disposal of the unprocessed spent LWR fuel, 0.92 mil/kWh (companion report NP-7263).

- Fuel cycle of those advanced LWRs that would not exist in the alternative (the processing) scenario, 9.2 mil/kWh (8.3 mil/kWh Advanced LWR Program target in reference 6-5, plus the above 0.92 mil/kWh for transport and disposal of the unprocessed spent fuel).

The fuel cycle cost-incurring elements unique to the processing scenario would be as follows:

- Transport of spent fuel from LWRs to a spent LWR fuel processing facility, $8/tonne (IHM) (6-2).

- Spent LWR fuel processing and waste packaging, $533/kg (IHM). (companion report NP-7264, after inclusion of the 15% first-few-of-a-kind costs, consistent with a conclusion, derived later in this chapter, indicating that several spent LWR fuel processing facilities would be needed to implement this scenario).

- Transport of the separated actinides to the LMR fuel facility, $700/kg (Pu) (6-2).

- Spent LWR fuel process waste packages transport and disposal, 0.73 mil/kWh (companion report NP-7263).

- Recovered uranium, 75% natural uranium price (subsection 6.1.1 of this chapter).

- Fabrication of LMR fuel and subsequent processing and refabrication, 4.2 mil/kWh (GE LMR data, adjusted to reflect 38% net plant efficiency, 75% plant capacity factor, and 150 MWd/kg average burnup).

- Spent LMR fuel process waste packages transport and disposal, 0.44 mil/kWh (companion report NP-7263).

6.4.2 Resulting Assessment

The above cost contributions are converted to levelized LMR fuel cycle cost units using the relevant conversion parameters identified in table 6-1, except that the fissile plutonium content of current spent LWR fuel, having an average burnup of 33 MWd/kg and having been stored so long that the plutonium-241 content would have mostly decayed away, would be only 0.55% (6-5).

The resulting cost comparison between the two scenarios is as follows:

No Processing Scenario

• Unprocessed spent LWR fuel transport and disposal	3.9 mil/kWh
• Advanced LWR levelized fuel cycle cost	9.2 mil/kWh
• TOTAL	13.1 mil/kWh

Processing Scenario

• Spent LWR fuel transport	0.1 mil/kWh
• Spent LWR fuel processing and waste packaging	6.0 mil/kWh
• Transport of separated actinides	0.1 mil/kWh
• Spent LWR fuel process waste transport and disposal	3.2 mil/kWh
• Value of recovered uranium	-0.5 mil/kWh
• Rest of the LMR levelized fuel cycle cost	4.2 mil/kWh
• Spent LMR fuel process waste transport and disposal	0.6 mil/kWh
• TOTAL	13.7 mil/kWh

The above comparison indicates that a small fuel cycle cost penalty would be incurred by each LMR that, for the purpose of using the transuranics, would be deployed instead of an advanced LWR. However, before drawing a conclusion from this comparison, each of its major cost contributors is reviewed below and judgments made as to its very likely, but not bounding range, so that the whole range may be considered very credible. Judgments are also made as to what extent the center of the cost range would be offset from its single-value cost contribution derived above.

Potentially, the biggest contributor to the comparison is one not identified above, a potential difference between LWR and LMR plant capital and operation and maintenance costs. As these would contribute a total of about 60 mil/kWh to the total levelized busbar cost of either the LWR or the LMR, a differential of only 1% between them would either eliminate or double the fuel cycle cost differential indicated above.

The only recent journal article that has been found addressing the potential LMR/LWR plant capital cost differential is reference 6-6, which reported a study performed by the UK nuclear industry and integrated by the Central Electricity

Generating Board. The study projected that after the first-of-a-kind costs for initiating LMR deployment have been absorbed, LMRs will incur essentially the same capital costs as future LWRs of the same reactor capacity. A discussion later in this chapter concludes that to implement the processing scenario of this cost comparison would indeed require an LMR deployment program extending far beyond first-of-a-kind cost considerations. Accordingly, no LMR/LWR differential for development and first-of-a-kind costs are included in this cost comparison, partly because of their small impact when spread over a large deployment program and partly because most of such costs either already are being or likely will be incurred anyway.

The more significant capital cost differences between the LMR and the LWR include the extra costs carried by the LMR because of its relatively complex reactor internal structure and fuel handling equipment and the existence of an intermediate heat transport system. These are essentially offset by the almost total absence of auxiliary systems serving the reactor itself and the cross-the-board reduction in the size of equipment and enclosing structures, due to the higher quality steam and dependent net plant efficiency. Reference 6-6 also projected that LMR and LWR operation and maintenance costs would also be essentially the same.

The judgment for this comparison is that the LMR/LWR plant capital and operation and maintenance cost differential is likely to fall within a 15% range centered on zero, i.e., within ±7.5%. Later in this discussion, this range plus those associated with the other cost contributions to the comparison are depicted graphically.

The biggest cost contribution identified in the above comparison is the 8.3 mil/kWh for the Advanced LWR Program target levelized fuel cycle cost, excluding spent fuel disposal. Assessment of this cost using the same inputs and assumptions defined and used in subsection 6.1 of this chapter yields a cost of only 6.0 mil/kWh. The dominant uncertainty in the calculation is the cost of uranium ore. Figure 6-1 plots DOE's projections (6-7) of the cost/consumption relationship for what are characterized as "assured," "estimated," and "speculative" uranium ore resources. The figure indicates the resources that would be consumed by potential deployment programs of advanced LWRs, assumed to operate for 50 years at 75% capacity factor. The figure endorses the $30/lb uranium ore cost recommended in reference 6-1 and used in the above assessment, if the advanced LWR deployment program were modest. However, for a program that would equal the existing deployment of 100 GW, the most optimistic of the curves of figure 6-1, i.e., the "speculative" curve, indicates that the average uranium ore cost over the plants' lives would be more than for a small program, i.e., about $35/lb instead of $30/lb. This would raise the levelized fuel cycle cost by about 0.5 mil/kWh. A larger deployment program or assumption of one of the alternative curves of figure 6-1 would, of course, raise the assessed fuel cycle cost further. Thus, the Advanced LWR Program target fuel cycle cost may be regarded as equaling an estimate based on a cautious projection

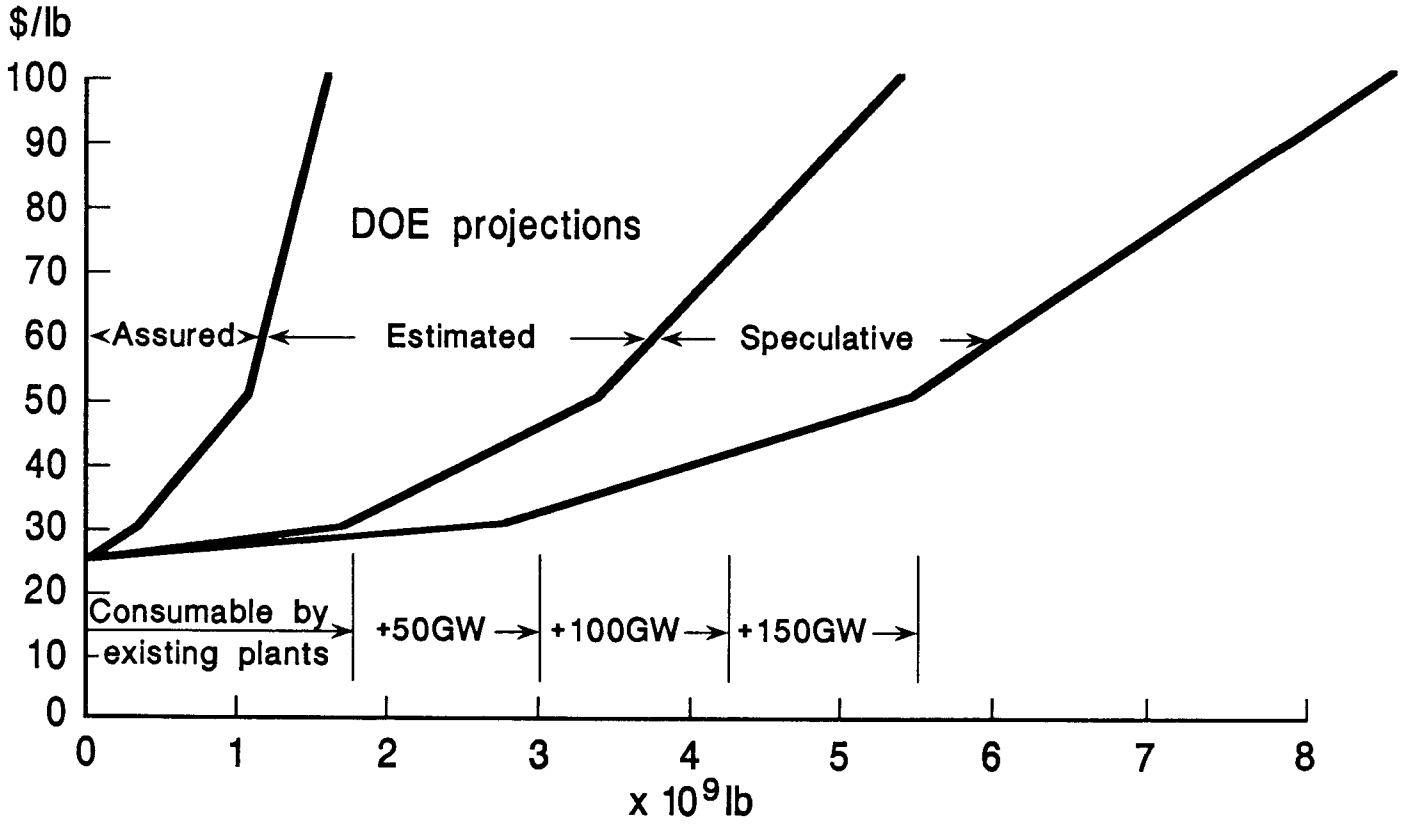

Figure 6-1. U.S. Uranium Ore Resources and Cost ('88$)

regarding the highly variable uranium ore cost. The judgment then for this comparison is that the advanced LWR's levelized fuel cycle cost is likely to fall within a 20% range stretching from the Advanced LWR Program target downwards.

The next biggest cost contribution is the 6 mil/kWh for the spent LWR fuel processing and waste packaging. Based on the prior discussion of this item in subsection 6.1.2 of this chapter, the judgment for this comparison is that the spent LWR fuel processing and waste packaging cost is likely to fall within ±20% of that assessed in the above comparison. It is recognized that as economically justified LMR deployment may not be far off anyway, the 15% first-few-of-a-kind costs included in the assessed cost would be incurred anyway, but later, so only enough of the 15% to recognize its accelerated schedule should be booked to the cost of processing current spent fuel for waste disposal purposes. However, the breadth of the above range is considered adequate to encompass this additional consideration.

Next is the 4.2 mil/kWh for fabrication of LMR fuel and subsequent processing and refabrication, derived from GE's LMR data. The only yardstick available with respect to this item is the observation that the same GE team recently, on a different project, assessed a spent LWR fuel processing facility cost a little lower than that assessed in companion report NP-7264 and discussed above. Accordingly, the judgment for this comparison is that the LMR fuel fabrication and subsequent processing and refabrication cost is also likely to fall within a 40% range, but centered 10% above the 4.2 mil/kWh assessed in the above comparison.

The observation in subsection 3.1.3 of this report, that GE's LMR fuel cycle cost estimates indicate a 0.5 mil/kWh fuel cycle cost reduction by adoption of metal instead of oxide fuel suggests that the LMR fuel fabrication and subsequent processing and refabrication costs could be lower than assessed above. However, this cost reduction would be offset by a cost increase to reduce to metal form the actinide product from the aqueous spent LWR fuel processing facility. This reduction step would be avoidable if the spent LWR fuel process were pyrochemical, but companion report NP-7264 does not encourage an expectation that this alternative scenario would be cost-effective. Although the conceptual status of the pyrochemical process for spent LWR fuel allows of the possibility that a very successful development program could demonstrate much lower costs than indicated in companion report NP-7264, an assumption in this comparison of a net resulting LMR fuel cycle cost lower than that indicated would not be justified.

The only remaining cost contributions worth reviewing are the disposal costs. As these appear in both scenarios of the comparison and are therefore essentially self-canceling as far as changes are concerned, assignment of cost ranges would serve no useful purpose. In passing, it may be noted that the two larger disposal costs in this comparison are biased towards the high side because all the disposal cost assessments in companion report NP-7263 are based on disposal 10 years after removal from the reactor, whereas this comparison addresses the dispositioning of current spent LWR fuel several decades after removal from its reactors.

The above cost comparison and assigned cost ranges are depicted in figure 6-2. This figure indicates that the midpoint of the likely range in which the net cost impact would fall would be a cost penalty of about 2 mil/kWh for the processing scenario.

6.4.3 Accumulating Cost Penalty

A cost penalty characterized as a busbar cost increment associated with each LMR that would be deployed instead of an advanced LWR gives no indication of the total cost impact unless the required LMR deployment program is also characterized. Accordingly, the following discussion defines a practicable scenario and assesses the total cost impact, then considers whether credible changes to the scenario would substantially change the total cost impact.

The selected scenario brings advanced LWRs on-line from the year 2005 at a rate of 5 GW per year, and development programs aggressively complete the tasks necessary to permit LMR deployment as soon as feasible. This implies retaining the scenario already identified and used in the above cost assessments, i.e., oxide fuel with aqueous processing of both spent LWR and spent LMR fuel. This is judged as making it credible to bring LMRs on-line from the year 2010. In so doing, the timeframe for starting permanent disposition of the current spent fuel (i.e., by processing it instead of burying it) would not materially change.

Thereafter, LMRs taking up half the total nuclear deployment program, i.e., 2.5 GW per year, would be a desirable compromise between wanting to attack the backlog of spent fuel as quickly as possible and wanting to maintain the momentum of the advanced LWR deployment program. Unfortunately, deployment of 2.5 GW per year of the LMR characterized in the above cost assessment would only take up spent LWR fuel at the rate the existing LWRs and the advanced LWRs would continue to produce it, and would soon get further behind as advanced LWR deployment continued. Two alternative technically feasible scenarios to overcome this hurdle are discussed below.

One would be to interrupt the advanced LWR deployment program from the year 2010 while enough LMRs are deployed to reduce the backlog of spent fuel to an acceptable level. Advanced LWR deployment would resume when the backlog had been reduced to five years' worth for every LWR. Thereafter, the mix of LWR and LMR deployment would retain the five-year backlog. This scenario and criterion would require an initial deployment of 65 GW of LMRs, thereby interrupting advanced LWR deployment for 13 years. This scenario is, therefore, considered impracticable and is not considered further.

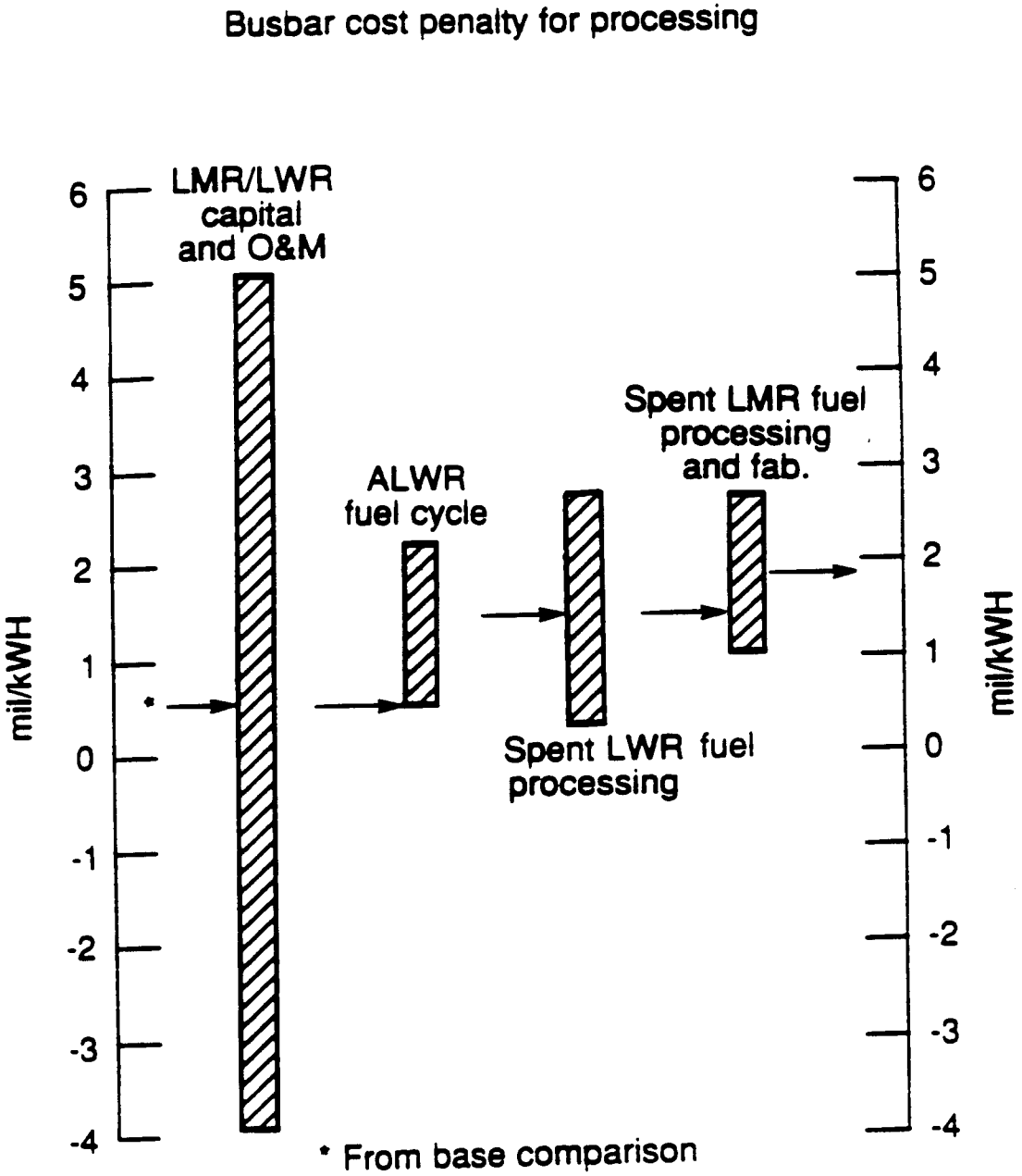

Figure 6-2. Likely Variations in Contributors to Cost Comparison. Processing Versus No-Processing

The other scenario would be to take advantage of the LMR's design flexibility, and design for a higher enrichment level and/or a lower breeding ratio, and thereby increase the take of LWR-generated plutonium. A doubling of the plutonium take would permit the 50/50, LMR/LWR deployment split from the year 2010, while still reducing the spent fuel backlog to five years' worth in 13 years. However, doubling the plutonium take per GW of LMR deployed would also double the quantity of spent LWR fuel that would have to be processed per GW of LMR deployed.

Reference to the fuel cycle cost comparison in subsection 6.4.2 of this chapter indicates a resulting increase to the busbar cost penalty of 5.5 mil/kWh on top of the previously assessed mid-range penalty of 2 mil/kWh, for a new mid-range penalty of 7.5 mil/kWh. Thus, although this way of reducing the size of the required LMR deployment would halve the kWh of LMR electricity carrying a busbar cost penalty, the busbar cost penalty would likely be almost quadrupled, thereby almost doubling the accumulating penalty.

Reference to subsection 6.1.2 indicates that the mid-range penalty would be 3.5 mil/kWh for those LMRs that would receive plutonium separated from 50 MWd/kg spent LWR fuel five years after the fuel leaves its reactors. This introduces the final scenario parameter that needs defining in order to convert the busbar cost increment to a total cost impact. It is assumed that the average existing LWR will spend half its 60-year extended plant life producing 33 MWd/kg spent fuel and the other half 50 MWd/kg.

The mid-range total cost impact of this scenario would then consist of an annual penalty which would rise from zero in the year 2010 at an approximate rate of $0.1 B per year over a 13-year period, to reach and level out at about $1.25 B per year. Thereafter, as the backlog criterion would have been met, the LMR could apply its further deployment GWs to an LMR design not burdened with an excessive fissile startup requirement, and further growth in the annual cost penalty would essentially terminate.

To reflect the uncertainties in this projection, this conclusion can be restated as an annual cost penalty likely to rise to between $0.5B and $2 B per year during the first quarter of the next century. To keep this penalty in perspective, it is as already stated, in '90$ incurred starting 20 years from now, not present-worthed to today.

The annual cost penalty could be trimmed somewhat by designing for something less than twice the necessary plutonium startup inventory, thereby extending beyond the year 2022 the date when the backlog would be cleared. However, even 2022 may be considered unacceptable.

A review of the scenario elements defined above for the purpose of converting a busbar cost increment into an annual cost increment indicates that the annual cost penalty is not very sensitive to likely variations in those scenario elements. However, the effects of two unlikely but large scenario variations deserve identification.

One arises from the observation that technical necessity maintains a finite backlog of spent fuel (five year's worth is selected in the above scenario), which, if the processing scenario were adopted, would have to be processed at the end of plant life, and thereby would incur a further increment to the accumulating cost penalty. However, a cost penalty is better later than sooner. This raises the question whether, if national policy should change to make extended spent fuel storage deliberate and much longer than the current de facto storage (e.g, to reduce spent fuel/waste heat output and thereby increase the geologic repository site's technical capacity), would the conclusion of this cost comparison change significantly. This option is currently being considered by the two nuclear utilities in the United Kingdom (6-8).

Subsection 5.1.2 has already noted that extended storage would reduce the heat output of unprocessed spent fuel by as much as it would reduce the heat output of the process waste packages, so extended storage would have negligible effect on the processing/no-processing cost comparison by reducing disposal costs disproportionately. However, the longer such storage, the greater the number of advanced LWRs likely to have been deployed by the time permanent disposition of a spent fuel assembly is due, the more the uranium ore price may have risen and the smaller would be the busbar cost penalty for adopting the processing-all-spent-fuel scenario (i.e., not just that required to serve economically justified LMR deployment). However, long before a rising uranium ore price caused a substantial reduction in this busbar cost penalty, this scenario would be interrupted by a clear economic incentive to deploy economically optimum LMRs having no requirement to accept more transuranics than they need. There would remain a strong economic disincentive to processing the backlog of spent LWR fuel.

The other unlikely variation that deserves identification is the possibility of a much larger nuclear deployment program, triggered, for example, by the greenhouse effect. The sequence of impacts would then be the same as in the extended storage variation above, except that a credible impact of the greenhouse effect would be to make the processing of all the spent LWR fuel economic (to support massive LMR deployment), regardless of the possible disposal benefits.

6.5 REFERENCES

6-1 J. G. Delene and C. R. Hudson, II. Cost Estimate Guidelines for Advanced Nuclear Power Technologies. Oak Ridge National Laboratory. ORNL/TM-10071/R2.

6-2 British Nuclear Fuels, Central Electricity Generating Board and United Kingdom Atomic Energy Authority. Review of Nuclear Fuel Cycle Costs for the PWR and Fast Reactor. FRJC/P(87)4, 1987.

6-3 "British Reprocessing." Nuclear Engineering International, 1990.

6-4 A. de la Garza. "Uranium-236 in Light Water Reactor Spent Fuel Recycled to an Enriching Plant." Nuclear Technology, February 1977.

6-5 Advanced Light Water Reactor Utility Requirements Document, Vol. 1. Palo Alto, Calif.: Electric Power Research Institute, 1990.

6-6 R. S. Hall, J. L. Gray, A. Green, R. H. Allerdice, and A. M. Broomfield. "Towards an Economic Fast Reactor." Nuclear Engineering International, 1989.

6-7 Department of Energy. Annual Energy Review. DOE/EIA-0384 (88), 1988.

6-8 "Datafile: UK." Nuclear Engineering International, 1990.

6-9 S. B. Ludwig and J. P. Renier. Standard and Extended Burnup PWR and BWR Reactor Models for the ORIGEN-2 Computer Code. Oak Ridge National Laboratory, 1989. ORNL/TM-11018.

Section 7

MERITS AND CONCLUSIONS

This chapter pulls together the more significant technical and economic merits and demerits identified in the preceding chapters with regard to the questions posed in chapter 2 and recapped at the beginning of chapter 6, and introduces some programmatic, institutional, political and public acceptance considerations. Conclusions are then drawn.

7.1 CHOICE OF LMR STARTUP FISSILE MATERIAL

An economic incentive of greater than 2 mil/kWh to use plutonium recovered from spent LWR fuel, rather than use enriched uranium, for startup of LMRs is projected. A sensitivity review indicates that the incentive would more likely be greater still rather than lower. Supplementing the economic incentive to use plutonium, there would be the avoidance of a further contribution to the near-term health risk from uranium mining and possibly a public perception benefit through the avoidance of a further contribution to the nation's inventory of transuranics. The technology for recovering the plutonium from the spent LWR fuel could be brought to commercial readiness with only a very modest development program, if the aqueous process were adopted.

A potential disadvantage would be the need to gain political and public acceptance of spent LWR fuel processing. However, if and when LMRs are deployed, whether started up with plutonium or enriched uranium, political and public acceptance of spent fuel processing would have to be obtained anyway, for the spent LMR fuel. The spent LWR fuel processing facilities would also be less numerous than the spent LMR fuel processing facilities.

7.2 MAXIMIZING THE RECOVERY OF TRANSURANICS FROM SPENT FUEL

No significant net cost impact is projected to result from separating the bulk of the minor transuranics or from maximizing the total transuranic separation efficiency, when either spent LWR or spent LMR fuel is processed to recover the bulk of the plutonium as part of an economically justified LMR deployment program. A public perception benefit may accrue through the avoidance of a further contribution to the nation's inventory of transuranics.

A significant and successful development program would be necessary to permit recovery of the minor transuranics, even with the well established aqueous process. The basic pyrochemical process for spent LMR fuel is less established and would therefore require a larger demonstration program, including demonstration of a licensable salt waste form. The pyrochemical process for spent LWR fuel would have the same plus additional development challenges.

7.3 CURRENT SPENT LWR FUEL

Adoption of a process-before-disposal policy to replace the current dispose-unprocessed policy for the spent fuel from LWRs would necessitate a large LMR deployment program to take up the separated transuranics. The flexibility of the LMR would permit a compromise between holding down the required LMR deployment program and holding down the overall economic penalty. For example, reducing, within the first quarter of the next century, the backlog of undispositioned spent LWR fuel to five years' worth for every LWR would likely require deployment of abut 30 GW of LMRs and incur an overall cost penalty rising to between $0.5B and $2B per year ('90$) by the end of that quarter century.

The substantial development effort alluded to in subsection 7.2 of this chapter would also be required, and the costs therefore would constitute a fractional increment (dependent on the selected basic separation processes) to the above economic penalty.

The qualitative returns for the above expenditure would be modest. The only tangible benefit would be the avoidance of a further contribution to the health risk from uranium mining and associated mill tailings, through deploying fewer advanced LWRs, but the obtaining of that reduction would justify only a very small fraction of the above overall cost penalty (per 10CFR50 guidance). There may be a small public perception benefit through the slow reduction in the nation's inventory of transuranics, and there would be a small possibility of an easing of the geologic repository licensing effort through vitrified or ceramic containment of the technetium.

Offsetting the above modest returns would be a major institutional issue, arising from the magnitude of the LMR deployment program required, nominally 30 GW within the first quarter of the next century. A government commitment to such a program would require statutory action or financial incentives large enough to overcome the economic disadvantage that would attend the LMRs when the energy sources for new power plants were selected. Similar government initiatives would be required to bring into being the associated spent LWR and LMR fuel processing facilities. The burden of resolving this issue would constitute a significant deterrent to adoption of a process-before-disposal policy.

The introduction of spent LWR fuel processing and spent LMR fuel processing into the nation's overall nuclear power program earlier than it would occur as a result of

market forces would necessitate undertaking some difficult tasks without the driving force of the nation's economic vitality in support. Foremost amongst these tasks would be that of obtaining licenses for those major activities, spent LWR and spent LMR fuel processing. The additional licensing effort that would be required to introduce such large new elements into the nuclear power industry, without a strong economic incentive, is visualized as outweighing the above easement that may or may not accrue to the geologic repository licensing effort. The impact of a process-before-disposal policy is more likely to constitute an increase in total program licensing cost rather than a decrease.

Similarly, the task of overcoming political and public opposition to the deployment of spent commercial fuel processing facilities, again without a strong economic incentive, is visualized as outweighing the above public perception benefit accruable through the slow reduction in the nation's inventory of transuranics. A major element in the anticipated political and public opposition to introducing spent fuel processing would be the associated introduction of new sources of strategic materials that may be divertable to weapons applications.

Reference 7-1 notes that, with regard to potential theft of strategic materials, the transport element may be judged to be the most vulnerable, and identified the value of mixing the plutonium and uranium, in the ratio needed for subsequent use, prior to leaving the processing facility. This would be accomplished in the processing scenario addressed in this evaluation; in fact, there would be an economic incentive to put the material into complete fuel assemblies before it leaves the facility. In addition, the plutonium would be accompanied by minor transuranics and contaminating fission products as well as by uranium.

Even at the less accessible locations within the total process, the plutonium would always be accompanied by fission product contamination and by at least one minor transuranic, neptunium in the aqueous process and americium in the pyrochemical process. Remote handling facilities and high radiation doses would also serve to reduce the theft risk. However, zero risk cannot be demonstrated, so the residual potential of theft would constitute a disadvantage that would have to be justified by the benefits from the process-before-disposal policy.

A complicating consideration would be the postulation that if the United States denied itself the supposed benefits of processing, other nations would follow that lead, and as a result there would be fewer foreign sources of strategic materials that could be overtly or covertly misused. However, reference 7-1 observes that misuse of facilities associated with a uranium-plutonium nuclear power cycle would be neither the easiest nor the most efficient route to acquire strategic materials. In addition, the existence of U.S. spent commercial fuel processing facilities would increase the likelihood that other nation's processing needs would be met by U.S. facilities, thereby under U.S. control.

7.4 CONCLUSIONS

An economic incentive greater than 2 mil/kWh to use plutonium recovered from spent LWR fuel, rather than use enriched uranium, for startup of LMRs is projected. Minor spin-off benefits would include avoiding a further contribution to the health risk from uranium mining.

Maximizing the total transuranic separation efficiency, including separating a very high fraction of the minor transuranics, when spent fuel is processed to recover the plutonium as part of an economically justified LMR deployment program is projected to have negligible net cost impact and to accrue modest benefits. Even if continuing development of the processing technologies achieves a tenfold improvement in transuranic separation efficiencies over those currently projected, none of the waste packages would be downgraded from geologic to near-surface disposal.

The breaking down (that would occur in the processing) of the spent fuel into different waste types, would cause few of the waste types to qualify for near-surface, instead of geologic disposal. Geologic repositories would still be needed, because of the waste packages' concentrations of residual transuranics, extremely long-life fission products, extremely long-life activation species, and medium-life fission products.

Removal of the plutonium and additional removal of the minor transuranics would reduce the waste heat output at time of disposal (by about 20% total for spent LWR fuel) and would thereby increase the GW-years of power generation that a repository could support if advantage were taken of the opportunity.

Adoption of a process-before-disposal policy for all the spent fuel would accrue only modest benefits; avoidance of a further small contribution to the health risk from uranium mining, a possible small public perception benefit through the slow reduction in the nation's inventory of transuranics and a small possibility of an easing of the geologic repository's licensing effort through vitrified or ceramic containment of the technetium.

Adoption of a process-before-disposal policy would incur several disadvantages of substance. A large LMR deployment program would be required during the first quarter of the next century, nominally about 30 GW, projected to incur a cost penalty likely rising to between $0.5B and $2B per year ('90S) by the end of that quarter century. Through introducing a major spent-fuel-processing/LMR-deployment program ahead of its market-driven time, a process-before-disposal policy would encounter major institutional difficulties, multiply licensing hurdles and amplify political and public opposition to the overall nuclear power program.

It is therefore concluded that spent LWR fuel should not be processed earlier than necessary to support an economically justified LMR deployment program.

7.5 LMR ROLE

The major disadvantages identified above with respect to processing current spent LWR fuel should not cloud the visualization of the merits of the LMR in its more appropriate role (as a reactor system whose busbar cost is independent of the price of uranium ore), nor thereby of the importance of the LMR's development. The major disadvantages identified above will disappear or substantially diminish when there arises an economic incentive to deploy LMRs. A review of the cost comparisons of subsections 6.1.2 and 6.4.2 in this report in combination indicate a mid-range projection of only a trivial LMR/LWR busbar cost differential when the LMR is not designed to take an unnecessarily high quantity of plutonium and is not required to take plutonium from old, 33 MWd/kg spent LWR fuel. That is, the mature LMR's busbar cost is as likely to be less than the mature LWR's busbar cost as it is more than. Thus, when the nation is embarking on a major advanced LWR deployment program, there will be merit in having available a reactor system that would protect the industry from modest as well as large increases in the price of uranium ore. Development tasks towards defining and developing the most cost-effective LMR and associated fuel cycle therefore remain very important.

7.6 DEFENSE PLUTONIUM

Developments in international relations during the last two years raise the possibility that the defense program may shortly have surplus plutonium, which is expensive to store and could provide an economic return by being used for power generation.

From reference 7-2 and from cost assessment data in this chapter can be derived a conclusion that each gram of plutonium whose cost of production has already been incurred would reduce the LMR busbar cost by about three times as much as it would the LWR busbar cost. LMRs would be the economic preference for use of surplus defense plutonium..

This possibility strengthens two of the conclusions of this evaluation. First, assignment of some of the future nuclear power plant deployment slots to LMRs started up on defense plutonium would make it even more difficult to deploy enough additional LMRs to take up the plutonium from current spent LWR fuel. Second, the possibility of LMR deployment based on defense plutonium reinforces the merit in completing the LMR's development program.

7.7 REFERENCES

7-1 Reprocessing, Plutonium Handling Recycle. Report of Working Group 43, International Nuclear Fuel Cycle Evaluation, 1980. INFCE/PC/2/4.

7-2 P.M.S. Jones. "Assessing the Merits of MOX." Nuclear Engineering International, 1989.

Section 8

FOREIGN PROGRAMS

This chapter constitutes a very brief identification of current foreign development tasks establishing base technology to support potential application of the transuranic burning concept. A detailed review by RI can be found in companion report NP-2765.

No nation appears to be promoting transuranic burning as a concept likely to be adopted in the near-term, but a few nations, particularly Japan and France, maintain cognizance of the concept's potential as an alternative to current HLW disposal policies. A possible guide to the seriousness of a nation's interest in a concept is the magnitude of the specific experimental work. By this criterion, the lead interest in the transuranic burning concept is in Japan.

The Tokai Research Establishment, which is colocated with the Tokai spent fuel processing facility and has the responsibility to develop aqueous technology, has recently reported initial success with Japan's version of an aqueous process step to separate the minor transuranics from the raffinate waste, post uranium and plutonium separation. Further development of the process is projected at the Nuclear Fuel Cycle Safety Engineering Research Facility, currently under construction.

Japan's Central Research Institute for Electric Power Industry (CRIEPI) is developing a pyrochemical alternative for separating the minor transuranics from the aqueous raffinate downstream of the separation of the uranium and plutonium from spent LWR fuel. Part of this work, specifically characterization of the electrochemical behavior of minor transuranics and lanthanides, is contracted to RI in the United States. CRIEPI has also contracted the European Institute for Transuranic Elements, in Germany, to characterize the metallography of metal fuel containing minor transuranics and lanthanides.

In the area of transmutation, Japan's Power Reactor and Nuclear Fuel Corporation is measuring the flux peaking and reactivity swing impacts of including minor transuranics in the fuel.

France's Commissariat a l'Energie Atomique (CEA) has recently made advancements in the development of aqueous technology for separating the minor transuranics from the raffinate downstream of the uranium and plutonium

separation, and is conducting bench-scale tests on alternative methods of achieving minor transuranics/lanthanides partitioning. CEA has also recently compiled minor transuranics characterization data obtained from fuel irradiation and core neutronics tests over the last few years.

In Germany, the nuclear research establishment, Kerforschunszentrum Karlsruhe has recently funded experiments in the blanket of the large French LMR, Superphenix, to measure the transmutation rate of minor transuranics. The Institut für Heise Chemie (hot chemistry) is awaiting funding for a two-year experimental program, again to investigate aqueous separation of minor transuranics from the raffinate downstream of the uranium and plutonium separation.

Summary descriptions of the transuranic burning application concepts currently being studied in the above nation's, having specifically related experimental programs, can be found in companion report NP-2765, plus summary descriptions of recent initiatives towards internationally collaborative evaluations of the concept.

Section 9

APPROPRIATE FOLLOW-ON WORK

The evaluation's conclusions provided in chapter 7 can be characterized as negative with respect to the application of the transuranic burning concept to current spent LWR fuel, neutral towards the separation of the minor transuranics when spent fuel is processed as part of an economically justified LMR deployment program, and positive towards both the use of plutonium from spent LWR fuel to start up LMRs and the value of having a least busbar cost LMR available as a reactor system that would protect the industry from large increases in the price of uranium ore.

Follow-on work that would be consistent with the evaluation's conclusions would therefore include a prototype project to demonstrate the most economic LMR design and associated fuel cycle. However, the financial commitment necessary for such a large undertaking is unlikely to be obtained until the nation is sure it is embarking on renewed deployment of a large capacity of nuclear power plants, based on the fully established and well-proven reactor system already available, the light water reactor. Thus, to be pragmatic, the appropriate follow-on work that would be consistent with the evaluation's conclusions would be a spectrum of development tasks that would bring the LMR design and associated fuel cycle to the point of being fully ready to embark on a prototype project as soon as a funding commitment is obtainable.

A logical approach to defining that spectrum of development tasks would be:

- First, to define the most economic LMR design and associated fuel cycle based on only high-confidence extrapolations beyond currently proven technology;

- Second, to define the design detailing and licensing effort necessary to achieve readiness for a prototype project;

- Third, to define the reactor component, fuel and fuel cycle development tasks necessary to demonstrate the validity of such high-confidence extrapolation; and,

- Fourth, to define development tasks that would investigate potential cost reducers and prioritize these tasks based on the magnitude of the development effort required, the magnitude of the economic return and the projected likelihood of success.

The subsequent implementation of the defined development tasks would then be integrated to achieve the full benefits of iteration between them as results emerge.

It is not within the intended scope of this evaluation to perform the development task definition effort suggested in the preceding paragraph. All that can be provided is this evaluation is an identification of a few tasks that would serve as examples.

Based on this evaluation, an obvious candidate for meeting the above criterion of the most economic LMR and associated fuel cycle based on only high-confidence extrapolations beyond currently proven technology would be an LMR designed to require a low inventory of startup fissile plutonium per MW of capacity and based on oxide fuel and aqueous processing for both spent LMR and spent LWR fuels.

Candidates for the category of reactor component, fuel and fuel cycle development tasks necessary to demonstrate the validity of such high-confidence extrapolations would be demonstration of long-term steam generator integrity under a bounding duty cycle, irradiation of prototypic fuel pins, and demonstration of elements that would be required for commercial spent fuel processing, such as a high-efficiency iodine trap and cryogenic collection of noble gases.

Candidates for the category of development tasks that would investigate potential cost reducers would be:

- Selection and demonstration of process steps to decontaminate recovered uranium adequately, and demonstration of a reenrichment flowsheet (completion of this development would permit a waste burden to be converted to a resource),

- Development tasks to establish the capability to incorporate the transuranic burning concept into the overall fuel cycle when LMRs are deployed on their economic merit (e.g., selection and development of a process step for partitioning the minor transuranics and lanthanides), and

- Development and demonstration of LMR metal fuel and its associated pyrochemical process, and development of the core design to use the metal fuel. (This composite development task is already in place and is a relatively large task with a potentially large economic return.)

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