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MRS SYSTEMS STUDY TASK G REPORT

The Role and Functions of Surface Storage of Radioactive Material in the Federal Waste Management System

**T. W. Wood
S. M. Short
M. G. Woodruff**

**M. K. Altenhofen
C. A. MacKay**

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ABSTRACT

This is one of nine studies undertaken by contractors to the U.S. Department of Energy (DOE), Office of Civilian Radioactive Waste Management (OCRWM), to provide a technical basis for re-evaluating the role of a monitored retrievable storage (MRS) facility. The study investigates the functions that could be performed by surface storage of radioactive material within the federal radioactive waste management system, including enabling acceptance of spent fuel from utility owners, scheduling of waste-preparation processes within the system, enhancement of system operating reliability, and conditioning the thermal (decay heat) characteristics of spent fuel emplaced in a repository.

While these are not required functions for the federal waste management system, each represents a potential benefit of storage capacity within the system, and was evaluated in the study to determine the storage capacity required to perform it. This evaluation was conducted for a wide range of MRS and repository-only scenarios, including variations in the deployment timing and storage capacity of MRS and repository, and the extent to which these are linked [as in the Nuclear Waste Policy Amendments Act of 1987 (NWPAA)] or independent.

The analysis focuses particularly on the effects of storage capacity and DOE acceptance schedule on power reactors. Figures of merit developed include the storage capacity [in metric tons of uranium (MTU)] required to be added beyond currently estimated maximum spent fuel storage capacities and its associated cost, and the number of years that spent fuel pools would remain open after last discharge (in pool-years) and the cost of this period of operation.

The principal findings of this report are: 1) the storage capacity provided by an MRS facility could be used to substantially limit the projected burden of utility storage requirements above pool capacities, 2) an MRS that began accepting spent fuel as early as possible with a storage capacity of at least 30,000 MTU would maximize this benefit, 3) the same MRS deployment scenario could also provide substantial benefit in terms of reduced length of

pool operations after last discharge if repository deployment were substantially delayed, 4) an MRS deployed per the NWPAA constraints on schedule and storage capacity, while still beneficial, would provide significantly fewer benefits in terms of avoided costs at reactors, 5) the storage capacity at an MRS facility could enhance system operating reliability by allowing continuation of either the emplacement or spent fuel acceptance functions in the event of long-duration reductions in the acceptance or emplacement rates, 6) the process-scheduling function can be provided satisfactorily in either a repository-only or MRS system, and 7) the heat management function, if it proves valuable, could be accomplished either through 25,000 MTU of storage capacity at an MRS or by selection of spent fuel from reactors in a repository-only system.

EXECUTIVE SUMMARY

This study is one of several undertaken at the direction of the U.S. Department of Energy (DOE), Office of Civilian Radioactive Waste Management (OCRWM), to support a comprehensive re-evaluation of the potential benefit of a monitored retrievable storage (MRS) facility as part of the federal radioactive waste management system. Collectively, these studies are termed the MRS Systems Study; Chapter 1 summarizes their overall scope.

The objectives of this study, which was performed under DOE's Systems Integration Program at Pacific Northwest Laboratory (PNL), include 1) identifying the functions that storage of radioactive material could provide in the operation of the waste management system, 2) quantifying the storage requirements for each, 3) examining the implications of federal storage levels and waste acceptance schedules for operating reactors, and 4) defining any relative advantages provided by an MRS in integration across the federal-utility interface. The systematic identification and analysis of several distinct roles or functions of storage in both MRS and repository-only system configurations allows an assessment of how well each configuration supports these functions, and leads to conclusions about the benefits of an MRS as part of the waste management system. Analysis of a wide range of scenarios allows assessment of the extent to which these benefits depend on deployment timing, linkages to the repository, and to a limited extent, the processes included at an MRS. The functions of storage identified and analyzed include enabling acceptance, process scheduling, enhancement of reliability, and heat management. The analysis of each of these functions is summarized in the following sections.

ENABLING ACCEPTANCE

Among the significant implications of variation in federal waste acceptance schedules for spent nuclear fuel is that the quantity and duration of required at-reactor storage are affected. At present, the 109 operating reactors have an aggregate maximum capacity of approximately 60,000 MTU of spent fuel, as estimated by their owners (DOE 1988). Once the maximum capacity is exceeded for a given pool, a requirement for "additional" at-reactor

storage is created. This requirement may be met by a variety of technically proven and safe storage methods, including dry casks, modular vaults, or at-reactor spent fuel consolidation. While the technical details of these additional storage methods differ, each is a qualitative departure in operating practice from storage of intact spent fuel in a reactor pool. Even the least expensive of these methods is more costly than storage in an existing pool.

Thus, the additional at-reactor storage requirement resulting from a combination of discharge rate and acceptance assumptions is a good measure of at-reactor impact of federal spent fuel acceptance capabilities and policy. Also calculated were estimates of the cost of this additional at-reactor storage capacity, the extent to which site decommissioning would be delayed, and the resultant cost associated with maintenance of operable spent fuel pools.

For a given spent fuel discharge forecast, three factors control the required quantity of additional at-reactor storage: the date at which acceptance begins, the rate at which it proceeds, and the manner in which it is allocated among reactors. Figure S.1 illustrates the growth of additional

FIGURE S.1. Additional At-Reactor Storage Inventory

at-reactor storage requirements for existing and planned power reactors for the four chosen from 91 MRS Systems Study acceptance schedules, and the Draft Mission Plan Amendment Schedule. All of the cases for which requirements are plotted in Figure S.1 assume the Energy Information Administration's "No-New Orders" discharge forecast and the allocation of spent fuel acceptance according to an "oldest-fuel-first" ("OFF") rule. Other assumptions are detailed in Section 3.1. Several conclusions are illustrated by this figure.

First, the rate at which additional at-reactor storage requirements are currently increasing is a modest one--less than 200 MTU per year, or about 10% of a year's discharge of spent fuel. Without the initiation of federal waste acceptance, however, requirements grow roughly exponentially, and are increasing at a rate of over 1300 MTU per year by 2005. Thus, from the perspective of limiting at-reactor storage, the initiation of federal waste acceptance becomes increasingly important in the next 10 to 15 years.

The most ambitious of the waste acceptance schedules analyzed assumes deployment of an operational MRS facility in 1996. This acceptance schedule (Schedule 31) is almost identical with one first set forth in Volume II of the Monitored Retrievable Storage Submission to Congress (DOE 1986b). Both minimize the need for additional at-reactor storage, limiting it to about 3000 MTU, or about 20% of the current inventory. The schedule developed for the MRS Systems Study is reported here. If federal acceptance were initiated on such a schedule, additional at-reactor storage would never grow faster than about 300 MTU per year, and after 2002 there would be no further additional storage requirements generated. While the projected discharges of about 2000 MTU per year would require storage, this could be accommodated within maximum pool capacities as currently estimated if acceptance proceeded on this schedule.

The waste acceptance schedule in the Draft Mission Plan Amendment (DOE 1988) is premised on initiation of acceptance in 2003, consistent with the currently estimated availability of a geologic repository and the NWPAA provision that links MRS operation to repository licensing and construction schedules. This schedule results in a total additional storage requirement of approximately 8300 MTU at 46 sites. A repository-only system deployed in

2003, and accepting spent fuel at the rates indicated for the repository in the Draft Mission Plan Amendment, would result in a requirement for 10,600 MTU among 53 sites.

The largest additional storage requirement is generated from a delayed waste acceptance schedule analyzed during the MRS Systems Study that calls for repository acceptance beginning in 2013. Additional storage requirements in this case are about 25,000 MTU. This represents about one-third of the total projected inventory of spent fuel discharged by 2020, and would be distributed among 66 reactor sites.

The cases analyzed in this study included a wide range of facility deployment dates and scenarios where the NWPAA linkages between an MRS facility and the repository were not observed. This analysis shows that early acceptance of spent fuel at a federal waste management facility is necessary if the system is to most effectively limit additional at-reactor storage. Given the current schedule for repository development, an MRS can be effective to the extent represented in the MRS Proposal (DOE 1987) in minimizing additional at-reactor storage only if these constraints are eliminated or relaxed.

The rate at which spent fuel is accepted (transferred to a federal facility) and the allocation of this acceptance among reactor sites also have implications for additional storage requirements. The rate at which these requirements increase, in the absence of federal acceptance, as shown in Figure S.1, is never greater than about 1500 MTU per year. Since the rate of spent fuel acceptance is greater (at 3000 MTU/yr) than this, the aggregate acceptance rate was not varied in the study of at-reactor impacts.

The allocation of spent fuel acceptance among reactors also influences the total amount of additional storage required. Since annual acceptance is, after the initial ramp-up period, greater than the aggregate rate of discharge, there are clearly allocation schemes that could limit the growth of additional storage. The allocation scheme presented in the Standard Contract (10 CFR 961), however, allocates acceptance rights based on an oldest-fuel-first (OFF) rule. This rule, which is grounded in considerations of equity, provides for spent fuel acceptance rights allocation on the basis of age since discharge. Allocation of annual acceptance under this rule typically

provides only a portion of the total spent fuel acceptance to those reactors with storage limitations. Storage requirements for all of the acceptance schedules reported here would be 20% to 40% lower if priority were granted to reactors in need of storage rather than on an OFF basis.

Satisfying the at-reactor storage requirements shown in Figure S.1 will be done at some cost to utility spent fuel owners. While several technically proven technologies are available for this storage, none are fully mature in a commercial sense, and the unit costs that would be typical of a full-scale additional at-reactor storage industry are thus still uncertain. To reflect this uncertainty, a set of unit costs incorporating various assumptions on the extent of further technological evolution were applied to the storage requirements shown in Figure S.1, resulting in the cost estimates shown in Figure S.2. As shown here, the total cost of additional storage will increase significantly as federal acceptance is delayed. For the early

FIGURE S.2. Variation in Additional At-Reactor Storage Costs

acceptance cases, costs are expected to be between \$100 million and \$400 million. The additional at-reactor storage capacity requirements generated under the Mission Plan Amendment acceptance schedule are expected to cost between \$350 million and just over \$1 billion, depending on the unit costs for storage technologies actually deployed.

If acceptance is delayed until 2013, total costs of additional at-reactor storage capacity could range from just under \$1 billion to over \$2.5 billion.

In addition to the increases in at-reactor storage capacity and associated costs, many of the acceptance schedules analyzed required extension of decommissioning schedules beyond a reference assumption that spent fuel removal would be complete 5 years after last discharge. The Draft Mission Plan Amendment system could provide enough acceptance capacity to allow decommissioning within 5 years of shutdown for almost all reactors, providing a second repository was deployed by 2027 and all acceptance capacity was allocated to decommissioning reactors. If this system were operated under OFF priorities, an average of 12.5 years would elapse between shutdown and last spent fuel removal, and an estimated total cost of \$2 billion would be incurred for maintenance of reactor pools after shutdown. (Approximately \$900 million of this cost is associated with the reference decommissioning schedule assumed.)

Acceptance scenarios involving a delayed repository could result in much higher costs for extended pool operations. A 2013 repository, with OFF priority, generates an estimated \$3.06 billion of such costs--about \$2 billion above the reference decommissioning case. If an MRS with 30,000 MTU of capacity were deployed in 2003 (decoupled from NWPAA constraints), about \$1 billion of this utility cost could be avoided, in addition to the savings associated with additional storage capacity.

PROCESS SCHEDULING

The federal waste management system is a series of processes that prepares spent fuel and other high-level waste for emplacement and isolation in a deep geologic repository. As in any such system, differences in process schedules lead to needs for storage between processes. These differences may

be random fluctuations in the time required to perform processes, or planned variations such as different shift or maintenance schedules, or the need to assemble batches of various sizes.

Since any well-engineered waste management system (with or without an MRS) will provide some storage to perform the process-scheduling function, the central questions for the analysis of process scheduling (or "lag") storage are whether the large component of MRS storage typically associated with early acceptance enhances performance of the process-scheduling function, or whether differences in system configuration among various MRS concepts lead to intrinsically different needs for process-scheduling storage.

The process-scheduling function of storage was evaluated using simulation analyses of waste management system configurations with and without an MRS. The model and data utilized were the same used in reliability analyses. This model calculated the utilization patterns for each of several lag storage locations in the current MRS and repository surface facility designs. Three cases were analyzed for each of the two (with and without MRS) system configurations: 1) normal variation in process times, 2) normal variation in process times and expected equipment failure, and 3) extreme variation in process times plus equipment failure.

For both repository-only systems and those with an MRS, the current design basis lag storage capacities are more than adequate to perform the process-scheduling function in all cases studied. Average utilization levels are low relative to capacity, and in most cases there was a significant margin between the capacity of lag storage locations and the maximum utilization levels observed in six facility-years of simulated operation. Thus, the large component of long-term storage present at an MRS will not confer any intrinsic advantage in performing the process-scheduling function in an MRS-based system.

In summary, the process-scheduling function of storage is expected to be performed well in either an MRS-based or repository-only system, requiring less than 300 MTU and 100 MTU, respectively. Performance of this function is not a significant discriminator between the two classes of system configurations.

If storage were to be employed to make up batches of spent fuel with appropriate characteristics (rather than simply assuring adequate quantities), a larger quantity of storage would be required. Two possible applications of this sort include providing batches of similar assemblies for consolidation or assuring an appropriate mix of PWR or BWR assemblies in the tuff hybrid waste package. Although spent fuel characteristics data expressed on an annual basis indicate that this batch assembly could be provided with 3000 MTU of storage capacity, the actual requirement could be much less. Batch assembly could be provided at either an MRS or a repository.

RELIABILITY ENHANCEMENT

The prospect of increased operational reliability in an MRS system has been a significant incentive for pursuing an MRS path. In this operational context, reliability is defined as the likelihood of achieving either local or global (system wide) throughput goals for the waste management system. Reliability is dealt with in detail in a separate report (Task I). To the extent that storage allows continuity of certain processing even during long interruptions of some other process steps, it can enhance reliability. In on-line repairable systems where reliability is expressed as the probability of achieving a certain production or throughput rate in a unit time, reliability can be satisfactorily high even when multiple "failure" events are expected.

The analyses of equipment failure and repair rates in Task I led to just this conclusion. In spite of fairly frequent failure, the ability to restore equipment functions quickly and to design equipment throughput rates high enough to make up any lost production together result in very high system reliabilities. The incremental effects of these failures on lag storage utilization are within the statistical "noise level" of the system simulation. Thus, storage capacity per se would contribute little to system reliability for equipment failures in the current designs. To fully define the potential for enhancing system reliability through the use of storage, a class of process "failure" events broader than equipment failures was also considered.

Included in this class of events are any unanticipated or consciously controlled events that would alter the throughput in any part of the system from the planned system throughput levels. In the context of system development and licensing, this could include extensions of the licensing process for a repository, or requirements for an extended performance confirmation period using less than full-production quantities of spent fuel. In this broader context, it is clear that there are many possible events that could diminish the throughput of the emplacement or other processes, and that the durations of the impaired throughput could be substantially longer than for the equipment failures analyzed. While there are no "data" on the probabilities of these events in a radioactive waste management system incorporating a deep geologic repository, the first-of-a-kind nature of the program and the institutional setting argue that system development to full-production capacity will be a deliberate, careful process, and that emplacement tonnage goals will be subordinate to demonstrations of operational safety and isolation effectiveness. This sort of long-term throughput reduction event is not confined to the emplacement function. A transportation accident, even without safety consequences, could lead to institutional restrictions which reduced the throughput of the transportation function for some time.

It is in this context that storage could prove valuable in enhancing system reliability. A significant quantity of storage capacity within the federal system will permit continued although partial system function in the face of such long-duration events. Specifically, unused storage capacity would allow continuation of spent fuel acceptance and packaging to continue at full rate if the emplacement rate were below planned goals, and available inventory would allow continuation of emplacement if the acceptance function were impaired. If the storage of spent fuel were in disposal-ready form, the emplacement function would also be protected against impaired throughput in the waste-preparation functions.

HEAT MANAGEMENT

Radioactive decay of spent fuel generates heat at a significant rate. Heat removal through conduction and convection is a primary consideration in the at-reactor storage of newly discharged fuel in water pools. Thermal

output of spent fuel declines roughly exponentially with time, and at five years after discharge averages about 1.5 kW/MTU (for 30,000 MWd/MTU burnup). This output no longer requires storage in water, but the rate of heat output is a key parameter in determining design details for spent fuel handling, storage, and disposal. Considerations that influence design include the benefit of maintaining fuel cladding temperature below a maximum value, the need to maintain surface storage package temperatures at safe levels, and several considerations related to the thermal-mechanical effects on the host rock in a repository.

Together, these effects may provide incentives for "heat management" in the operation of the federal waste management system, and the concept is now under study by the Yucca Mountain Project. Heat management could be accomplished by preferentially selecting spent fuel with appropriate heat output for disposal at some point in time, by blending spent fuel with diverse thermal characteristics in a single package or repository region, and perhaps in other ways. Since these operations could influence storage requirements and utilization, heat management was analyzed as a function of storage in this task.

The particular heat management strategies analyzed included a "levelization" strategy aimed at producing a constant level of long-term (350-year) integrated decay heat deposition among repository panels. This strategy may be of value in maintaining a high fraction of emplacement borehole walls at $>97^{\circ}\text{C}$ for at least 300 years, thus limiting contact of liquid water with waste containers and potentially enhancing the confidence with which substantially complete containment can be met. The analysis of this strategy for an MRS system derives storage capacity required to resequence spent fuel selected under OFF and other allocation schemes among repository panels.

Levelizing the integrated decay heat of spent fuel emplaced can be accomplished by resequencing the spent fuel received at an MRS. Producing a roughly constant pattern of average decay heat emplaced could be accomplished with between 20,000 MTU and 25,000 MTU of storage capacity, assuming that fuel was initially received at an MRS in an OFF sequence. The same quantity

of storage also suffices to achieve similar levelization for receipt sequences based on full-core-reserve (FCR) priority, or decommissioning priority.

A levelization strategy within a repository-only system could be achieved by selection of spent fuel to be shipped from utilities. This could be done without altering the quantities of fuel schedules to be accepted from each reactor site under the Standard Contract, provided that utilities cooperated regarding the selection of spent fuel for dry storage and shipment.

Heat management strategies aimed at controlling intra-year variation in thermal characteristics could be used alone or in conjunction with levelization. These strategies would assure efficient loading (and thus minimum numbers) of waste packages, and could be implemented at either a repository or an MRS. Storage requirements for this type of heat management might be as great as 3000 MTU, but no greater. A more detailed analysis might show the 750 MTU currently planned for surface storage at a repository to be sufficient.

Two qualifications should be kept in mind relative to the heat management results. First, the strategies examined herein are only plausibly useful ones. Their value needs to be further examined using thermal analysis of the repository system. Second, the storage quantities shown to be sufficient to accomplish these strategies were obtained with trial-and-error modeling techniques and may not represent minimum necessary requirements.

With these qualifications in mind, a general conclusion is that an MRS facility could add, by virtue of its storage capacity, an additional degree of flexibility to manage the thermal characteristics of spent fuel emplaced in a fashion not possible in a repository-only system.

SUMMARY OF STORAGE REQUIREMENTS

Each of the storage functions analyzed may be interpreted as generating some required level of storage. A summary of these levels for various performance criteria within each function is presented in Table S.1. These spent fuel storage requirements are not additive across functions.

TABLE S.1. Summary of Spent Fuel Storage Requirements by Function(a)

Function and Performance Criterion	Federal Storage Requirement, MTU			
	MRS-Based System with Repository Start in:		Repository-Only System ^(b)	
<u>Enable Acceptance</u>				
Limit additional at-reactor storage requirements to:	2003	2013	2003 ^(c)	2013 ^(c)
20,000 MTU	0	10,000	0	NA
15,000 MTU	0	20,000	0	NA
10,000 MTU	<5,000	32,000	NA	NA
5,000 MTU	15,000	45,000	NA	NA
<u>Process Scheduling and Batch Makeup</u>				
- buffer normal operational fluctuation		<300		<100
- buffer normal operational fluctuation and expected equipment failures		<300		<100
- allow minimum cost batch sizes for consolidation		<100		<100
- permit preferred mix of assembly types (PWR/BWR)		<3,000		<3,000
<u>Reliability Enhancement</u>				
- permit continued acceptance for:				
1-year emplacement outage		3,000		3,000
2-year emplacement outage		6,000		NA
<u>Heat Management</u>				
Levelizing to produce uniform energy deposition as received at repository over time				
OFF		<25,000		NA
FCR Priority		<25,000		NA
DECOM-only Priority		<25,000		NA
Blending SNF within waste packages to prevent derating of packages with a heat limit of 1.5 kW/MTU				
OFF		<3,000		<3,000
FCR Priority		<3,000		<3,000
DECOM-only Priority		<3,000		<3,000

- (a) Results assume an OFF acceptance sequence, an on-time repository (2003 startup) and the acceptance rate of 3,000 MTU/year given in the Task A schedules unless otherwise specified.
- (b) Repository surface storage currently limited to 3 months inventory. In this table any function requiring more than 1 year's inventory (3000 MTU) at the repository is indicated as not achievable (NA).
- (c) Repository start dates.

FEDERAL-UTILITY INTEGRATION

In addition to the storage functions that can be summarized quantifiably in terms of storage requirements, this study addressed the extent to which an MRS facility might facilitate integration across the federal-utility interface. An MRS could contribute to this integration by facilitating early acceptance of fuel from utilities, providing utility managers with increased certainty in the DOE waste acceptance schedule, and possibly helping to avoid purchasing more at-reactor storage capacity than will eventually be required. Some potential exists for economic use of utility storage casks regardless of

the configuration of the DOE system. This potential is much greater in MRS-based systems, where up to 341 utility-supplied casks could be used for purposes of transportation, lag storage, and MRS storage within the federal system. In contrast, the repository-only system could utilize only 75 utility-supplied casks. Most (240 casks) of this difference is due to the fact that an MRS system shares the pre-emplacement storage function with reactor sites. The remainder of the difference is due to differences in use for lag storage between the MRS-based and repository-only systems.

The configuration of the DOE system. The potential for much greater data-based systems, where up to 100 million data points could be used for purposes of investigation, for storage, and for storage within the system. In contrast, the repository system could only be used for utility-related cases. Most likely, this difference is due to the fact that the DOE system does not have a storage function with respect to the repository. The repository is due to differences in storage between the DOE and repository-only systems.

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1.0 INTRODUCTION

This study, conducted by the Pacific Northwest Laboratory (PNL), is one of several undertaken during 1988, at the direction of DOE's Office of Civilian Radiation Waste Management (OCRWM), to support a comprehensive re-evaluation of the role and benefits of a monitored retrievable storage (MRS) facility within the federal radioactive waste management system. Table 1.1 summarizes the study topics included in this re-evaluation. Collectively these studies are referred to as the "MRS Systems Study." This series of studies will be used to refine the OCRWM policy on MRS deployment and on design and facility operation concepts most advantageous in light of the overall OCRWM mission. The results of these studies may also be provided by OCRWM to the MRS Commission appointed under the Nuclear Waste Policy Amendments Act (NWPAA) of 1987, which must report to Congress by November 1, 1989, on the need for an MRS facility.

In light of this perspective, this and the other elements of the MRS Systems Study examine a broad range of MRS concepts and operational modes. MRS concepts similar to that previously proposed by DOE as well as concepts that differ both quantitatively and qualitatively are included.

This study focuses on the roles that storage plays in the federal waste management system, and on integration concerns across the utility-federal

TABLE 1.1. Tasks Comprising the MRS Systems Study

- A. Scenario Development and System Logistics
- B. Facility Design (Repository/MRS)
- C. MRS Storage Concept
- D. High-level Wastes
- E. Waste Package Design
- F. Transportation Analysis
- G. System Storage, At-Reactor Impact, and Integration
- H. Licensing
- I. System Reliability Analysis
- J. Summary Analyses and Final Reporting

interface. The systematic identification and analysis of several distinct roles or functions of storage in both MRS and repository-only system configurations supports an assessment of how well each configuration meets these functional needs. Storage functions identified and analyzed include enabling acceptance, process scheduling, enhancement of reliability, and heat management.

Since all of the alternative MRS configurations studied included storage of spent fuel, and since the spent fuel acceptance-related benefits of storage are independent of the location of packaging processes within the federal system, the results of this study bear more directly on the value of an MRS per se, and the influences of timing and storage capacity, than on the best allocation of packaging processes between an MRS and repository.

As used in the context of this report, "storage" refers to surface storage. Emplacement in geologic repository is referred to as disposal. The surface storage function is an important focus for analysis of waste management system configurations for several reasons: 1) surface storage is one functional requirement of the waste management system needed in the near term; 2) storage of spent fuel and other highly radioactive material requires shielding, material control, and cooling, and is thus a major driver of facility design features; and 3) much of the benefit attributed to MRS-based systems in providing system flexibility and reliability are directly attributable to differential storage capabilities vis-a-vis a repository-only system.

In addition to this functional analysis of storage, an analysis of the extent to which an MRS influences issues of technical integration across the federal-utility interface is included in this report. This analysis addresses issues of waste stream diversity, utility storage planning, and joint use of spent fuel casks by utilities and DOE.

The general approach adopted for this study is illustrated in Figure 1.1, showing key points of input from other elements of the MRS Systems Study.

FIGURE 1.1. Task G--Approach and Coordination with Other Tasks

2.0 FUNCTIONS OF STORAGE IN THE WASTE MANAGEMENT SYSTEM

This chapter introduces and briefly describes several functions performed by storage within the federal waste management system. These functions are potentially useful or beneficial consequences of storage capacity within the federal waste management system. They are not in all cases required for adequate system operation, but would in most cases offer advantages in operational convenience or economy. Each of these functions is analyzed in subsequent sections.

2.1 ENABLING ACCEPTANCE

Acceptance of spent fuel by the federal government is, from the perspective of utilities, the single most important function of the waste management system. As used here, acceptance is synonymous with removal from the utility site, and marks transfer of legal and operational responsibility to the government.

An obvious function of surface storage in the federal waste management system is that of enabling such acceptance of spent fuel prior to the time that disposal is possible. A specific quantity of storage required for this function is not specified by OCRWM program control documents. While the standard contract (10 CFR 961) calls for the initiation of spent fuel acceptance in 1998, no specific minimum quantity is mentioned. What is clear is that federal storage, if implemented on a timely basis, is a direct substitute for additional storage capacity at reactors, and for extended duration of at-reactor storage. Thus, avoided at-reactor storage capacity, shortening of the required duration of storage, and the resultant avoided costs are all quantitative measures of performance for the acceptance-enabling function.

2.2 PROCESS SCHEDULING

The federal waste management system is a series of processes that prepares spent fuel and other high-level waste for emplacement in a deep geologic repository. As in any serial materials processing system, differences in process schedules lead to needs for storage between processes. These

differences may be random fluctuations in the time required to perform processes, or planned variations such as different shift or maintenance schedules. The need to assemble batches of various sizes also influences process-scheduling storage requirements. This process-scheduling function makes it possible to increase system throughput for any given set of unit processing rates, or conversely to operate more economically at a given system throughput rate.

Since any well-engineered waste management system (with or without an MRS) will provide some storage to perform the process-scheduling function, the central question for this portion of the functional analysis is whether the large component of MRS storage typically associated with early acceptance enhances performance of the process-scheduling function, or whether differences in system configuration among various MRS concepts lead to intrinsically different needs for process-scheduling storage.

2.3 RELIABILITY ENHANCEMENT

The prospect of increased operational reliability in an MRS system has been a significant incentive for pursuing an MRS path. In this operational context, reliability is defined as the likelihood of achieving either local or global (system-wide) throughput goals for the waste management system. This aspect of system performance is dealt with in detail in a separate report (Task I). To the extent that storage allows continuity of certain processing even during long interruptions of some other process steps, it can enhance reliability. This function of storage is discussed in Section 3.3, based on analysis results obtained in Task I.

2.4 HEAT MANAGEMENT

Radioactive decay of spent fuel generates heat at a significant rate. Heat removal is a primary consideration in the at-reactor storage of newly discharged fuel in water pools. Thermal output of spent fuel declines roughly exponentially with time, and at five years after discharge averages about 1.5 kW/MTU. This power level no longer requires storage in water, but the rate of heat output is a key parameter in determining design details for

spent fuel handling, storage, and disposal. Considerations that influence design include the need to maintain fuel cladding temperature below a maximum value, the need to maintain surface storage package temperatures at safe levels, and several considerations related to the thermal-mechanical effects of emplacing spent fuel in a repository. In addition, it is possible that selection of spent fuel for emplacement to achieve long-term heat release that is relatively constant among repository panels can result in a higher fraction of emplacement boreholes with wall temperatures above 97°C for at least 300 years. This is thought to provide a benefit in terms of preventing corrosion.

Together, these effects may provide an incentive for "heat management" in operation of the federal waste management system. Heat management may be accomplished by preferentially selecting spent fuel with appropriate heat output for disposal, by blending spent fuel with diverse thermal characteristics in a single package or repository region, and perhaps in other ways. These operations influence storage requirements and utilization. Although the value of heat management is only now being studied in detail, the opportunity to accomplish it is provided by a wide range of spent fuel thermal output. The ability to which this diversity can be utilized as a function of storage capacity and storage medium available is the focus of Section 3.4.

2.5 SCENARIOS ANALYZED FOR STORAGE FUNCTION

As noted above, the range of MRS concepts examined in the MRS Systems Study is a broad one. One of the most fundamental differences among concepts is the allocation of waste management system functions between the MRS and repository. The various possibilities considered for functional allocation are summarized in Table 2.1. These functional allocations and the physical system configurations they imply were combined with variations in MRS and repository start dates, MRS locations, and strategies for handling spent fuel from western reactors, and various defense waste management options to define a large number of possible scenarios for analysis. A complete description of these scenario possibilities is given in the Task A report.

TABLE 2.1. Basic Waste Management System Configurations

<u>MRS Functions</u>	<u>Repository Functions</u>
None (No-MRS)	Consolidate and containerize
None (No-MRS)	Containerize intact
Storage only	Consolidate and containerize
Storage only	Containerize intact
Consolidate and canister	Containerize
Containerize intact	Check containers and return
Containerize intact	Check and repair containers
Consolidate and containerize	Check containers and return
Consolidate and containerize	Check and repair containers

Since not all of these variables are important in assessing storage functions, cases were selected from this suite for analysis of each function. The considerations bearing on these selections are briefly discussed in each functional analysis subsection. In general, the functional analysis results depend principally on storage capacity and are thus largely insensitive to the allocation or inclusion of consolidation and packaging functions.

3.0 FUNCTIONAL ANALYSES

This chapter documents the analysis of each of the functions of storage-enabling acceptance, process scheduling, reliability enhancement, and heat management. In each case, an estimate of storage utilization (or storage "requirement") is derived for MRS-based and repository-only systems.

3.1 ACCEPTANCE-RELATED STORAGE REQUIREMENTS

The storage of spent fuel from nuclear reactors prior to disposal can be performed by either the generators of the spent fuel or the federal government. Figure 3.1 illustrates the general relationship between at-reactor storage and federal storage for a 1996 MRS and 2003 repository system. As the graph illustrates, any spent fuel not already emplaced in the repository is either in at-reactor storage or federal storage. As noted in Chapter 1, the cases analyzed in this study included a broad range of acceptance scenarios. In particular, several scenarios are analyzed in which an MRS would accumulate more spent fuel than that provided for under the Nuclear Waste

FIGURE 3.1. Components of Surface Storage

Policy Amendments Act (NWPAA) of 1987. The constraints on an MRS included in the NWPAA are summarized in Appendix C. These "unconstrained" cases allowed for storage capacity requirements to be determined for given emplacement and acceptance schedules. The emplacement and acceptance schedules used to illustrate the components of surface storage in Figure 3.1 are from such an unconstrained case, and imply a federal storage requirement of about 20,000 MTU.

Acceptance-related storage requirements are defined as that storage generated due to the timing and rate of acceptance of spent fuel into the federal waste management system. This storage can take three forms:

- Additional at-reactor storage: that storage needed by waste generators that is above current utility estimates of maximum pool capacities. The required additional at-reactor storage varies with both the date of waste acceptance initiation and the rate of acceptance by the federal waste management system.
- Interim waste storage: that storage generated in the federal waste management system due to either a lag time between beginning of acceptance and beginning of emplacement or differences in the rate of acceptance and the rate of emplacement.
- Federal interim storage (FIS): that storage provided by the federal government for the purpose of relieving waste generators with severe on-site storage problems. Legislative conditions established under the Nuclear Waste Policy Act of 1982 (NWPA) include [from Sections 131(a) and 136(a)]: a) the federal government is authorized to provide interim storage of spent fuel (not to exceed 1900 MTU) for civilian nuclear power reactors that cannot reasonably provide adequate storage capacity on-site and b) any contracts between generators of spent nuclear fuel and the federal government to provide federal interim storage must be in place by January 1, 1990.

Long-term surface storage of spent fuel at a repository was not specifically considered an alternative because of the limitations set forth in the NWPA [Sections 135 (a) and 141 (g)], which specify that neither an MRS nor a FIS may be located in any state in which there is located any site approved for site characterization of a repository. With the exception of the analysis of process-scheduling storage, however, the functional analysis of storage in this report is independent of location. Thus the benefits estimated for early acceptance, heat management, and reliability in various MRS scenarios

would also accrue to a system incorporating storage (in the same quantity and on the same schedule) as part of a repository. Given the proximity of the FIS contractual deadline and the state of development of at-storage technology, FIS deployment seems unlikely, and FIS scenarios were not analyzed. Thus, for the purposes of this analysis of acceptance-related storage, only additional at-reactor storage and storage at an MRS are analyzed.

3.1.1 Additional At-Reactor Storage Requirements

This section analyzes the additional quantity of at-reactor storage required by waste generators and the costs of providing this storage, as a function of the various facility start dates defined in the MRS Systems Study Task A report.

The acceptance ramp-up rates in the Task A report were modified during the course of this study to be consistent with those in the Draft Mission Plan Amendment. Cases employing a three-phase MRS also included an additional 750 MTU of acceptance (in transportable storage casks) in the first year of MRS operation.

3.1.1.1 Overview of Case Structure

Of the 91 schedules presented in the MRS Systems Study, Task A report, 16 were selected for analysis of at-reactor storage requirements. Table 3.1 identifies the 16 schedules selected.

Schedules 48 through 91 were eliminated from the analysis since the spent fuel schedules were the same as in previous schedules. The only difference between these and previous schedules was the destination of HLW, which has no impact on at-reactor storage requirements.

Several schedules in the Task A report that replicated the basic acceptance schedules in the Table 3.1 cases and that differed only in the matter of western spent fuel logistics, emplacement sequence, or MRS phasing were not separately analyzed since these factors do not substantially influence at-reactor storage requirements.

TABLE 3.1. Acceptance Schedules Analyzed for At-Reactor Storage Requirements

Schedule Number ^(a)	Facility Start Dates	
	MRS	Repository
1	NA ^(b)	2003
8	NA ^(b)	2008
17 ^(c)	NA ^(b)	2013
26 ^(d)	2003	2003
27	2000	2003
28	1999	2003
30	1997	2003
31 ^(e)	1996	2003
32	2008	2008
33	2005	2008
34	2004	2008
37	2002	2008
39	2001	2008
40	2013	2013
41	2010	2013
42	2009	2013

(a) Schedule numbers are from the MRS Systems Study Task A report.

(b) Not applicable.

(c) This acceptance schedule is the upper bound case on at-reactor storage requirements.

(d) Draft Mission Plan Amendment Schedule.

(e) This acceptance schedule is the lower bound case on at-reactor storage requirements.

Each of the remaining acceptance schedules was analyzed to determine at-reactor storage requirements. Of these schedules, two bound all of the others. Schedule 31, with a 1996 MRS startup, generates the smallest additional storage requirement. The upper bound on at-reactor storage requirements is found for Schedule 17, with a 2013 repository startup and no MRS.

Besides the acceptance schedules already mentioned above, two additional benchmark schedules (not included in the MRS Systems Study Task A report) were analyzed for purposes of comparison only. These are:

- The MRS Proposal (DOE 1987) schedule with a 1998 MRS startup and a 2003 repository startup.
- The reference low estimate case in the Dry Cask Storage Study (DOE 1988), with a 2003 repository startup.

Including these two schedules, a total of 18 schedules were analyzed for at-reactor storage requirements.

3.1.1.2 Estimating Additional At-Reactor Storage Requirements

The primary analysis tool used to generate additional at-reactor storage requirements was the WASTES-II computer model (Ouderkirk 1988). This model uses discrete event simulation techniques to model the generation of commercial spent nuclear fuel, the buildup of spent fuel inventories within the system, and the transportation of radioactive waste throughout the system.

The generation of at-reactor storage requirements is dependent upon several variables in addition to the acceptance schedules. These factors and the assumptions made in the analysis of acceptance related storage requirements are as follows:

- Discharge Quantities - Historical spent fuel discharges through 1986 were used after which the Energy Information Administration (EIA) No-New-Orders, Increased Burnup discharge projection (NNO-87) was used.
- Acceptance Priority - The process of spent fuel acceptance, from a system modeling perspective, consists of an allocation of system acceptance capacity among reactor sites, and a selection of the particular spent fuel to meet the allocations at each reactor. While the selection step is important in controlling spent fuel thermal characteristics, and was modeled explicitly in the analysis of heat management, the generation of additional at-reactor storage requirements depends only on the allocation rules which govern acceptance quantities per site per year. Three of these were used:
 - Oldest-Fuel-First (OFF) - Fuel is queued for acceptance according to time since discharge. Each year of operation, aggregate acceptance capacity determines how much of the queue is processed, and thus tons shipped per site. The allocation of tonnage shipped may be met by other than the oldest fuel.

- Full-Core-Reserve (FCR) - Any site that would violate FCR in any of its pools due to discharges during the year is allocated a sufficient quantity of spent fuel acceptance to preserve FCR.
- Decommissioning (DECOM) - Fuel from reactors that have shut down is granted priority in allocation. Allocations among multiple shutdown sites are made according to order of shutdown.

These allocation rules are referred to by their acronyms throughout the report. The FCR and DECOM rules typically are used with a default to OFF--e.g., any residual annual acceptance capacity not allocated under these rules is allocated according to OFF. In all cases, allocations of acceptance capacity were constrained to fuel greater than or equal to five years out-of-core.

- Selection for Additional Storage - Spent fuel is selected for additional storage on an OFF basis.
- Transportation Cask Capacities - Transportation cask capacities were assumed to be 3 PWR and 7 BWR assemblies for truck casks and 21 PWR and 48 BWR assemblies for rail casks. This assumption affects at-reactor storage since shipment allocations are rounded to integral numbers of casks.
- Transshipment Between Pools - No transshipment between reactor pools was assumed. Previous studies (DOE 1988) showed that while transshipment could reduce additional storage requirements in the short run by more efficiently matching available capacity with need, long run reductions were less significant as all reactors incurred additional storage need. [Year 2000 additional storage requirements were decreased by 4884 MTU (~40%) by intra-utility transshipment, while year 2007 (the last year calculated in this reference) were reduced by 4985 MTU (about 15%).]

After simulation of spent fuel logistics by the WASTES-II model, computer codes developed for the Dry Cask Storage Study (DOE 1988) were used to summarize additional at-reactor storage requirements on both a site-by-site and a reactor-by-reactor basis.

The results of these analyses are summarized in Table 3.2 for each of the 16 acceptance schedules listed in Table 3.1 and the two benchmark schedules. Besides showing the maximum additional at-reactor storage requirement for each acceptance schedule, the peak inventory of additional at-reactor storage, the average duration of additional storage, and the maximum number of sites requiring additional storage are also shown. Maximum requirements

TABLE 3.2. Summary of Additional At-Reactor Storage Requirements

<u>Acceptance Schedule</u>	<u>Maximum Requirement (MTU)</u>	<u>Maximum Inventory (MTU)</u>	<u>Average Duration (years)^(a)</u>	<u>Maximum Number of Sites</u>
1	10,620	7,940	12	53
8	17,950	13,890	14	63
17	24,840	20,110	15	66
26 ^(b)	8,310	5,890	12	46
27	5,240	3,630	11	38
28	5,000	3,360	12	36
30	3,220	2,030	10	25
31	3,010	1,830	10	24
32	15,040	11,030	13	60
33	10,800	7,710	13	55
34	10,290	7,260	13	54
37	7,180	5,060	12	44
39	6,700	4,710	12	43
40	23,050	17,760	15	64
41	18,130	13,640	14	63
42	17,530	13,050	14	63
Reference Low Estimate-Dry Cask Storage Study	12,220	9,660	12	54
MRS Proposal	4,330	2,780	12	32

(a) After placement in additional storage.

(b) Draft Mission Plan Schedule.

are the total additional storage that was ever required by all waste generators, while maximum inventory is the largest quantity of spent fuel that was ever in inventory at the same time.

Table 3.2 shows that the acceptance schedule yielding the minimum storage requirement is Schedule 31 (with a 1996 MRS startup) while the acceptance

schedule yielding the maximum storage requirement is Schedule 17 (with a 2013 repository startup and no MRS). These two acceptance schedules not only bound the schedules given in the MRS Systems Study Task A report, but also bound the two benchmark schedules. The results in Table 3.2 show that reduction of additional at-reactor storage requirements is achieved by early acceptance of spent fuel. There is, however, an exception to this principle. If early acceptance is achieved by restriction of the form of spent fuel accepted, as in a phased MRS configuration in which only transportable storage casks can be accepted (and stored without unloading), the effect of early acceptance on additional requirements is less than if intact spent fuel has been accepted, since utilities would be required to purchase storage capacity in the form of transportable casks. Benefits of early acceptance due to phasing would accrue in only one version of this phased MRS scenario: that in which DOE purchases the casks.

The sensitivity of estimated additional storage requirements to the priority for allocation of federal acceptance among reactors is given in Table 3.3, which compares the maximum MTU of storage required and the number of sites ever having an additional storage requirement under OFF and FCR priorities.

TABLE 3.3. Sensitivity of Additional At-Reactor Storage Requirements to Acceptance Allocation Priority

<u>Acceptance Schedule</u>	<u>Maximum Storage Requirement (MTU)</u>		<u>Number of Sites</u>	
	<u>OFF</u>	<u>FCR</u>	<u>OFF</u>	<u>FCR</u>
1996 MRS, 2003 repository	3,010	1,790	24	15
2000 MRS, 2003 repository	5,320	3,330	38	29
Draft Mission Plan Amendment (2003 MRS, 2003 repository)	8,310	5,210	46	38
2003 Repository-Only	10,620	7,000	53	38
2013 Repository-Only	24,860	19,500	66	59

Figure 3.2 shows the accumulation of the additional at-reactor storage requirements over time for each of the acceptance schedules. The build-up and draw-down of the additional storage inventory is displayed in Figure 3.3.

FIGURE 3.2. Additional At-Reactor Storage Requirements

FIGURE 3.3. Additional At-Reactor Storage Inventory

As shown in Figure 3.3, the duration of additional at-reactor storage on a system-wide basis is expected to be substantial. This is also true on a site-by-site basis, and even in the minimum requirement cases, fuel is projected to require storage at some reactor sites for about 30 years.

Another observation in Figure 3.3 is that the draw-down of inventory shown is a lower bound, given the assumption that the oldest fuel at each waste generator is placed into additional storage. In this case, fuel acceptance into the federal waste management system preferentially unloads the inventory in additional storage at the site before the in-pool storage. Figure 3.4 shows the sensitivity of inventory draw-down to this assumption for schedule 17. In this figure, the oldest-fuel-first into additional storage assumption is compared against an assumption of the youngest-fuel-first greater than 10 years of age into additional storage. Since spent fuel is shipped from reactors on an OFF basis, the inventory for the case of OFF into additional storage is drawn down faster than for the youngest-fuel-first greater than 10 years of age into additional storage case.

Figures 3.5 and 3.6 are similar to Figures 3.2 and 3.3, respectively, except that the number of waste generator sites, rather than metric tons of

FIGURE 3.4. Sensitivity of Additional At-Reactor Storage Inventory to Storage Selection Rule - 2013 Repository-Only

FIGURE 3.5. Cumulative Number of Sites Requiring Additional At-Reactors Storage

FIGURE 3.6. Number of Sites with Inventory

uranium, is the independent variable. As with tonnage, the number of sites requiring storage begins to increase rapidly about 1995.

Summary tables detailing additional at-reactor storage requirements on a site-by-site basis for each of the five acceptance schedules are given in Appendix A.

3.1.1.3 Additional At-Reactor Storage Costs

The cost estimates for additional at-reactor storage were calculated using bounding unit cost curves (per MTU) developed for and documented in the Dry Cask Storage Study (DOE 1988). A total of four unit cost curves, as illustrated in Figure 3.7, were developed representing varying assumptions on technology development and conservativeness in the unit-cost values.

The "upper bound" cost curve in Figure 3.7 represents the unit-cost range for a storage technology that has been fully proved and demonstrated in the United States. This technology is the current design of the metal

FIGURE 3.7. Alternative Life-Cycle Cost for Additional At-Reactor Spent Fuel Storage

storage cask: a cask designed without taking credit for fuel burnup in criticality control. Assuming that several hundred casks will be required, the cask-purchase price should be about \$90 per kilogram of heavy metal. This price is about 15% lower than the price paid for the casks used in cooperative agreement demonstrations between the utilities and the DOE. To this cask purchase price would be added the costs of licensing, construction of storage pad, and security to arrive at the life-cycle costs shown in Figure 3.7.

The "lower bound 1" cost curve makes the same technical assumptions as the "upper bound" cost curve, but assumes slightly less conservative input cost assumptions.

The "lower bound 2" cost curve represents technology developments that are believed to be likely. These likely developments include, for metal storage casks, the increased capacities and less-expensive fuel baskets that would result from the NRC's allowing credit for fuel burnup; they also include the successful demonstration of other technologies, such as concrete modular storage components, but not necessarily at their lowest current cost estimates.

The "lower bound 3" cost curve represents the lowest cost estimate for any of the technologies now under development as estimated in the Dry Cask Storage Study (DOE 1988). This estimate has two components: for storage capacity increases of 70 MTU to 350 MTU of heavy metal (MTHM), it represents the lowest cost estimated for storing consolidated spent fuel in pools, whereas for capacity increases of less than 70 MTHM or more than 350 MTHM, it represents the lowest cost estimated for horizontal concrete modules.

The cost curves illustrated in Figure 3.7 were utilized in a model to estimate the cost of additional at-reactor storage for each of the 18 acceptance schedules. The results of the cost analysis of additional at-reactor storage is summarized in Table 3.4 for each of the acceptance schedules analyzed. Aggregate costs are provided for each of the four assumptions on unit costs for additional at-reactor storage. As with storage requirements, acceptance schedules for Schedules 31 and 17 bound (for each unit

TABLE 3.4. Summary of Costs for Additional At-Reactor Storage

<u>Acceptance Schedule</u>	<u>Aggregate Cost (\$ millions)</u>			
	<u>Upper Estimate</u>	<u>Lower Estimate 1</u>	<u>Lower Estimate 2</u>	<u>Lower Estimate 3</u>
1	1,112	827	615	424
8	1,846	1,382	1,023	698
17(a)	2,512	1,891	1,394	957
26(b)	880	652	486	325
27	565	417	312	208
28	539	397	297	198
30	351	258	194	130
31(c)	328	241	181	122
32	1,554	1,164	863	591
33	1,133	842	626	427
34	1,082	803	598	406
37	768	568	424	285
39	721	532	398	265
40	2,337	1,758	1,297	887
41	1,864	1,393	1,031	700
42	1,805	1,352	1,001	675
Reference Low Estimate- Dry Cask Storage Study	1,267	945	701	468
MRS Proposal	467	344	257	170

(a) Upper bound case for storage requirements.

(b) This acceptance schedule is identical to the Draft Mission Plan Amendment schedule.

(c) Lower bound case for storage requirements.

cost assumption) the cost estimates for all of the other schedules.

Figure 3.8 graphically illustrates the comparison of the potential range of additional at-storage costs for the two bounding schedules and the three benchmark schedules.

More detailed cost tables, showing the range of additional at-reactor storage costs for various capacity expansion ranges, are given in Appendix A.

FIGURE 3.8. Variation in Additional At-Reactor Storage Costs

3.1.1.4 Use of Storage Cost Estimates in System Cost Calculations

The additional at-reactor storage costs developed in this report represent but one of several components of waste management system costs that are sensitive to the inclusion of an MRS. This section briefly addresses considerations relative to using storage cost estimates in the system cost calculations.

The four unit cost estimates used in this study reflect legitimate uncertainty over the commercial evolution of technology. For purposes of aggregation with or comparison to other system costs, it is suggested that the lower bound cost estimates be used. The assumptions underlying this series of estimates are in the authors' judgment most closely aligned to those in the total system life-cycle cost (TSLCC) estimates.

For use in generating estimates of expense streams over time, it is suggested that the unit costs be applied to the storage requirements forecast, advanced by 1 year in time. While this approach does not account for front-end loading or licensing and other one-time costs, the overall

(system-wide) expenditure pattern over time is largely controlled by the variation in storage addition timing among sites rather than by the timing of expenses within sites.

3.1.1.5 Costs Associated with Reactor Decommissioning

In addition to influencing the storage capacity required at reactors, the schedule for federal acceptance of spent fuel can also affect the schedule for decommissioning reactors, and the costs associated with the decommissioning sequence. Under some acceptance scenarios, it is possible that reactor sites would be required to remain open longer than planned after the last fuel discharge, storing fuel that was awaiting federal acceptance.

While detailed decommissioning plans have not been finalized for most operating reactors, several studies of alternative typical decommissioning sequences have been made. Two NRC studies on the cost of decommissioning nuclear power stations (NUREG/CR-0130 and NUREG/CR-0672) assumed that spent fuel would be removed within 1.5 years of last discharge, while some alternative decommissioning sequences call for much longer periods of spent fuel storage. Since the Standard Contract (10 CFR 961) between DOE and spent fuel owners provides for fuel less than 5 years out-of-core to be classified as nonstandard, and thus subject to delayed acceptance, a reference decommissioning schedule that provided for the earliest decommissioning possible given this constraint was assumed. This reference schedule calls for initiation of spent fuel acceptance in the year a reactor shuts down, and removal of the last shipments of spent fuel at 5 years after the last discharge.

Unlike the need for additional storage capacity, any effect of federal acceptance on decommissioning schedules is more sensitive to long run cumulative spent fuel acceptance than to the date for initiation of acceptance. As shown in Figure 3.9, substantial numbers of sites are now scheduled for last discharge only after 2010. (The data in this figure assumes 40 years of operating life for most reactors in the EIA 1988 no-new-orders database.)

If the data from Figure 3.9 are combined with spent fuel inventory data and the assumption that all spent fuel is removed within 5 years of last discharge, it is possible to calculate the cumulative federal spent fuel acceptance necessary to avoid delay in decommissioning, as illustrated in

FIGURE 3.9. Distribution of Last Discharge Dates for Reactor Spent Fuel Pools

Figure 3.10. Also shown for comparative purposes is the planned cumulative acceptance curve for an MRS and first repository deployed in 2003 and a similar curve for the extreme delay (2013) repository-only case. As indicated, an MRS and first repository deployed in 2003 with capacity for 63,000 MTU of spent fuel would have capacity just sufficient to facilitate decommissioning on the schedule assumed, provided that all of the capacity were allocated to "decommissioning" reactors--e.g., those that would otherwise incur delay. It also follows that an earlier deployment of federal receiving capacity devoted to servicing decommissioning reactors would achieve little in the way of shortening operations after last discharge, since cumulative acceptance requirements for decommissioning reactors are minimal until about 2010. While not shown in Figure 3.10, any effects due to second repository scheduling could be controlled by adjusting its start date and acceptance rate. Such an adjustment was made to the acceptance scenarios reported in this section, changing the second repository start date from 2032 to 2027. This change reduced estimated costs of pool operations after last discharge between 20% and 25%.

FIGURE 3.10. Cumulative Acceptance Comparison

For reasons discussed below, the operation of the Draft Mission Plan Amendment system using OFF priorities would not allow for decommissioning on the schedule assumed. While there is an obvious correlation between the age of spent fuel on a reactor site and its need for acceptance to allow timely decommissioning, application of the OFF rule in allocation of acceptance rights among reactors will not result in minimizing impacts on decommissioning schedules. This occurs because reactors that are in the relatively early stages of operation (e.g., 10 years after initial criticality) will have fuel as old as those older reactors whose inventories are being drawn down in preparation for decommissioning. Allocation of capacity to these younger sites under an OFF rule can result in some delay in decommissioning beyond the reference 5 years after last discharge at some sites.

Also illustrated in Figure 3.10 is the effect of delay in federal acceptance in providing for timely decommissioning. A first repository deployed in 2013 would be unable to support the decommissioning schedule assumed, regardless of how its acceptance capacity was allocated.

Figure 3.11 illustrates the sensitivity of reactor decommissioning schedules to federal spent fuel acceptance by plotting the inventory of spent fuel greater than 5 years out-of-reactor for two repository-only and two MRS system cases, all assuming OFF. As shown here, the addition of an MRS that began operations concurrently with a repository (as called for in the Draft Mission Plan Amendment) would have little effect on the inventory at shutdown reactors. (The minor effect shown is due to the difference in ramp-up assumptions for the two facilities.) The limiting case shown in Figure 3.11 is the extreme repository delay (2013) case.

Since the schedules for and cost of reactor decommissioning are sensitive to the timing and allocation of federal acceptance capacity, several acceptance scenarios were analyzed to quantify this sensitivity.

The cost of maintaining spent fuel storage at shutdown reactors has been investigated in a preliminary fashion. This analysis, documented in Appendix B, found that the cost of maintaining spent fuel storage at a site following shutdown was independent of the quantity of spent fuel stored. A cost of approximately \$2.2 million per year was developed for sites with one

FIGURE 3.11. Inventory at Shutdown Reactors

or two reactors, while maintaining a site with three reactors was estimated to cost about \$2.7 million. The incremental cost of maintaining spent fuel storage at a reactor awaiting decommissioning is significantly less if it is co-located with an operating reactor. On an aggregate basis, the cost of pool operations after last discharge is determined by the number of pool-years of additional operation required.

Table 3.5 summarizes the results for expected site-years of operation and resultant total cost to reactor owners due to the effects of timing and allocation of federal acceptance capacity. The costs shown include approximately \$900 million of cost for the reference decommissioning schedule. These represent fixed costs that cannot be avoided without alteration of the reference decommissioning sequence. The cost of \$1115 million associated with the Draft Mission Plan Amendment case under decommissioning priorities is consistent with the conclusion from Figure 3.10--i.e., that this scenario provides enough disposal capacity to allow timely decommissioning if it were allocated solely to decommissioning reactors. The difference of approximately \$215 million between this case and the costs when the reference

TABLE 3.5. Site-Years of Operation After Last Discharge and Associated Costs for Alternative Acceptance Scenarios

<u>Facility</u>	<u>Start Dates</u>	<u>Priority</u>	<u>Site-</u>	<u>Mean</u>	<u>Cost of</u>
<u>MRS</u>	<u>Repository</u>	<u>Scheme</u> ^(a)	<u>Years of</u>	<u>Duration</u>	<u>Operation</u>
			<u>Operation</u>	<u>After</u>	<u>(\$ million)</u>
				<u>Shutdown</u>	
				<u>(years)</u>	
--	2003	DECOM	690	7.19	1134
--	2003	OFF	1244	12.96	2049
--	2013	DECOM	1084	11.29	1803
--	2013	OFF	1853	19.30	3059
2003	2003	DECOM	681	7.09	1115
2003	2003	OFF	1204	12.54	1984
1996	2003	OFF	1060	11.04	1744

(a) Decommissioning priority cases use OFF allocation if sufficient spent fuel is not available at shutdown reactors.

sequence is met exactly at all sites is due to reduced acceptance capacity during the ramp-up of the second repository, and the fact that the acceptance rate requirement (slope of the requirements curve in Figure 3.10) is slightly greater than 3000 MTU/year.

Comparisons on an OFF basis show that the effects of an MRS facility on incremental decommissioning cost are small if the repository is deployed in a timely fashion. Thus, the addition of an MRS deployed in 2003 to a system with a timely (2003) repository saves only \$63 million, an insignificant amount in the context of overall waste management costs.

The effects of an MRS that accepts spent fuel earlier than a repository are significant if the comparison involves a delayed repository. Again, providing for acceptance earlier than 2003 is of little benefit under decommissioning priority. An early MRS deployment, however, would reduce the cost of pool operations by \$305 million relative to the 2003 repository-only case assuming OFF priorities for both. The maximum effect of MRS deployment on decommissioning sequences and cost is found by comparing the case for a delayed first repository (2013) and the earliest possible MRS deployment (1996). In this comparison, an MRS decreases costs by \$1.31 billion if OFF allocation is assumed or \$456 million if decommissioning priorities are assumed. (Section 3.1.1.6 addresses the role of acceptance priorities in calculation of MRS benefits.)

Thus, for a delayed repository scenario, the benefit provided by an early MRS deployment could be substantial. This benefit would require that the MRS facility was not constrained by the provisions of the NWPAA that link the development of the two facilities. Since this benefit depends only on the schedule for spent fuel acceptance, any of the MRS system configurations could provide it equally well. As noted earlier, all of the cases shown in Table 3.5 assume that second repository operations begin in 2027 (rather than 2032 as shown in the Task A report). A second repository start date of 2032 would increase the site years for the Oraft Mission Plan Amendment Case from 1204 to 1566 and costs from \$1984 million to \$2594 million.

In summary, the currently projected schedules for reactor shutdown and cumulative federal acceptance, along with assumed rules for allocation of

federal acceptance among sites, allow calculation of the number of years each site will be required to remain open after last discharge. The cost of this period of operation has been assessed using a preliminary estimate that accounts for the numbers of reactors per site. These costs are comparable in magnitude, on a system-wide basis, to those for additional at-reactor storage capacity. An MRS could provide some benefit in terms of avoided operations costs of this type only to the extent to which it allows accelerated acceptance of spent fuel. These benefits are most significant in cases where the repository is delayed or reallocation of the spent fuel acceptance rights granted under an OFF rule to sites awaiting decommissioning is limited.

3.1.1.6 Spent Fuel Acceptance Rules and the Value of an MRS

As noted in the preceding sections, the costs of at-reactor storage capacity and site operations after last discharge are sensitive to the early acceptance that could be provided under some MRS deployment scenarios. Since reactors differ in their maximum storage capacities and the timing of shut-down dates relative to the schedule for federal waste acceptance, these costs are also sensitive to the assumed rule for allocation of acceptance among reactors. Thus, calculation of the storage or operations cost that may be avoided by inclusion of an MRS is influenced by the rules assumed regarding allocation of acceptance. This section reviews these considerations briefly as they affect accounting for the benefit of an MRS facility, using cost data developed for the cases discussed in the preceding sections.

The oldest-fuel-first (OFF) rule established by the Standard Contract is based in equity rather than economic efficiency considerations. The equity principle underlying this rule is that those spent fuel owners who first generated nuclear power established a prior right to disposal services. This rule, if implemented by actually removing from each site the MTU of spent fuel prescribed, would, for any given acceptance schedule, lead to higher costs of additional storage capacity than if acceptance were allocated to those sites facing encroachment on full-core-reserve (FCR rule). Thus, the difference in additional at-reactor storage costs calculated by comparing two cases (with and without an MRS) will also be greater if both cases assume an OFF rule.

Similarly, an OFF rule will result in higher costs of operations after last discharge than a rule that allocates capacity only (or first) to those sites preparing to decommission (DECOM rule). Thus, measuring the value of an MRS in terms of avoided costs of this kind is subject to the same sort of effect--an OFF assumption will result in higher estimated costs for each case and higher avoided costs due to an MRS than will an assumption of decommissioning priorities.

The question raised by these different possibilities for calculating MRS benefits is one of practical importance, since the cost differences involved are substantial. The benefit of an early, decoupled MRS in terms of avoided cost of operations after last discharge changes in a delayed (2013) repository scenario is roughly \$0.5 billion assuming DECOM priorities and \$1.3 billion under OFF.

If the costs of additional at-reactor storage or operations after last discharge are considered separately, benefits of an MRS can be accounted for using a range. The high bound is provided by an assumption of OFF, and the low bound by either FCR or DECOM priority calculations. In effect, this range bounds the set of possibilities for avoided cost associated with different degrees of freedom in reallocating the OFF acceptance rights in a market. The OFF calculation assumes no reallocation is possible, and the FCR or DECOM calculations assume complete flexibility to reallocate acceptance. Upper and lower bounds for the avoided utility cost benefits of an MRS are given in Table 3.6 for four pairs of cases.

While this interpretation allows the data on two different types of avoided utility costs to be treated in an individually sensible fashion, the question of what total avoided utility costs should be counted as an MRS benefit remains. While it is clear that the OFF priority calculation gives an upper bound on MRS benefits from avoided utility costs, the lower bound depends on the specifics of the cases compared. Any change in priorities away from OFF, which compresses cost differences for one cost measure, will magnify cost differences for the other. Thus, in Table 3.6, the lower bound for total avoided utility costs occurs under DECOM priorities for two of the four pairs of cases and under FCR priorities in two cases. Figure 3.12 plots

TABLE 3.6. Avoided Utility Cost Benefits of an MRS Facility Under Alternative Acceptance Priority Rules and Deployment Dates

<u>Cases and Priority Rule Compared</u>	<u>MRS Benefit (\$ million)</u>		<u>Total</u>
	<u>Avoided Cost of Storage Capacity</u>	<u>Avoided Cost of Pool Operations</u>	
2003 MRS vs. 2003 Repository Only			
OFF	175	65	240
FCR/OFF	134	55	189
DECOM/OFF	230	19	249
1996 MRS vs. 2003 Repository Only			
OFF	586	305	891
FCR/OFF	405	338	743
DECOM/OFF	648	(213)	435
1996 MRS vs. 2013 Repository Only			
OFF	1652	1315	2967
FCR/OFF	1349	1341	2690
DECOM/OFF	1989	456	2445
2003 MRS vs. 2013 Repository Only			
OFF	1241	1075	2316
FCR/OFF	1078	1055	2133
DECOM/OFF	1571	688	2259

FIGURE 3.12. Summary of At-Reactor Cost Impacts--Effects of Delay and Priorities

components of utility costs as a function of priorities and acceptance schedule. Figure 3.12 suggests the following conclusions:

1. Total utility costs appear more sensitive to decommissioning priorities than to FCR priorities. Thus, decommissioning priority calculations give the lowest total utility costs in all four cases.
2. A hybrid priority scheme might allow lower total utility costs than either decommissioning or FCR priorities. The shape of the cost-component curve under OFF allocation suggests that the extended operations component of cost becomes relatively more important with acceptance delay. This suggests a scheme in which FCR priorities are used early and phased out in favor of decommissioning priorities.
3. The reduction in MRS benefits due to accounting on an FCR basis or DECOM basis declines as a percentage of the benefit (as measured under OFF) for increasing repository delay. Thus, for those cases where MRS benefits in terms of avoided utility costs are roughly comparable to MRS costs, the matter of which priority scheme to use in accounting is less important.

3.1.2 Federal Storage

As mentioned previously, federal storage of spent fuel can be at either an MRS or a FIS. Given the extensive constraints on FIS, only an MRS is analyzed in this report. Legislative conditions established under the NWPAA of 1987 for an MRS include [from Section 148(d)]: a) construction may not begin until a construction authorization has been issued for a high-level nuclear waste repository, b) the quantity of spent nuclear fuel or high-level radioactive waste stored onsite at any one time may not exceed 15,000 MTU, and c) the quantity of spent nuclear fuel or high-level radioactive waste stored onsite at any one time may not exceed 10,000 MTU until the repository first accepts spent nuclear fuel or solidified high-level radioactive waste. Because this analysis investigated MRS storage requirements in general, the broad spectrum of acceptance schedules analyzed was not necessarily constrained by the storage limitations established in the NWPAA.

As noted in Section 3.1, the benefits of federal storage capacity in terms of reactor storage capacity, duration, and cost are insensitive to the location of the federal storage. The same principal applies to the federal storage requirements derived in this section, and MRS storage requirements calculated from different MRS and repository start dates can be more

generally interpreted as federal surface storage requirements due to different acceptance and emplacement schedules.

3.1.2.1 Overview of Case Structure

All of the 91 schedules presented in the MRS Systems Study Task A report were analyzed for federal storage requirements. Table 3.7 identifies the 88 schedules analyzed (3 schedules were repository-only schedules).

TABLE 3.7. Acceptance Schedules Analyzed for MRS Storage Analysis

<u>Schedule Numbers(a)</u>	<u>Facility Start Dates</u>	
	<u>MRS</u>	<u>Repository</u>
2, 26, 48, 70	2003	2003
3, 27, 49, 71	2000	2003
4, 28, 50, 72	1999	2003
5, 29, 51, 73	2000	2003
6, 30, 52, 74	1997	2003
7, 31, 53, 75	1996	2003
9, 32, 54, 76	2008	2008
10, 33, 55, 77	2005	2008
11, 34, 56, 78	2004	2008
12, 35, 57, 79	2000	2008
13, 36, 58, 80	1997	2008
14, 37, 59, 81	2002	2008
15, 38, 60, 82	1996	2008
16, 39, 61, 83	2001	2008
18, 40, 62, 84	2013	2013
19, 41, 63, 85	2010	2013
20, 42, 64, 86	2009	2013
21, 43, 65, 87	2000	2013
22, 44, 66, 88	1997	2013
23, 45, 67, 89	2002	2013
24, 46, 68, 90	1996	2013
25, 47, 69, 91	2001	2013

(a) Schedule numbers are from the MRS Systems Study Task A report.

In addition, one benchmark schedule was analyzed for comparison: the MRS proposal schedule, as described in Section 3.1.1.1.

3.1.2.2 MRS Storage Requirements

The analysis of MRS storage requirements involved calculating the maximum MRS inventory required to maintain the acceptance schedule, given the lag time between beginning of acceptance and beginning of emplacement and/or variations between the rates of acceptance and emplacement. Table 3.8 summarizes the results of this analysis for selected cases. A complete set of results appears as Appendix E. Also shown in Table 3.8 are the number of years that the peak inventory was maintained at the MRS, the total duration of storage at the MRS, and the cumulative MTU-years of storage required for each of the acceptance schedules. Spent fuel and high-level waste storage requirements are tabulated separately.

The last column in Table 3.8 compares the maximum spent fuel storage inventory required for a given acceptance schedule against the 15,000-MTU storage capacity of the existing MRS design. Several of the schedules

TABLE 3.8. Acceptance-Related Storage Requirements at the MRS

Schedule Number (a)	Acceptance-Related Requirements						Maximum Spent Fuel Inventory as Fraction of MRS Design Capacity (%)
	Maximum MRS Inventory (MTU)		Years of Peak Inventory	Total Storage Required (MTU-yr)		Total Duration of Storage (yr)	
	Spent Fuel	HLW		Spent Fuel	HLW		
26(b)	5,200	--	18	110,740	--	24	35
27	14,200	--	15	299,800	--	27	95
43	44,200	--	5	930,000	--	37	295
44	53,200	--	2	1,119,060	--	40	355
45	38,200	--	7	803,960	--	35	255
70	5,200	0	18	110,740	0	24	35
71	14,200	1,200	15	299,800	20,940	27	95
87	44,200	5,200	5	930,000	90,740	37	295
88	53,200	6,400	2	1,119,060	111,680	40	355
89	38,200	4,400	7	503,960	76,780	35	255
MRS Proposal	14,700	--	16	333,900	--	30	98

(a) MRS Systems Study Task A report.

(b) Mission Plan Amendment Schedule.

analyzed require MRS inventories several times greater than the 15,000 MTU provided for under the NWPA. Many of the schedules also require considerable high-level waste storage.

The magnitude of MRS storage requirements is governed by the time lag between spent fuel acceptance and emplacement, as shown on Figure 3.13.

3.1.3 Substitution of MRS Storage for Additional At-Reactor Storage

As noted earlier, federal and at-reactor storage are direct substitutes for one another in the sense that either can meet a requirement for pre-emplacement storage of spent fuel. This does not imply, however, that every ton of available federal storage capacity will automatically displace a ton of additional at-reactor storage capacity. In order for this to occur, the federal storage must be allocated only to reactors that require additional storage. While this happens to some extent under an OFF rule (as provided in the Standard Contract), the correlation between acceptance rights as allocated under this rule and need for acceptance to minimize additional

FIGURE 3.13. MRS Storage Capacity for Different Lag Times Between SF Acceptance and Emplacement

storage requirement is imperfect. Figure 3.14 illustrates this by plotting the additional at-reactor storage required for a variety of the acceptance schedule cases. Four sets of data are plotted--two for OFF allocation of acceptance and two for an acceptance allocation based on the need to preserve FCR (and thus correlated with need for additional storage). In each case, both 2003 and 2013 repository start-up dates are included.

Figure 3.14 illustrates that the allocation of federal storage capacity under an OFF rule could limit the effectiveness of an MRS in minimizing additional at-reactor storage. In these cases, about 1 MTU in 3 of MRS storage capacity goes to reduce additional at-reactor storage (thus the slope of the data points for these two cases).

In the cases where FCR priority is used to allocate acceptance (and thus MRS storage space), the effect on additional at-reactor storage is essentially one-for-one, as shown by the slope of the data for these cases.

A final observation on this analysis is that the OFF allocation rule is primarily motivated by considerations of equity among utilities. The equity principle involved is that early spent fuel discharges establish a prior

FIGURE 3.14. Substitution of MRS Storage Capacity for Additional At-Reactor Storage

right to disposal services. While an FCR rule imposed by DOE would maximize the effect of MRS storage capacity in minimizing additional at-reactor storage, this would come at the price of these equity considerations if imposed by fiat. An allocation scheme that might preserve both equity and efficiency of the allocation of federal storage capacity is a market for federal acceptance rights as allowed under the Standard Contract.

Such a market could, in principle, reallocate acceptance capacity to those who valued it the most (presumably the utilities who would have substantial avoided storage costs) while preserving equity for the original owners in the form of compensation at market prices. The incentive to trade in a market in spent fuel acceptance rights is roughly equal to the difference in additional at-reactor storage costs between the OFF and FCR cases--about \$400 million. Whether a market of this type would actually function given the institutional complexities involved is an open question.

3.2 PROCESS SCHEDULING

This section investigates storage requirements and utilization due to the "process-scheduling" function of storage in MRS-based and repository-only variants of the federal waste management system. The conceptual framework for analysis of process-scheduling storage is discussed briefly below.

3.2.1 Introduction and Conceptual Framework

Any practically operable serial materials processing system must incorporate some storage "between" processing steps or work stations to facilitate process scheduling. In identifying the factors that give rise to this need, it is helpful to visualize a serial system in which there is no requirement for interprocess storage. Such a system would operate in a perfectly synchronous manner, with each unit of material starting a process immediately after it was discharged from the previous process. The system would either have exactly the same instantaneous throughput rate at each unit process, or would operate at a system throughput rate equal to the minimum process rate.

For several reasons, this idealized system picture will not be achieved. First, there will be good reasons to design different processes to different throughput rates (some examples are varying maintenance needs

and the changing physical nature of the material processed as it flows through the system). In addition, the actual throughput rate achieved at each process will not exactly equal the design specification. It may also be advantageous, in actual plant operations, to run different parts of the plant on different shift schedules. Finally, different processes may need, by virtue of design, to operate on different-sized batches of material, or favor accumulation of batches with specific material characteristics for economic reasons.

All of these departures from the ideal picture of a synchronized serial system lead to the need for interprocess, or "lag," storage. These factors will exist, and generate a requirement for lag storage, even if all components of a system are perfectly reliable. In practice, lag storage is also used to buffer operational fluctuations due to routine equipment failure and repair.

3.2.2 Process Representation of the Waste Management System

To investigate the types of system operational effects leading to process-scheduling storage needs, repository-only and MRS-based versions of the waste management system were modeled as series of discrete process steps. The model utilized to simulate system operation and process-scheduling storage utilization was the FASIT model, previously developed by PNL to conduct system reliability studies. Based on the general scheme shown in Figures 3.15 through 3.17, the unit processes account for features of the current facility designs (e.g., separate PWR and BWR consolidation lines) and for non-waste material movements (empty casks, cranes, etc.). Also shown in the figures are lag storage locations and capacities.

The functions assumed in Figures 3.15 through 3.17 correspond to system configuration cases 1 and 5 from the array of system configurations shown in Table 2.1. Since each of these cases contains all of the possible functions for the system configuration, they should represent reasonable bounding cases for analysis of process-scheduling storage, producing conservatively high estimates of storage utilization or requirements.

FIGURE 3.15. MRS Facility Simulation Flowsheet

FIGURE 3.16. No-MRS System: Repository Facility Simulation Flowsheet

FIGURE 3.17. MRS Facility Simulation Flowsheet Repository Facility

A complete exposition of the FASIT model structure and application in the MRS Systems Study is given in the Task I report, System Reliability Analysis (Clark and Myers 1989).

Important to predictions of the lag storage utilization are the process times, failure and repair rates, and shift schedules characteristic of each FASIT process. Assumptions on process times and failure/repair rates are given for the unit processes in Tables D.1 and D.2 in Appendix D. In the use of the model, process times were assumed to vary $\pm 10\%$ in a triangular distribution from the values shown, thus introducing normal operational variation. Shift scheduling assumptions for the two basic system configurations are summarized in Table 3.9.

Since both the process scheduling and reliability assumptions can impact lag storage requirements, a case structure was designed to discriminate between the effects of the two on storage utilization. Six simulation analyses were performed.

1. Repository-only system - normal operational fluctuations ($\pm 10\%$).
2. Repository-only system - normal operational fluctuations ($\pm 10\%$) and expected equipment failure.
3. Repository-only system - high operational fluctuations ($\pm 50\%$) and expected equipment failure.
4. MRS-based system - normal operational fluctuations ($\pm 10\%$).
5. MRS-based system - normal operational fluctuations ($\pm 10\%$) and expected equipment failures.
6. MRS-based system - high operational fluctuations ($\pm 50\%$) and expected equipment failures.

Results from these analyses are discussed for the repository-only and MRS-based systems below, followed by a comparative and sensitivity analysis.

3.2.3 Repository-Only Systems

Table 3.10 summarizes process-scheduling storage utilization results by location. The average utilization and range of maximum utilization (for the

TABLE 3.9. Shift Schedule Assumptions for Process-Scheduling Analysis

Configuration	Facility	Process	Shift Schedule		
			shifts/day	days/week	weeks/yr
Repository-only	Repository	Cask receiving	3	7	52
		All others	2	5	52
MRS-based	MRS	Cask receiving	3	7	52
		All others	3	5	52
	Repository	Cask receiving	3	7	52
		All others	2	5	52

TABLE 3.10. No-MRS System Lag Storage Summary

Storage Location	Design Capacity (MTU)	Storage Utilization (MTU)			
		Normal Operational Fluctuations	Average Utilization		Peak Utilization Range
			Normal Operational Fluctuations ($\pm 10\%$) and Equipment Failures	High Operational Fluctuations ($\pm 50\%$) and Equipment Failures	
Repository Rail Cask Storage	95 - 529 ^(a)	0.1	0.1	0.1	19
Repository Truck Cask Storage	26 - 39 ^(b)	0.3	0.4	0.4	10 - 11
WHB2 Hot Cell 1 Storage (PWR)	31	1.4	1.7	2.1	19 - 21
WHB2 Hot Cell 2 Storage (PWR)	31	1.5	1.5	1.6	19 - 22
WHB2 Hot Cell 3 Storage	32	4.8	4.8	5.0	21 - 24
WHB2 Hot Cell 4 Storage	32	0.2	0.2	0.3	7 - 10

(a) Minimum assumes all HLW casks in storage yard; maximum assumes all at-reactor consolidated BWR assemblies.

(b) Minimum assumes at-reactor consolidated PWR assemblies; maximum assumes intact PWR assemblies.

2-year period simulated) are given for both normal equipment failures and perfect reliability cases. Two general conclusions are:

1. The storage utilization is generally very low relative to design capacity. Average utilization never exceeds 15% of capacity, and maximum utilization is typically well below design capacity.
2. Random equipment failure at the frequencies and repair times given in Appendix D makes a very slight contribution to process scheduling storage utilization. In some cases, this contribution is within the statistical "noise level" of the model, and storage utilization is lower for the equipment failure case.

In summary, for a waste management system utilizing only a repository with a mature operation, normal operational fluctuations in processing times and routine equipment failures lead to a very modest interprocess storage requirement, certainly well within the current design assumptions for the facility.

An additional sensitivity concern is the effect of the extent of random variation in process times. The $\pm 10\%$ used as an assumption is probably representative of the type of mature, routine operation assumed. Given that the equipment that will perform the various processes has not yet reached even the detailed design stage, a sensitivity analysis incorporating a larger variation $\pm 50\%$ was conducted. While storage utilization is generally a bit higher, the differences are not significant from an overall system perspective.

3.2.4 MRS-Based Systems

Table 3.11 summarizes process-scheduling storage for an MRS-based system. Utilization is also low relative to design capacity in this system, but total storage is significantly higher than in the repository-only system. Comparison of Tables 3.10 and 3.11 reveals that much of this difference is found in the MRS facility canister lag storage areas. Canistering is an intermediate step in some MRS-based systems that collects consolidated fuel pins into canisters for storage and subsequent transfer to the repository. This process immediately precedes the loading of silo storage casks or MRS-to-repository rail transport casks, both of which are high capacity casks. Filling these casks requires the accumulation of canisters and thus increases storage requirements. The canistering process is not performed in a repository-only system, where disassembled fuel assemblies are consolidated directly into disposal containers. The extra process-scheduling storage utilized in the MRS-based system is thus a consequence of an extra process and the fact that this system configuration operates in larger increments in the final transportation leg.

Even though process-scheduling storage utilization is significantly larger in the MRS-based systems than in a repository-only system, it is nevertheless very low relative to both design capacity and throughput. As

TABLE 3.11. Design Basis MRS System Lag Storage Summary

Storage Location	Design Capacity (MTU)	Storage Utilization (MTU)			
		Average Utilization		Peak Utilization Range	
		Normal Operational Fluctuations	Normal Operational Fluctuations ($\pm 10\%$) and Equipment Failures	High Operational Fluctuations ($\pm 50\%$) and Equipment Failures	
MRS Rail Cask Storage	179 - 268	0.8	0.6	0.9	19 - 29
MRS Truck Cask Storage	25 - 39	0.5	0.4	0.5	9 - 10
MRS Canister Storage (PWR)	497	21.1	21.3	20.9	69 - 74
MRS Canister Storage (BWR)	512	21.6	21.6	21.9	73 - 83
MRS Hot Cell 1 Storage (PWR)	83	1.1	1.3	1.1	14 - 19
MRS Hot Cell 2 Storage (PWR)	83	1.0	1.1	1.4	14 - 18
MRS Hot Cell 3 Storage (BWR)	60	0.9	1.0	0.7	13 - 14
MRS Hot Cell 4 Storage (BWR)	60	0.7	0.7	0.9	12
Rep. Rail Cask Storage (PWR)	107 - 313 ^(a)	4.6	1.8	8.8	56 - 98
Rep. Truck Cask Storage	23 - 35	0.5	0.0	0.1	2 - 4
Rep. Hot Cell Storage (PWR)	10	0.0	0.0	0.1	5
Rep. Hot Cell Storage (BWR)	9	0.0	0.0	0.0	1
Rep. Surface Vault	221 - 446 ^(b)	0.0	0.0	0.0	0 - 18

(a) Minimum assumes all defense casks in storage; maximum assumes all casks are from MRS.

(b) Minimum assumes all intact PWR fuel; maximum assumes all at-reactor consolidated BWR.

in the repository-only system, the storage utilization level and distribution among locations appear to be largely determined by the shift schedule and mean process time assumptions, inasmuch as the addition of routine equipment failures or additional variance in process times adds little to storage levels.

3.2.5 Comparative and Sensitivity Analysis

From a perspective of overall system functional comparisons between a repository-only and an MRS-based system, a key question is whether either system will intrinsically perform the process-scheduling function better. In

this regard, it is clear that the storage present in long-term MRS storage would not routinely be utilized for process scheduling. MRS-based systems using an intermediate package (canister) would require slightly larger process-scheduling storage. This result appears to be independent of design details for system configuration 5, but would not apply in other configurations. The fact that the MRS to repository casks represent larger increments of material and thus require larger amounts of storage for batch accumulation seems to be intrinsic to the MRS concept and valid for all system configurations.

As noted in the introduction, one factor leading to process-scheduling storage is differences in shift schedules between serial processes. Since the shift schedules were assumed to be largely consistent within the two plants, the previous results may not be conservative in accounting for this source of storage need. In order to assess the potential impact of this factor, note that a single shift represents the processing of between 3 MTU and 6 MTU of spent fuel depending on which of the three typical shift schedules is assumed. If every other process was switched to a 24-hour-per-day, seven-day-per week operation, this would lead to an additional 18 MTU of storage at each process. Conservatively, there are 13 active processes (not counting storage locations and processes handling empty casks) in the MRS system. Thus, changing shift schedules in the extreme manner hypothesized might require an additional 126 MTU of storage for processes scheduling. This is a significant quantity in terms of the projected utilization levels from the FASIT analyses, but would not increase total requirements beyond current design levels.

3.2.6 Storage Requirements for Selective Batching

The FASIT model simulations discussed above account for the need to assemble batches of material in cases where containers or shipment sizes dictate this. There are also other incentives for assembly of batches that are not included in the FASIT results. In general, these are cases in which both the quantity and the characteristics of the inventory at some storage locations are relevant to the next processing operation.

Other than cases where thermal characteristics lead to selectivity of this type (which are discussed in Section 3.4), the most important instance of selectivity arises in the consolidation process. Due to diversity in fuel assembly designs, it may be necessary to incorporate several tool designs in the operations of the consolidation equipment. Each type would handle some subset of the fuel population, and tool changeouts would be required when switching between fuel types, leading to a tradeoff between the frequency of tooling changes and the amount of batch assembly storage employed. This tradeoff was analyzed in previous work under the Systems Integration Program at PNL. This work was re-evaluated and reported as it applies to the current study objectives.

Figures 3.18 and 3.19 illustrate the tradeoff between storage costs and tooling changeout costs for PWR and BWR fuel, respectively, assuming \$1500 tooling change costs and storage capacity costs of \$35,000/PWR assembly and \$14,000/BWR assembly. The least cost campaign lengths derived from this

FIGURE 3.18. Determination of Optimal Average Consolidation Campaign--PWR Fuel

FIGURE 3.19. Determination of Optimal Average Consolidation Campaign--BWR Fuel

analysis were about 12 MTU for PWR fuel and 18 MTU for BWR fuel. Since assembly of this size batch from among a spent fuel process stream that is effectively random with respect to fuel design will require temporary storage of the other fuel types, the storage requirement arising from batch selection can exceed the optimal average campaign length. The factor that relates this storage requirement to the optimal campaign length is a function of the number of fuel types, the degree to which they are mixed in the process stream, and the confidence level deemed appropriate in assuring that an optimal batch will be available. An analysis of these factors lead to the result that storage requirement is approximately equal to the optimal campaign length for BWR and about three times the optimal campaign for PWR fuel.

The extent to which versatile tooling (covering several fuel types) can be designed, or tool changeout can be automated, as well as the relative unit costs of tool changeout and storage, are subject to considerable uncertainty. To reflect this uncertainty and provide a conservative upper bound

for batch assembly storage, a sensitivity analysis was performed using the cost data from Figures 3.18 and 3.19. Since the upper bound for optimum batch size (and thus storage) will be found for low storage costs and high changeout costs, this analysis assumed that storage costs were 1/2 the standard assumption and that changeout costs were twice the standard assumption. This set of assumptions results in optimum batch sizes of 28 MTU for PWR fuel and 36 MTU for BWR fuel, and thus requires batch assembly storage of 84 MTU for PWR fuel and 36 MTU for BWR fuel.

The results from this selective batch assembly analysis are compared with the results of the FASIT simulation for the same storage location in Table 3.12. Since the same storage location would serve both process-scheduling needs and for aggregation of batches of similar assemblies, these requirements are not additive. The maximum requirement for process-scheduling storage, based on a sensitivity analysis with an extreme ratio of storage to changeout costs, is slightly above current design capacity for PWR fuel in SFA lag storage in a repository-only system. Since system operation could be slightly modified (slightly smaller than minimum cost batch size) at

TABLE 3.12. Summary of Process-Scheduling Storage Requirements and Capacity (MTU) for SFA Lag Storage

<u>Storage Requirements</u>	<u>Repository-Only System</u>		<u>MRS-Based System</u>	
	<u>PWR</u>	<u>BWR</u>	<u>PWR</u>	<u>BWR</u>
Process scheduling				
• normal operational variation and equipment failure	37	31	33	25
• $\pm 50\%$ operational variation and equipment failure	40	29	32	26
Batch assembly				
• reference unit costs	36	18	36	18
• bounding case	84	36	84	36
Maximum requirement	89	36	84	36
Capacity	63	62	166	137

little cost, it is concluded that current design basis storage capacity for SFA lag storage prior to the consolidation process is adequate in both repository-only and MRS systems.

3.3 RELIABILITY ENHANCEMENT FUNCTION OF STORAGE

A comprehensive analysis of the reliability of the waste management system was conducted under the MRS Systems Study Task I and is reported in detail in the Task I report (Clark and Myers 1989). To the extent that storage capabilities influence reliability, a summary of those results is reported here.

Reliability is defined in a broad sense as the likelihood of accomplishing a specific goal in a specified time period. In systems where the goal is continuous operation (e.g., aircraft), reliability is the probability of "failure-free" operation. In on-line repairable systems (e.g., materials processing operations such as the waste management system), reliability is expressed as the probability of achieving a certain production or throughput rate in a unit time, and can be satisfactorily high even when multiple "failure" events are expected.

In the waste management system context, the analyses of equipment failure and repair rates summarized in the Task I report led to just this conclusion. In spite of a pattern of fairly frequent failure, the ability to restore equipment functions quickly and design equipment throughput rates high enough to make up any lost production together result in very high system reliabilities. As shown in Tables 3.10 and 3.11, the incremental effects of these failures on lag storage utilization are within the statistical "noise level" of the system simulation. The conclusion to be drawn from this, however, must be carefully qualified - storage capacity per se contributes little to system reliability for equipment failures in the facilities as presently designed. To fully define the potential for enhancing system reliability through the use of storage, a class of process "failure" events broader than equipment failures must be examined.

Included in this class of events are any unanticipated or consciously controlled events that would alter the throughput in any part of the system

from the planned system throughput levels shown. In the context of system development and licensing, this could include extensions of the licensing process for a repository, or requirements for an extended performance confirmation period using less than full-production quantities of spent fuel. In this broader system development and institutional context, it is clear that there are many possible events that could diminish the ability of the emplacement or other processes in the system, and that the durations of the impaired throughput could be substantially longer than the equipment failures analyzed. While there are no "data" on the probabilities of these events in a radioactive waste management system incorporating a deep geologic repository, the first-of-a-kind nature of the program and the institutional setting argue that system development to full-production capacity will be a deliberate, careful process, and that tonnage of emplacement is a goal subordinate to demonstration of operational safety and isolation effectiveness. This sort of long-term throughput reduction event is not confined to the emplacement function. A transportation accident, even without safety consequences, could lead to institutional restrictions that reduced the throughput of the transportation function for some time.

It is in this context that storage may prove valuable in enhancing system reliability. A significant quantity of storage capacity within the federal system will permit continued although partial system function in the face of such long-duration events. Specifically, unused storage capacity would allow continuation of spent fuel acceptance (and, in some configurations, packaging) to continue at full rate if the emplacement rate were below planned goals, and available inventory would allow continuation of the emplacement function if the acceptance function were impaired. If the spent fuel stored were in disposal-ready form, the emplacement function would also be protected against impaired throughput in the waste-preparation functions.

The analysis of such long duration events is reported in detail in Task I. The resulting requirements for storage capacity are simple, with available storage capacity requirements equal to the system throughput rate (nominally 3000 MTU/year) times the duration of the design basis emplacement interruption, and spent fuel inventory requirements equal to the product of the planned throughput rate and the duration of the design-basis acceptance

interruption. Thus, for example, a system with the 15,000 MTU capacity MRS now specified under the NWPAA would insure against any pair of acceptance and emplacement interruptions with a combined duration of 5 years, provided that the system storage capacity was properly allocated between capacity available and inventory in storage.

3.4 HEAT MANAGEMENT FUNCTION OF STORAGE

"Heat management" encompasses several types of variation in system operation to take advantage of possible performance or cost sensitivities to thermal output. Broadly speaking, these operational variations involve changing the sequence in which spent fuel is accepted, packaged, or emplaced. These changes in processing sequences are translated into changes of the distribution of thermal characteristics within and among transport casks, storage locations, and ultimately waste packages and repository emplacement panels.

Whether or not these effects warrant any special effort to accomplish heat management has not been determined at this time, and is a subject of continued study by the Yucca Mountain Project. One of the possible effects of heat management, reduction of waste package corrosion by maintenance of emplacement borehole temperatures above 97°C, was allocated a repository performance burden in the SCP-CD (DOE/RW-0160). This performance allocation has been dropped in the final SCP (DOE/RW-0199).

Whether or not there proves to be sufficient incentive for heat management schemes, many of the schemes for altering processing sequences would require storage, and are thus functions of interest for this task. This section explores the extent to which MRS and repository-only system configurations could accomplish postulated heat management objectives. It includes background discussions on the possible motivation and opportunity for heat management (3.4.1 and 3.4.2), a description of the thermal characteristics for reference operation scenarios for both classes of systems (3.4.3), and analyses of specific heat management objectives (3.4.4 and 3.4.5).

3.4.1 Design and Operational Sensitivity to Heat Output

As shown in Figure 3.20, the heat output of spent fuel is dependent on the time exposed in reactor (i.e., exposure or burnup level) and the time since reactor discharge (i.e., "age"). Several studies (Wang 1983; Dippold 1984; O'Brien 1984; DOE 1985) have concluded that spent fuel burnup and age have important implications for the design, performance and costs associated with the nuclear waste disposal system.

The sensitivity of repository system design and operational parameters to the thermal characteristics of spent fuel is based on limits in the repository system, grounded in considerations of waste form integrity, repository structural stability, or other performance measures. Table 3.13 summarizes a set of thermal criteria and limits for the waste package, repository and site subsystems of a geologic repository system (Scott 1983). These criteria and limits are illustrative, and serve only to demonstrate the possible number and diversity of design and operating sensitivities and constraints. Thermal limits analogous to those in Table 3.13 will be used to support design studies through the identification of the most restrictive thermal limits or constraints.

FIGURE 3.20. Decay Heat as a Function of Time and Exposure for PWR Fuel Assemblies

TABLE 3.13. Illustrative Thermal Criteria and Limits for the Waste Package, Repository, and Site Subsystems of a Geologic Repository (Scott 1983)

Mined Geologic Disposal System	Objective of Thermal Constraint	Waste Form/Material/Media	Failure Mechanism	Maximum Temperature (°C) or Temperature Change
Waste Package Composition	Prevent alteration of chemical fuel $\text{UO}_2\text{-U}_3\text{O}_8$	Spent fuel	Oxidation of ceramic	250
			Degradation of protective oxide film on Zircaloy clad	200
		Borosilicate glass HLW	Softening of glass	500
			Transition	500
	Prevent loss of physical integrity	Spent fuel	Rupture of clad by internal pressure	396 (PWR) 427 (BWR)
			Stress-rupture of the clad	380
			Stress-corrosion cracking of the clad	300
		Borosilicate glass HLW	Devitrification	500
			Cracking of waste glass	500 - 800
Containment	Prevent loss of physical or chemical integrity	304L stainless steel	Structural changes leading to increased susceptibility to stress cracking	375
Waste handling	Prevent loss of safe working conditions	Air in open rooms		50
		Air during retrieval operations in previously sealed rooms		28
		Tuff during retrieval operations		49
Geologic	Prevent excessive ground surface temperature rise	Tuff		<4 within 3 meters of the surface
Hydrologic	Prevent excessive temperature rise in neighboring aquifers	Tuff		<6 in stagnant aquifers
Geochemical	Prevent loss of geochemical integrity	Tuff		100 from the near field outward to a distance equal to 15% of the repository depth
				75 outside the region defined above

Since repository and waste package design are currently at the conceptual level, and the interaction of thermal effects and overall repository performance is still being studied, the benefits of heat management in the waste management system have not yet been fully evaluated. At present, the Yucca Mountain Project is in the early stages of a study that will define a preferred spent fuel emplacement schedule based on some of the thermal effects anticipated in the repository. This study is premised on selection of emplacement sequences that (via management of variation in decay heat among repository panels) allow maintenance of high [$>97^{\circ}\text{C}$] emplacement wall temperatures in all areas of the repository for the longest time. This is considered desirable as a means of assuring that aqueous corrosion by liquid water contacting the waste package containers will be minimized.

Although not to be quantitatively analyzed during the Yucca Mountain study, there is possibility and potential benefit of "package-scale" heat management schemes. Such package-scale schemes would include minimizing the variance of spent fuel energy deposition among waste packages within a panel, or alteration of the inter-package spacing ("pitch") in the repository.

3.4.2 Variation in Spent Fuel Population

Spent fuel from civilian nuclear power reactors has been accumulating since 1968 and some of the fuel will be up to 35 years old when the first geologic repository begins scheduled operation in 2003. Table 3.14 provides data for spent fuel discharged from U.S. reactors through 1986. As indicated, spent fuel exposure levels have varied, which, in turn, affects heat generation rates. The variation in spent fuel exposure levels is due to variation in reactor design and refueling schedules among plants. The future trend is toward higher exposure levels (EIA 1987) because it has the potential of lowering fuel, operating, and at-reactor storage costs.

Higher exposure increases the heat generation rate and radiation source intensity of the spent fuel. Spent fuel age is important for thermal characteristics because of the exponential decay of heat-producing isotopes following reactor discharge.

TABLE 3.14. Quantity (MTU) of Spent Fuel by Burnup Range, Type of Reactor, and Year of Discharge for the Energy Information Administration (EIA) 1987 No New Orders - Increased Burnup Projection

Burnup (Gwd/MTU) Versus Year in MTIHM																	
Discharge Year	0	5	5	10	10	15	15	20	20	25	25	30	30	35	35	40	
	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	
1968	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	1	0	1	0	7	0	0	0	0	0	0	0	0	0	0
1970	0	0	0	0	0	2	0	37	0	0	0	0	0	0	0	0	0
1971	47	0	9	5	2	0	11	0	2	3	0	19	0	0	0	0	0
1972	72	0	38	0	31	12	4	29	1	31	0	23	0	22	0	0	0
1973	10	0	17	0	28	0	36	26	2	0	1	33	0	8	0	0	0
1974	0	7	78	2	121	86	44	13	3	40	0	57	0	1	0	0	0
1975	0	3	1	43	45	95	124	54	24	77	2	25	0	23	0	0	0
1976	1	0	66	0	94	4	154	192	3	83	0	58	0	55	0	0	0
1977	0	0	46	0	43	3	197	87	97	132	1	125	0	87	0	15	
1978	2	0	33	2	18	48	76	90	239	37	15	335	0	118	0	61	
1979	0	0	0	0	19	31	109	107	115	64	153	232	0	236	0	43	
1980	14	0	0	0	1	1	95	0	377	73	123	237	10	285	0	26	
1981	0	0	0	0	0	17	58	2	224	27	164	225	10	370	1	31	
1982	0	0	0	5	5	2	19	83	137	84	184	57	13	301	1	117	
1983	0	0	0	5	1	6	3	72	91	51	358	170	45	315	0	138	
1984	0	0	5	0	10	54	0	46	124	53	190	215	123	379	0	107	
1985	17	0	43	0	18	20	37	26	68	20	287	223	11	334	0	234	
1986	51	0	39	0	43	27	67	144	51	12	147	193	69	381	0	247	
1987	51	30	49	0	72	28	41	105	116	85	245	127	8	401	20	356	

Burnup (Gwd/MTU) Versus Year in MTIHM														
Discharge Year	40	45	45	50	50	55	55	60	60	65	Total	Total	Total	Cumulative
	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	MTU	MTU
1968	0	0	0	0	0	0	0	0	0	0	1	0	1	1
1969	0	0	0	0	0	0	0	0	0	0	10	0	10	10
1970	0	0	0	0	0	0	0	0	0	0	0	39	39	49
1971	0	0	0	0	0	0	0	0	0	0	70	26	97	147
1972	0	0	0	0	0	0	0	0	0	0	146	118	264	410
1973	0	0	0	0	0	0	0	0	0	0	93	67	160	570
1974	0	0	0	0	0	0	0	0	0	0	247	207	454	1,024
1975	0	0	0	0	0	0	0	0	0	0	196	319	515	1,540
1976	0	0	0	0	0	0	0	0	0	0	318	392	710	2,249
1977	0	0	0	0	0	0	0	0	0	0	383	449	832	3,081
1978	0	0	0	0	0	0	0	0	0	0	383	691	1,075	4,156
1979	0	0	0	0	0	0	0	0	0	0	396	714	1,109	5,265
1980	0	2	0	0	0	0	0	0	0	0	620	625	1,244	6,510
1981	0	1	0	0	0	0	0	0	0	0	457	672	1,130	7,639
1982	0	2	0	0	0	2	0	0	0	0	359	653	1,012	8,652
1983	0	5	0	0	0	0	0	0	0	0	498	763	1,261	9,913
1984	0	4	0	0	0	0	0	0	0	0	452	858	1,310	11,223
1985	0	24	0	0	0	0	0	0	0	0	480	1,042	1,509	12,586
1986	0	35	0	1	0	1	0	0	0	0	467	1,042	1,509	14,095
1987	0	23	0	0	0	0	0	0	0	0	601	1,154	1,755	15,850

By virtue of variation in age and exposure, there is a wide distribution of thermal power levels among the spent fuel population. Figure 3.21 illustrates this distribution for the current fuel inventory. This distribution will get more diverse as the thermal power output of the current inventory declines with time and new, generally higher exposure fuel is discharged. This diversity of thermal characteristics provides an opportunity for heat

management by altering the emplacement sequence. The current reference emplacement sequence (DOE 1986a) is based on an oldest-fuel-first rule, which will produce a generally increasing spectrum of spent fuel power output at time of emplacement. This sequence is described in the next section for both repository-only and MRS system configurations.

3.4.3 Reference Spent Fuel Thermal Characteristics

This section describes the pattern of thermal characteristics typical of spent fuel acceptance for both repository-only and MRS-based waste management systems. These characteristics provided a starting point for the analysis of specific heat management strategies in Sections 3.4.4 and 3.4.5.

3.4.3.1 The Acceptance Sequence and System Operations

The OFF rule ensures that there is a "queue" for distribution of disposal services among those requiring them. While the contracts also specify

FIGURE 3.21. Decay Heat Distribution of Current Spent Fuel Inventory

that no fuel will normally be accepted less than 5 years after discharge, there is the possibility that the actual fuel shipped, while equal in tonnage to that calculated under an OFF rule, might not actually be the oldest fuel in the inventory at a particular reactor. Thus, there are two steps to the acceptance sequence determination--an allocation of tonnage among reactors and a selection of fuel to be shipped. Both of these steps could be used as heat management tools.

3.4.3.2 Repository-Only System

While the Standard Contract allows for selection of fuel other than the oldest, the OFF rule has been broadly interpreted as governing selection as well as allocation of acceptance tonnages. [See, for instance, Generic Requirements for Mined Geologic Disposal Systems (DOE 1986a)]. This interpretation, when combined with facility schedule and logistics assumptions, leads to reference patterns of spent fuel thermal characteristics over time. In a repository-only system, the acceptance and emplacement sequences are the same on an annual basis, and the OFF rule leads to the pattern of spent fuel thermal power shown in Figure 3.22. This reference pattern exhibits significant variation among annual average thermal power, with a clear trend toward greater heat output in later years. There is also significant variation in power levels within any given year--the "hottest" fuel typically has a power level over ten times as great as the "coolest."

The long-term (350-year) energy deposition (kW-yr/MTU) of spent fuel emplaced under an OFF rule in a repository-only system is illustrated in Figure 3.23. This parameter is of interest in repository design, and spent fuel with equivalent thermal power output at time of emplacement can have different long-term energy deposition due to differences in burnup. Thus, the shapes of the power (Figure 3.22) and energy (Figure 3.23) curves are slightly different.

FIGURE 3.22. Trend and Range of Spent Fuel Decay Heat (at time of emplacement)--Repository-Only System--OFF Allocation and Selection

FIGURE 3.23. Annual Average of 350 Year Integrated Heat Emplaced--Repository-Only System--OFF Allocation and Selection

3.4.3.3 MRS-Based System

The operations plan for the integrated MRS called for three basic phases of operation: 1) a period, prior to repository operation, during which spent fuel receipts would be canistered and stored in long-term storage, 2) a period during which both the MRS and repository are operational and spent fuel is canistered for direct shipment to the repository without storage in long-term storage, and 3) a period after the spent fuel inventories at reactors are depleted, during which time the inventory in long-term storage is drawn down. This operational scheme, which has been referred to as "pass-through" operation, is illustrated in Figure 3.24. This method of operation has the advantage of minimizing the number of storage/retrieval cycles in long-term storage. This may be an important consideration if long-term storage is in large casks as called for by the current design for the integrated MRS.

If combined with the reference oldest-fuel-first acceptance and spent fuel selection rule, however, this operational scheme produces a significant change in the pattern of average spent fuel thermal power at time of emplacement. This is illustrated in Figure 3.25, which compares this profile with the OFF repository-only reference case.

The discontinuous pattern of thermal power at time of emplacement shown in Figure 3.25 is caused by the fact that the oldest fuel in the system remains in inventory at the MRS while younger, "hotter" fuel is passed through to be emplaced. At the point when this older fuel begins to be unloaded (2017), a sharp decrease in spent fuel power level would be observed with this particular operational scenario.

FIGURE 3.24. Pass-Through MRS Operational Scheme

FIGURE 3.25. Average Heat Generation of Spent Fuel Emplaced--Pass-Through and No-MRS Cases

From the perspective of an overall evaluation of an MRS, it is important that an MRS system could be operated to restore the OFF emplacement sequence, if this were desired, although at the cost of either cycling all fuel through long-term storage or reducing the spent fuel acceptance rate from reactors.

In this sense the reference pattern of thermal characteristics at emplacement is less important for the MRS-based system, since the long-term storage (provided there is enough) in the MRS allows the emplacement and acceptance sequences to differ.

3.4.4 Analysis of Levelized Integrated Heat Strategy

Following preliminary analysis conducted by the Yucca Mountain Project, the analysis of particular heat management schemes in this report concentrated on the ability of alternative system configurations to generate emplacement sequences having relatively constant long-term energy deposition rates.

This analysis assumed that the overall timing and rates of spent fuel acceptance were fixed. The levelized integrated heat strategy was analyzed in a slightly different fashion for MRS-based and repository-only systems. With an MRS in the system, the emplacement sequence may be altered independently of the acceptance sequence, with storage capacity allowing the resequencing. In simulating these cases, spent fuel is selectively either shipped for disposal or retained in inventory according to some heat-based rule. The results of these analyses consist of the amount of storage required to achieve certain patterns of average annual heat at emplacement, given a reference pattern of acceptance into the waste management system. These analyses assume only that an MRS can store and selectively ship fuel to a repository, and apply to all of the MRS configurations studied. (See, however, the discussion of timing requirements in Section 3.4.4.1.)

Analysis of the levelized integrated heat strategy in the repository-only case was done by modeling selection of spent fuel accepted from reactors. The selection was constrained so that the total tonnages of spent fuel shipped per year were fixed by some allocation rule (e.g., OFF).

3.4.4.1 MRS-Based System

The operational scheme in which MRS inventory is mixed with spent fuel accepted from reactors to produce a constant pattern of integrated heat is illustrated in Figure 3.26. Using the WASTES-II simulation model and controlling the maximum heat output shipped from the MRS in a trial-and-error fashion, a levelization heat management strategy of this type was modeled for the same acceptance rules used for the reference case described earlier, and for two alternative acceptance rules.

FIGURE 3.26. Levelizing Heat Management MRS--Operation Scheme

These results are illustrated in Figure 3.27, and compared to the reference profile (for integrated heat output with an OFF selection and pass-through operation). By selecting the fuel for shipment, an MRS can be used to levelize the pattern of integrated heat at emplacement for an OFF selection rule for acceptance from reactor. This ability extends to cases where the input stream to the MRS is based on allocation priority to either decommissioning reactors or reactors where additional storage would soon be required (FCR).

All of these input streams can be resequenced to produce an integrated heat level of 83 ± 3 kW-yr/MTU.

Meeting the target of constant kW-yr imposes requirements on the MRS. The operational simulations for these cases produced a maximum MRS inventory of 23,800 MTU. While this figure, generated with trial and error of selection algorithms, may not be a minimum requirement, it is considered highly unlikely that even sophisticated optimization-based selection rules could achieve the levelization using the 15,000-MTU limit on MRS inventory imposed by the NWPAA.

FIGURE 3.27. Effect of Levelization Strategy on Average Annual Integrated Heat Output

With the currently planned acceptance rates for the MRS and repository, accumulation of sufficient inventory to levelize integrated heat requires about 7 years between initiation of acceptance at the MRS and emplacement. Thus, the results shown in Figure 3.27 assume a 1996 MRS deployment and a 2003 repository operating date. Figure 3.28 illustrates the best levelization results achieved with later MRS start dates (and an OFF input stream). The case with a 1999 MRS start most closely matches the NWPAA schedule constraints, and is also consistent with the maximum inventory constraint of 15,000 MTU specified in the NWPAA, requiring 14,800 MTU. The maximum MRS inventory prior to repository operation in this case is 7100 MTU, also consistent with NWPAA provisions.

The 4 years of relatively low integrated heat emplacement in this case are years in which the repository is scheduled to emplace at less than design rate. (Emplacement quantities in the initial years are 400 MTU, 900 MTU, 1500 MTU, and 2250 MTU.) Thus, any affect on the repository would be confined to two panels (5050 MTU) rather than four.

FIGURE 3.28. Effect of Alternative MRS Starting Schedules on Levelization of Average Annual Integrated Heat Output for an OFF Acceptance Allocation and Selection with a 2003 Repository

In addition to the requirements for storage capacity generated by the levelization of kW-yr, this mode of MRS operation requires significant cycling of spent fuel through long-term storage. This is illustrated in Figure 3.29, which shows MTU of spent fuel loaded and unloaded per year. A total of 15,500 MTU of additional storage cycling is required compared to the reference (pass-through) scenario.

3.4.4.2 Repository-Only System

Achieving a levelized energy deposition pattern for a repository-only system was modeled by selecting fuel based on its integrated heat level from reactors. This selection was constrained so that the quantities of spent fuel accepted were governed by the same allocation rules used in the MRS analysis--OFF, FCR, and DECDM.

Although the Standard Contract between DOE and utilities does not explicitly provide for this selection, it does provide DOE with approval authority over utility proposals for specific spent fuel to be shipped. This

FIGURE 3.29. MRS Cycling Requirements for Integrated Heat Levelization

contractual background combined with the fact that the selection of spent fuel to levelize integrated heat will generally result in the shipment of radiologically hotter fuel than an OFF selection, makes such a selection scheme plausible.

Figure 3.30 shows the pattern of integrated heat output emplaced on a year-by-year basis under such a selection scheme for each of the three allocation rules. In all three cases, the selection of fuel accepted allows reasonably constant level ($\sim 85 \pm 4$ kW-yr) after the initial 2 years of operation. These results are quite comparable to those achieved for the entire emplacement period using MRS storage to resequence spent fuel. In the case of FCR priority, it is possible to achieve this same degree of constancy throughout the entire emplacement period. Both the OFF and decommissioning priority cases produce a lower integrated heat output for the first 2 years. This is unavoidable due to the fact that the fuel inventory at the very oldest reactors (which are selected for early shipment under either rule) is

FIGURE 3.30. Effect of Spent Fuel Selection on Average Annual Integrated Heat Output--Repository Only

both low-burnup and old by 2003. Just as in the MRS analysis, however, the quantity of fuel involved is small--a total of only 1300 MTU in this case.

These results show that much of the benefit of achieving a constant number of kW-yr/MTU in the spent fuel emplaced from year to year can be achieved in a repository-only system by selection of spent fuel shipped, under any of three possible allocation priority schemes, including the contractual reference (OFF). Achieving these results in practice would require the cooperation of utilities in selecting fuel for dry storage and in making fuel from particular batches available for pickup.

3.4.5 Intra-Year Heat Management

In addition to the heat management strategies that attempt to control the annual average of thermal output spent fuel emplaced (or total thermal power emplaced), there are also strategies motivated by the distribution of package heat output levels within a year. The basic consideration in reducing this intra-year variation of package heats is packaging efficiency. Local thermal constraints limit the heat output of a waste package (to 4 kW for intact fuel or 5 kW for consolidated fuel in a tuff repository) (DOE 1986a). This corresponds to about 1.8 kW per MTU for the intact fuel case, and to about 1.3 kW/MTU for the consolidated case. (Slight variations in these limits arise from considerations of the PWR/BWR mix package, but are ignored here.) A value of 1.5 kW/MTU was used for the analysis. A packaging scheme that attempts to load fuel with higher thermal power than these limits would thus violate this design constraint, and would require "derating" the waste package (e.g., reducing the quantity of spent fuel in some packages). This leads to a larger number of packages required (and more boreholes drilled) than if spent fuel could be selected to keep all packages just within the thermal limit. Strategies to accomplish this have been referred to as "blending" or "package scale" strategies. These strategies were analyzed by inspection of the annual distribution of spent fuel power outputs for various receipt scenarios.

This is a first-order analysis, since little is known about the degree of variation in spent fuel characteristics within years. The approach taken

allows for conclusions stated in terms of the sufficiency of storage capacity equal to a year's throughput (3000 MTU) to achieve constant thermal loadings among waste packages.

Blending strategies could be employed alone or in combination with management of the annual average thermal characteristics (e.g., levelization). Such strategies, even without the control of average annual thermal power offered by levelization strategies, offer benefits in terms of packaging efficiency. Figures 3.31, 3.32, and 3.33 illustrate the effects of this strategy for three acceptance sequences.

Slight improvement is produced in the OFF case, with about 3,000 MTU of spent fuel above 1.5 MTU/ton being blended with cooler fuel to produce packages with heat output of <1.5 MTU/ton. More drastic changes are evident in the case where the blending strategy is applied to a distribution of package heat output arising from decommissioning priority. In this case, about

FIGURE 3.31. Distribution of Package Decay Heat Before and After Blending--OFF Receipts

FIGURE 3.32. Distribution of Package Decay Heat Before and After Blending--Decommissioning Priority Receipts

FIGURE 3.33. Distribution of Package Decay Heat Before and After Blending--FCR/Priority Receipts

10,000 MTU of fuel above 1.5 kW is blended with cooler fuel to produce packages less than 1.5 kW. The FCR/DECOM case shows a reduction of about 12,000 MTU in fuel over 1.5 kW.

An important result for system configuration comparisons is that these blending results are all achievable with 3000 MTU of storage capacity. Thus, an MRS or a repository with expanded storage capacity could provide this type of heat management.

4.0 THE ROLE OF AN MRS IN SYSTEMS INTEGRATION

The Nuclear Waste Policy Act, as amended, directs the U.S. Department of Energy (DOE) to develop and implement a federal waste management system that contains specified components. If the site proves technically suitable and other conditions of the Act are met, a geologic repository is to be developed at Yucca Mountain, Nevada. A monitored retrievable storage (MRS) facility is authorized for construction subject to a confirmation of its benefits by the MRS Commission. These federal facilities will accept, handle, and dispose of spent fuel from about 120 reactors at about 80 sites around the U.S. The spent fuel population is made up of many distinct designs that will be transported in a relatively small number of transport cask types and may be handled by different equipment during cask unloading, disassembly, and packaging operations. In addition to the diversity of fuel designs per se, there will probably be several technologies employed for at additional at-reactor storage, including dry casks, modular vaults, and at-reactor consolidation. Each of these technologies presents a different set of handling requirements for transfer of stored fuel to the federal system, and there can be significant differences in design even within one of these categories.

These and other similar considerations make it clear that integration of the federal radioactive waste management system with the at-reactor operations is an important concern in system development. This chapter examines the extent to which development and deployment of an MRS facility would facilitate this integration, and the type of MRS best suited to this purpose.

4.1 DEFINITION AND ASPECTS OF INTEGRATION

For the purpose of this analysis, integration of the federal and private components of the waste management system is defined as:

"Development and operation of all components of the system in a fashion that recognizes constraints or exploits opportunities in the others."

This definition points to several specific aspects of development or operation of the federal system that contribute to integration, and that were used as the framework for the analysis and organization of this chapter. They include;

- Definition of Interfaces
- Standardization
- Accommodation of Diversity
- Reduced Handling
- Efficient Use of Equipment

In the following sections, each of these aspects is described and used in comparing various MRS systems with a repository-only system.

4.2 DEFINITION OF FEDERAL-UTILITY INTERFACES

Since the decisions on development and design of the federal and private components of the waste management system are being made by many different groups, a prerequisite for integrated system development of the extended system is clear communication of the evolving status of each component to the others. This could be accomplished by frequent communication of design information of the type that would occur if the various decisions were made within a single systems engineering framework, but this is institutionally impossible. In practice, this sort of communication is best achieved by a clear definition of a small set of interface features. These features include hardware specifications for fuel canisters and casks and specifics of the spent fuel transfer process. Since utility and vendor decisions on types and design details are beginning to be made now, this sort of interface definition needs to occur relatively early in the development of the federal system to be most useful. Thus, the question for the current analysis is the extent to which inclusion of an MRS in the system would facilitate this clear, early definition of the federal-utility interface.

A characteristic of any system with an MRS facility, regardless of the particular configuration, is that the spent fuel acceptance function is allocated to a separate facility than is the emplacement function. This, and the

need to conduct site characterization for a repository, means that the actual implementation of the spent fuel acceptance function could probably be accomplished earlier in a system with an MRS than in a repository-only system. This early acceptance benefit was quantified in terms of avoided at-reactor storage capacity and cost in Section 3.1. More relevant to the question of integration is whether the interface features can be defined earlier in a system including an MRS.

This question was first examined with reference to current design schedules. The program milestone that corresponds most closely to the definition of design details is the submission of a License Application Design to the NRC. The current schedule for development of the federal waste management system calls for submission of the License Application Designs for both the MRS and repository in mid-1995. Thus, there is no relative advantage in terms of the current program schedule. While an MRS program that was scheduled specifically for simplicity and early design might allow definition of interface features earlier than the 1995 date, the same appears to be true in principle of a repository facility, insofar as the design of the receiving and handling portion of the facility is concerned. A practical question remains as to whether the licensing process for a repository could allow for acceleration of design of elements of the surface facility. This is suggested as a potential follow-on study for the Licensing task.

While the uncertainty about the ability to segregate the surface and underground portions of the repository licensing process may confer some degree of advantage of an MRS-based system in final definition of interface design details, it is clear that some broad but important features of the federal-utility interface could be defined much earlier in either system. These include the extent to which acceptance of consolidated fuel will be delayed and the feasibility of acceptance of multiple-element sealed canisters (MESCs) at the federal facility. The provision of this sort of information in definitive form requires some study for either MRS-based or repository-only systems, but appears to be equally possible in both.

A final consideration in this aspect of integration is whether the acceptance schedule itself is regarded as any more certain (apart from perhaps being accelerated) in a system with an MRS. The acceptance schedule determines additional at-reactor storage requirements for each reactor site. If this schedule is uncertain, utilities will tend to adopt a conservative planning horizon for additional storage. This could result in higher capacity and higher expense than a situation in which the acceptance schedule is relatively certain.

A survey of utility views on the MRS (GAO 1986) indicated generally low confidence that a repository could be deployed on the then current schedule (1998). Only 3 of 47 respondents who felt they had sufficient information to judge expressed at least "moderate" confidence that the schedule could be met. While no specific analogous question was asked relative to an MRS, answers to related questions offer some insight on utility perceptions of relative schedule certainty. First, a majority of respondents preferred the MRS (versus at-reactor storage) as the appropriate location for spent fuel storage if repository deployment were delayed. Second, most respondents felt that the long-term storage function of the MRS (the only function that could not be transferred to a repository) was "neither necessary nor beneficial" if a repository could be deployed by 1998. Thus, a general view in favor of MRS development seems to have been linked specifically to a perception of increased certainty that the federal government could accomplish the long-term storage function with an MRS.

Even though the prevailing attitude of the utilities seems to be that inclusion of an MRS in the OCRWM system will increase schedule certainty vis-a-vis a repository-only system, a question still remains as to whether this relative advantage has any practical significance for utility planning. It is possible that the perceived difficulty of siting and licensing any proposed federal facility to handle spent fuel is great enough to warrant conservative planning, and resulting in plans for life-of-plant storage at reactors regardless of the status of an MRS. It is clear that whatever advantage an MRS may have in the area of perceived certainty of acceptance would be maximized by an MRS that was simple and easy to site, and that could be deployed and operated independently of a repository.

4.3 STANDARDIZATION

A system in which at-reactor storage and transfer of spent fuel was accomplished in a uniform fashion would simplify acceptance and processing in the federal system and result in lower total federal system cost than a system with significant diversity. From a technical perspective, such a system would be perfectly integrated. There are, however, significant institutional barriers to such standardization. DOE lacks the authority to require that utilities select any particular storage method, and a number of storage methods are currently in commercial development and competition with each other. An attempt to standardize on a single method or a single design for each method could result in legal difficulties. The uniformity of storage technology across reactor sites could also increase storage costs, since different storage technologies are least costly for different quantities of fuel. Free choice among technologies allows utilities to select the least-cost solution for each site. This effect would be at least partially offset by economies of scale in the production of a single storage system for use at all sites.

The one scenario in which standardization appears to be institutionally feasible might be termed a "distributed" MRS. In this scenario, the DOE would assume responsibility for all additional at-reactor spent fuel storage and would select the appropriate storage technologies to be deployed. Previous analysis (DOE 1987), indicates that only the storage function, and not the consolidation or waste packaging functions, is a reasonable candidate for distribution among reactor sites. This scenario has a clear advantage from a standardization perspective. The drawbacks appear to be in the areas of institutional feasibility and legal liability for federally managed spent fuel storage on many private sites, and assuring proper consideration of many subtle site-specific considerations when choosing and implementing a standard storage method.

Although the diversity that already exists among fuel types and storage hardware and the institutional factors discussed above are barriers to standardization among at-reactor storage installations, it would be possible and beneficial to standardize specifications for consolidated and failed fuel

canisters. Minimal requirements for these canisters could be set with reference to in-pool storage and transportation functions, and thus could be set independently of the decision on inclusion of an MRS in the federal system. By the same logic, inclusion of an MRS in the system offers no special advantage or disadvantage in achieving standardization for spent fuel canisters.

4.4 ACCOMMODATION OF DIVERSITY

Lacking the ability to standardize the interface between the federal system and reactor sites, the ability to accommodate a diversity of packaging types, including MESCs and transportable storage casks (TSCs), is an important consideration in system development. The ability to handle these and other possible spent fuel packagings appears to be a matter of the functional requirements adopted for the system as a whole and not how they are allocated between facilities. Either an MRS-based or a repository-only system configuration can be designed to handle a wide variety of packages.

4.5 REDUCED HANDLING

Handling of spent fuel generates small amounts of routine occupational exposure, results in some financial cost, and creates some incremental risk of accidental exposure. For these reasons, minimizing handling to the extent compatible with overall system functions is desirable. Any system configuration with an MRS will increase handling requirements to some extent compared to a repository-only system. The increase in routine dose may be minimal, as in a configuration where an MRS receives transportable storage casks and transfers them to a storage field without opening them. (This would be typical of the first phase of the three-phase MRS.) In general, the largest share of incremental routine dose is associated with the extra loading and unloading of transport casks. Changes in routine public dose associated with transportation are covered in the MRS Systems Study Task F report.

4.6 EFFICIENT USE OF EQUIPMENT

As described in the Draft 1988 Mission Plan Amendment (DOE 1988), the authorized waste management system calls for utilities with spent fuel in dry cask storage to transfer that fuel into DOE-supplied transport casks for shipment off-site. In the MRS system, the casks would be unloaded at the MRS, and the fuel would then be consolidated and canistered. Fuel that was to be stored at the MRS would be loaded into concrete MRS storage casks. In the repository-only system, all consolidation and packaging functions would be performed at the repository. A key feature of this system is that utility storage casks, after unloading, would be reused only if they could be transferred to another site owned by the same utility or sold to another utility.

To the extent that the federal system can use equipment purchased for at-reactor storage use, the extended system can be more cost-effective. The potential to utilize at-reactor storage casks for continued storage or transportation, or to utilize MESC's for MRS storage present opportunities of this type.

The economics of such equipment re-use have been explored in detail in two recent studies. Use of Transportable Storage Casks in the Nuclear Waste Management System (ORNL 1987) found that some potential exists for economic use of utility storage casks regardless of the configuration of the DOE system. This potential is much greater in MRS-based systems, where up to 341 utility-supplied casks could be used for purposes of transportation, lag storage, and MRS storage within the federal system. In contrast, the repository-only system could utilize only 75 utility-supplied casks. Most (240 casks) of this difference is due to the fact that an MRS system shares the pre-emplacement storage function with reactor sites. The remainder of the difference is due to differences in use for lag storage between the MRS-based and repository-only systems. The direction of these differences as calculated by ORNL (greater lag storage required in an MRS-based system than at a repository) is consistent with the lag storage findings reported in Section 3.2, but the absolute magnitude is not. The ORNL results show lag storage of up to 800 MTU at an MRS. This is over twice the total requirement derived for an MRS in Section 3.2.

Regardless of the absolute value of the differential use of utility casks for lag storage, the general conclusion is that an MRS-based system could economically make use of more utility-supplied casks than a repository-only system. This conclusion depends only on the storage function of the MRS, and thus is valid for all of the various MRS configurations in this study.

The potential for use of MESCs within the federal system is analyzed in Waste Acceptance Criteria Study (EPRI 1988). This study broadly examined integration issues for MESCs, using as models two MESC designs by NUPAC.

The MESCs to be used in these designs hold either 7 or 24 PWR assemblies. It would be advantageous to a utility to be able to ship the loaded MESC to DOE rather than to open the MESC at the reactor, remove and inspect the fuel assemblies, and load them into a transport cask. However, the 24-element MESC is too large to fit into the casks currently planned for use in the federal waste management system. The 7-element version could be accommodated with an attendant reduction in the cask capacity of about 50%. In addition, a new basket would be required for the cask, increasing the weight of the loaded cask by almost 2 tons.

To provide a more integrated waste management system, it is of interest to determine whether it is most efficient to require the utilities to open the MESCs at the reactor site and load intact fuel into DOE-supplied transportation casks or to accept the sealed canisters directly into the DOE system. Estimated cost impacts to the DOE system resulting from the transportation, storage, handling, and disposal of MESCs as calculated in EPRI (1988) are given in Table 4.1. Handling and transportation costs are higher for MESCs than for intact fuel in both the repository-only and the MRS system. However, because the storage at the MRS of the 24-element MESCs is less expensive than storage of canistered fuel, the net system cost of MESC acceptance is less in the MRS system than in the repository system.

Thus, although an MRS-based system is closer to break-even for utilization of MESCs, such re-use would still result in a net cost to the DOE system. The net costs of handling 24-element MESCs within the DOE system

TABLE 4.1. Estimated Additional Costs to the DOE System from Acceptance of Spent Fuel in MESC's (\$/kgU, 1986)(a)

	<u>Repository-Only System</u>		<u>MRS System</u>	
	<u>24-PWR Assembly MESC</u>	<u>7-PWR Assembly MESC</u>	<u>24-PWR Assembly MESC</u>	<u>7-PWR Assembly MESC</u>
Transport - Reactors to DOE Facilities	\$6.6-\$7.5	\$12-\$14	\$6.6-\$7.5	\$12-\$14
MRS Casks	--	--	(7.7)	(1)
Operating Costs	0.3	0.7	0.3	0.7
MESC Disposal	<u>3.2</u>	<u>2.1</u>	<u>3.2</u>	<u>2.1</u>
Total	\$10.1-\$11.0	\$14.8-\$16.8	\$2.4-\$3.3	\$13.8-\$15.8

(a) Adapted from EPRI (1988).

appear to be within the possible range of cost savings relative to other at-reactor storage methods. Thus, the extended system might achieve a cost advantage if an MRS were operated to accept MESC's directly.

5.0 SUMMARY OF CONCLUSIONS

Storage of spent fuel in the federal waste management system performs the functions of enabling acceptance from utilities, process scheduling, enhancement of reliability, and heat management. To the extent described below, these functions are performed better by systems including a monitored retrievable storage (MRS) facility. In addition, storage of spent fuel can serve to facilitate integration of the federal and at-reactor systems by increasing the relative certainty with which utilities plan for storage, and by offering better economics of equipment reuse.

5.1 ACCEPTANCE-RELATED STORAGE

- Regardless of the acceptance schedule, utilities will be faced with a significant at-reactor storage burden that cannot be accommodated by projected pool capacity. The magnitude of this "additional" storage is 10,600 MTU for a 2003 repository-only system.
- By enabling acceptance of spent fuel significantly prior to emplacement, an MRS could relieve the utilities of a significant fraction of this additional storage requirement.
- The earliest MRS deployment schedule consistent with NWPAA provisions and a 2003 repository could limit additional storage to 5200 MTU, if the repository proceeded on schedule.
- An MRS specifically configured to minimize additional at-reactor storage would:
 - be deployed as early as possible (1996)
 - have significantly more than 15,000 MTU of storage capacity
 - be operable independently of repository operational status.
- Such an MRS could limit additional at-reactor storage to 3000 MTU, regardless of the repository schedule achieved.
- Since the effects on additional at-reactor storage are independent of the functional allocation between an MRS and repository, any of the MRS configurations studied would perform this function equally well.

- While phased MRS configurations allow acceptance of spent fuel as early as possible, the limitations on the form of acceptance in early phases implies that additional storage requirements at reactor are not decreased in a significant fashion by this earlier acceptance.
- Regardless of the schedule for MRS deployment, allocation of acceptance rights under an oldest-fuel-first (OFF) rule could limit the effectiveness of an MRS in substituting federal storage for utility storage, requiring as much as 3 MTU of MRS capacity for each MTU of additional at-reactor storage displaced.
- Costs of additional at-reactor storage will be between \$150 million and \$2.5 billion, depending on the date when acceptance begins and the unit cost of storage.
- The portion of these costs that can be avoided by inclusion of an MRS depends directly on the speed with which an MRS can be deployed and the ultimate repository deployment date. The earliest possible MRS (1996), combined with a 2003 repository deployment, would save between \$400 million and \$1 billion, depending on the unit costs of storage and the allocation priority scheme.
- These savings could be greater if a repository were delayed beyond 2003, and the MRS had capacity and authority to continue storing spent fuel.
- All of the acceptance schedules analyzed when combined with OFF priorities result in substantial quantities of spent fuel stored at reactors after an assumed reference of five years after last discharge.
- For the Draft Mission Plan Amendment schedule, this storage could require up to 700 pool-years of additional pool operation beyond nominal decommissioning, costing up to \$1.1 billion.
- This extension of pool operating life requirement could be mitigated by granting priority to decommissioning reactors.
- An MRS could play a role in assuring timely decommissioning of reactors in the scenario where the first repository is delayed until 2013. In this case, an MRS deployed as late as 2003 would save an estimated \$1.0 billion in costs of pool operations after last discharge. This is in addition to savings associated with avoided at-reactor storage capacity.

5.2 PROCESS SCHEDULING

- Process-scheduling storage sufficient to buffer variations in process times and normal equipment failures can be easily included

in any MRS-based or repository-only system. Quantities required are on the order of hundreds of MTU.

- Providing storage sufficient to allow scheduling of processes based on spent fuel characteristics will require more storage. Reasons for this type of selectivity would include assembly of batches of similar fuel for consolidation or providing the most efficient mix of intact PWR and BWR assemblies for the hybrid waste package. A storage capacity of 3000 MTU at either an MRS or repository would be sufficient to provide for all known requirements of this type.

5.3 ENHANCING RELIABILITY

- The storage capacity available within an MRS or repository-only system is not a factor in determining system reliability for normal equipment failures.
- The larger quantities of storage available in an MRS would confer a higher degree of system reliability in the face of long-term outages in particular functions.
- The storage required to perform this function is directly related to the duration of the "design outage" - 3000 MTU per year would be required.

5.4 HEAT MANAGEMENT

- "Levelizing" strategies, which attempt to produce a constant value for average integrated thermal power emplaced, can be accomplished with storage capacity at an MRS. This can be achieved for any of three spent fuel input sequences analyzed, including OFF, FCR, or decommissioning.
- These strategies would allow a higher fraction of emplacement boreholes to be maintained above 97°C for at least 300 years.
- Using an MRS to resequence any of the three input sequences is possible with 24,000 MTU of spent fuel storage capacity.
- An MRS constrained by the NWPAA provisions would be slightly less effective in accomplishing this function, due to limitations on storage capacity and deployment date.
- A degree of levelization almost equivalent to that produced by resequencing at an MRS could be achieved by spent fuel selection in a repository-only system. This selection could be accomplished

without altering the allocation of acceptance rights granted to utilities under three priority scenarios, but would require the cooperation of the utilities.

- Control of within-year variation in package heat outputs, motivated by package thermal power limits, could be accomplished with less than a year's worth of spent fuel receipts in inventory, for a variety of receipt sequences. Thus, this sort of heat management could be accomplished either at an MRS or within a repository-only system. The latter might require expansion from the current 750 MTU surface storage specification.

5.5 INTEGRATION

- Aspects of system development and performance that contribute to integration of the federal and at-reactor waste management operations include:
 - clear, early definition of the federal system
 - standardization
 - accommodation of diverse waste forms
 - reduced handling
 - efficient use of equipment.
- An MRS-based system provides a relative advantage in defining the federal spent fuel acceptance capacity with certainty (even if the projected start date is the same as for a repository).
- The qualitative aspects of system definition, including what packaging types are acceptable, can be defined early for either an MRS or repository-only system.
- Standardization of utility storage technology is equally possible with or without an MRS, but may be institutionally difficult in either case.
- Either an MRS or repository-only system would be designed to accommodate diverse waste forms, including transportable storage casks (TSCs) and multiple-element sealed canisters (MESCs).
- An MRS-based system would increase spent fuel handling. This increase would be minimized by storage-only configurations and a "pass-through" operational scheme.

- An MRS system would allow better economics for federal reuse of utility storage equipment. Up to 341 transportable storage casks could be used economically in an MRS-based system (configuration 5 with cask storage) versus 75 in a repository-only system.
- The incremental cost of acceptance of MESCs at a federal facility is lower in a system with an MRS. This incremental cost appears to be less than potential utility savings (versus other storage schemes) for a 24-element PWR MESC.

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APPENDIX A

DETAILS OF AT-REACTOR STORAGE REQUIREMENTS AND COSTS

TABLE A.1. Summary of At-Reactor Storage Requirements and Cost--
Schedule 1^(a)

Capacity Range (MTU)	Storage Requirement		System Cost Range (\$ million) ^(b)			
	Sites	MTU	Low Proven	High Proven	Likely	Goal
0 - 50	9	160	17	26	14	12
50 - 100	12	980	83	116	64	47
100 - 150	7	870	70	96	52	34
150 - 200	6	1,080	85	114	64	38
200 - 250	4	1,110	87	115	64	37
250 - 300	2	560	43	58	32	17
300 - 350	1	320	24	33	18	10
350 - 400	3	1,120	85	113	63	48
400 - 450	41	680	128	170	94	71
450 - 500	0	0	0	0	0	0
500 - 550	0	0	0	0	0	0
550 - 600	1	570	43	57	31	23
600 - 650	1	600	45	60	33	25
650 - 700	0	0	0	0	0	0
700 - 750	1	700	53	69	39	28
750 - 800	0	0	0	0	0	0
800 - 850	0	0	0	0	0	0
850 - 900	1	860	65	85	47	34
900 - 950	0	0	0	0	0	0
950 - 1000	0	0	0	0	0	0
1000 - 9999	0	0	0	0	0	0
Total	53	10,620	827	1,112	615	424
Average Cost (\$/kgU)			78	105	58	40

(a) Minimum Case, MRS Systems Study Task A, Schedule 3 (No Western Strategy), system cost by capacity range.

(b) The amount of additional storage space that can be created through in-pool consolidation and spent fuel storage is limited by the storage capacity of the pool. At a typical reactor not much more than 300 MTHM of additional storage space can be gained in the storage pool through rod consolidation.

TABLE A.2. Summary of At-Reactor Storage Requirements and Cost--
Schedule 17^(a)

Capacity Range (MTU)	Storage Requirement		System Cost Range (\$ million) ^(b)			
	Sites	MTU	Low Proven	High Proven	Likely	Goal
0 - 50	4	50	5	8	4	4
50 - 100	2	140	12	17	9	7
100 - 150	6	720	58	79	43	28
150 - 200	8	1,400	111	148	83	49
200 - 250	10	2,260	176	235	131	75
250 - 300	5	1,410	109	145	80	44
300 - 350	5	1,640	125	167	92	49
350 - 400	1	390	30	39	22	17
400 - 450	2	840	64	85	47	35
450 - 500	6	2,870	218	287	161	121
500 - 550	2	1,030	78	103	58	42
550 - 600	4	2,340	176	234	129	96
600 - 650	0	0	0	0	0	0
650 - 700	3	2,020	152	200	111	83
700 - 750	2	1,490	112	148	82	60
750 - 800	0	0	0	0	0	0
800 - 850	0	0	0	0	0	0
850 - 900	1	890	67	88	49	36
900 - 950	2	1,860	140	184	102	74
950 - 1000	1	950	71	94	52	38
1000 - 9999	<u>2</u>	<u>2,530</u>	<u>190</u>	<u>250</u>	<u>139</u>	<u>101</u>
Total	66	24,840	1,891	2,512	1,394	957
Average Cost (\$/kgU)			76	101	56	39

(a) Maximum Case, MRS Systems Study Task G, Schedule 17 (No MRS), system cost by capacity range.

(b) The amount of additional storage space that can be created through in-pool consolidation and spent fuel storage is limited by the storage capacity of the pool. At a typical reactor not much more than 300 MTHM of additional storage space can be gained in the storage pool through rod consolidation.

TABLE A.3. Summary of At-Reactoer Storage Requirements and Cost--
Schedule 26^(a)

Capacity Range (MTU)	Storage Requirement		System Cost Range (\$ million) ^(b)			
	Sites	MTU	Low Proven	High Proven	Likely	Goal
0 - 50	9	270	29	43	23	21
50 - 100	9	650	55	77	42	31
100 - 150	9	1,080	86	119	65	42
150 - 200	5	860	68	91	51	30
200 - 250	2	440	34	46	26	15
250 - 300	3	810	62	83	46	25
300 - 350	3	1,000	76	102	56	30
350 - 400	2	740	56	75	41	32
400 - 450	0	0	0	0	0	0
450 - 500	0	0	0	0	0	0
500 - 550	2	1,030	78	103	58	42
550 - 600	0	0	0	0	0	0
600 - 650	1	640	48	64	35	26
650 - 700	0	0	0	0	0	0
700 - 750	0	0	0	0	0	0
750 - 800	1	780	59	77	43	31
800 - 850	0	0	0	0	0	0
850 - 900	0	0	0	0	0	0
900 - 950	0	0	0	0	0	0
950 - 1000	0	0	0	0	0	0
1000 - 9999	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>
Total	46	8,310	652	880	486	325
Average Cost (\$/kgU)			78	106	58	39

(a) Schedule 26 (same as Draft 1988 Mission Plan Amendment), system cost by capacity range.

(b) The amount of additional storage space that can be created through in-pool consolidation and spent fuel storage is limited by the storage capacity of the pool. At a typical reactor not much more than 300 MTHM of additional storage space can be gained in the storage pool through rod consolidation.

TABLE A.4. Summary of At-Reactors Storage Requirements and Cost--
Schedule 27^(a)

Capacity Range (MTU)	Storage Requirement		System Cost Range (\$ million) ^(b)			
	Sites	MTU	Low Proven	High Proven	Likely	Goal
0 - 50	13	290	31	47	25	22
50 - 100	8	530	45	63	34	25
100 - 150	3	370	30	41	22	14
150 - 200	5	860	68	91	51	30
200 - 250	2	460	36	48	27	15
250 - 300	3	810	62	83	46	25
300 - 350	1	330	25	34	18	10
350 - 400	0	0	0	0	0	0
400 - 450	1	400	30	40	22	17
450 - 500	0	0	0	0	0	0
500 - 550	1	510	39	51	29	21
550 - 600	0	0	0	0	0	0
600 - 650	0	0	0	0	0	0
650 - 700	1	680	51	67	37	28
700 - 750	0	0	0	0	0	0
750 - 800	0	0	0	0	0	0
800 - 850	0	0	0	0	0	0
850 - 900	0	0	0	0	0	0
900 - 950	0	0	0	0	0	0
950 - 1000	0	0	0	0	0	0
1000 - 9999	0	0	0	0	0	0
Total	38	5,240	417	565	312	208
Average Cost (\$/kgU)			80	108	60	40

(a) Schedule 27 system cost by capacity range.

(b) The amount of additional storage space that can be created through in-pool consolidation and spent fuel storage is limited by the storage capacity of the pool. At a typical reactor not much more than 300 MTHM of additional storage space can be gained in the storage pool through rod consolidation.

TABLE A.5. Summary of At-Reactor Storage Requirements and Cost--Schedule 31^(a)

Capacity Range (MTU)	Storage Requirement		System Cost Range (\$ million) ^(b)			
	Sites	MTU	Low Proven	High Proven	Likely	Goal
0 - 50	10	220	23	35	19	17
50 - 100	1	80	7	9	5	4
100 - 150	3	330	26	36	20	13
150 - 200	7	1190	94	126	70	42
200 - 250	0	0	0	0	0	0
250 - 300	1	300	23	31	17	9
300 - 350	0	0	0	0	0	0
350 - 400	1	380	29	38	21	16
400 - 450	0	0	0	0	0	0
450 - 500	0	0	0	0	0	0
500 - 550	1	510	39	51	29	21
550 - 600	0	0	0	0	0	0
600 - 650	0	0	0	0	0	0
650 - 700	0	0	0	0	0	0
700 - 750	0	0	0	0	0	0
750 - 800	0	0	0	0	0	0
800 - 850	0	0	0	0	0	0
850 - 900	0	0	0	0	0	0
900 - 950	0	0	0	0	0	0
950 - 1000	0	0	0	0	0	0
1000 - 9999	0	0	0	0	0	0
Total	24	3010	241	328	181	122
Average Cost (\$/kgU)			80	109	60	40

(a) Schedule 31 cost by capacity range.

(b) The amount of additional storage space that can be created through in-pool consolidation and spent fuel storage is limited by the storage capacity of the pool. At a typical reactor not much more than 300 MTHM of additional storage space can be gained in the storage pool through rod consolidation.

TABLE A.6. Storage Requirements by Site--Schedule 1^(a)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
ARK NUCLEAR 1	210	1997	2006	2012
BEAVER VALLEY 1	153	1997	2007	2018
BIG ROCK 1	6	1997	1999	2006
BRAIDWOOD 1	703	1996	2011	2031
BROWNS FERRY 1	15	2006	2006	2007
BRUNSWICK 1	445	1991	2006	2018
CALLAWAY 1	98	2007	2010	2013
CALVERT CLF 1	412	1992	2006	2017
CLINTON 1	136	2005	2012	2023
COOK 1	355	1997	2006	2015
COOPER STN	121	2000	2007	2014
CRYSTAL RVR 3	190	1989	2007	2015
DAVIS-BESSE 1	131	1998	2008	2017
DUANE ARNOLD	50	2002	2006	2008
ENRICO FERMI2	410	1997	2011	2028
FITZPATRICK	87	2000	2007	2008
FORT CALHOUN	82	1996	2006	2010
GINNA	7	2002	2002	2003
GRAND GULF 1	83	2008	2010	2011
HADDAM NECK	68	1998	2002	2007
HATCH 1	102	2004	2007	2009
HOPE CREEK	76	2002	2007	2012
INDIAN PT 1	163	1995	2005	2010
KEWAUNEE	98	1999	2006	2011
LASALLE CTY 1	857	1991	2009	2031
LIMERICK 1	410	2002	2014	2030
MAINE YANKEE	112	1997	2004	2007
MILLSTONE 1	396	1987	2004	2013
NINE MILE PT1	85	1998	2003	2007
NORTH ANNA 1	197	2001	2007	2010
OCONEE 1	602	1987	2006	2015
OYSTER CRK 1	64	1997	2002	2006
PALISADES	215	1988	2004	2013
PALO VERDE 1	218	2008	2011	2018
PEACHBOTOM 2	199	2000	2005	2008
PERRY 1	66	2010	2011	2015
PILGRIM 1	132	1995	2004	2008
POINT BEACH 1	140	1996	2003	2010
PRAIRIE ISL 1	284	1994	2005	2015
ROBINSON 2	224	1990	2007	2015
RVR BEND 1	82	2007	2010	2016
SAN ONOFRE 1	573	1996	2009	2023
SEABROOK 1	95	2011	2014	2018
SEQUOYAH 1	275	2000	2008	2022

TABLE A.6. (contd)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
ST LUCIE 1	324	1988	2006	2020
SUSQUEHANNA 1	240	2004	2009	2014
TROJAN	13	2007	2007	2007
TURKEY PT 3	1	2004	2004	2004
VOGTLE 1	39	2011	2012	2013
VT YANKEE 1	22	2003	2003	2004
WASH NUCLEAR2	174	2002	2009	2022
WATERFORD 3	11	2010	2010	2010
ZION 1	<u>372</u>	1996	2006	2013
TOTAL	10,620			

(a) MRS Systems Study Task A, Schedule 1.

TABLE A.7. Storage Requirements by Site--Schedule 17^(a)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
3 MILE ISL 1	7	2013	2013	2015
ARK NUCLEAR 1	465	1997	2016	2025
BEAVER VALLEY 1	454	1997	2018	2029
BIG ROCK 1	6	1997	1999	2016
BRAIDWOOD 1	1,151	1996	2022	2034
BROWNS FERRY1	498	2006	2014	2018
BRUNSWICK 1	669	1991	2014	2027
BYRON 1	403	2012	2021	2028
CALLAWAY 1	296	2007	2019	2028
CALVERT CLF 1	747	1992	2014	2026
CLINTON 1	338	2005	2022	2030
COMANCHE PK 1	28	2024	2026	2027
COOK 1	742	1997	2016	2025
COOPER STN	224	2000	2012	2024
CRYSTAL RVR 3	285	1989	2015	2025
DAVIS-BESSE 1	233	1998	2016	2026
DIABLO CANYON 1	199	2014	2019	2025
DRESDEN 1	165	2003	2010	2016
DUANE ARNOLD	130	2002	2012	2019
ENRICO FERMI 2	657	1997	2022	2032
FARLEY 1	166	2010	2016	2020
FITZPATRICK	208	2000	2013	2020
FORT CALHOUN	137	1996	2011	2020
GINNA	64	2002	2007	2016
GRAND GULF 1	268	2008	2019	2027
HADDAM NECK	123	1998	2005	2017
HATCH 1	486	2004	2017	2022
HOPE CREEK	515	2002	2017	2028
INDIAN PT 1	223	1995	2009	2020
KEWAUNEE	175	1999	2012	2021
LASALLE CTY 1	1,375	1991	2022	2034
LIMERICK 1	926	2002	2025	2033
MAINE YANKEE	213	1997	2010	2018
MCGUIRE 1	322	2009	2018	2025
MILLSTONE 1	596	1987	2014	2023
NINE MILE PT1	213	1998	2021	2028
NORTH ANNA 1	563	2001	2017	2026
OCONEE 1	953	1987	2013	2025
OYSTER CRK 1	116	1997	2006	2016
PALISADES	280	1988	2009	2023
PALO VERDE 1	888	2008	2021	2029
PEACHBOTTOM 2	437	2000	2012	2018
PERRY 1	326	2010	2021	2029
PILGRIM 1	195	1995	2010	2019

TABLE A.7. (contd)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
POINT BEACH 1	320	1996	2010	2020
PRAIRIE ISL 1	498	1994	2013	2025
QUAD CITIES 1	244	2008	2011	2017
RANCHO SECO 1	75	2009	2013	2018
ROBINSON 2	244	1990	2008	2025
RVR BEND 1	281	2007	2019	2028
SAN ONOFRE 1	933	1996	2019	2030
SEABROOK 1	336	2011	2024	2031
SEQUOYAH 1	582	2000	2018	2029
SOUTH TEXAS 1	8	2022	2022	2022
ST LUCIE 1	470	1988	2017	2028
SUMMER 1	100	2014	2019	2022
SUSQUEHANNA 1	599	2004	2019	2029
TROJAN	152	2007	2014	2019
TURKEY PT 3	227	2004	2012	2017
VOGTLE 1	512	2011	2022	2030
VT YANKEE 1	116	2003	2010	2017
WASH NUCLEAR 2	392	2002	2020	2029
WATERFORD 3	181	2010	2020	2026
WATTS BAR 1	234	2015	2024	2030
WOLF CREEK 1	169	2013	2020	2026
ZION 1	699	1996	2013	2023
TOTAL	24,840			

(a) MRS Systems Study Task A, Schedule 17.

TABLE A.8. Storage Requirements by Site--Schedule 26^(a)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
ARK NUCLEAR 1	129	1997	2004	2009
BEAVER VALLEY 1	124	1997	2005	2015
BIG ROCK 1	6	1997	1999	2004
BRAIDWOOD 1	637	1996	2010	2031
BRUNSWICK 1	383	1991	2004	2017
CALLAWAY 1	28	2007	2007	2010
CALVERT CLF 1	331	1992	2004	2015
CLINTON 1	103	2005	2009	2016
COOK 1	261	1997	2004	2010
COOPER STN	85	2000	2005	2012
CRYSTAL RVR 3	162	1989	2004	2012
DAVIS-BESSE 1	105	1998	2006	2010
DUANE ARNOLD	27	2002	2004	2004
ENRICO FERMI 2	358	1997	2010	2028
FITZPATRICK	82	2000	2004	2005
FORT CALHOUN	52	1996	2003	2008
GINNA	7	2002	2002	2002
GRAND GULF 1	33	2008	2008	2008
HADDAM NECK	68	1998	2002	2004
HATCH 1	37	2004	2005	2006
HOPE CREEK	43	2002	2004	2005
INDIAN PT 1	134	1995	2003	2009
KEWAUNEE	58	1999	2003	2007
LASALLE CTY 1	783	1991	2008	2031
LIMERICK 1	324	2002	2012	2031
MAINE YANKEE	87	1997	2002	2004
MILLSTONE 1	344	1987	2002	2011
NINE MILE PT 1	61	1998	2001	2003
NORTH ANNA 1	142	2001	2005	2008
OCONEE 1	514	1987	2004	2013
OYSTER CRK 1	64	1997	2002	2002
PALISAOES	191	1988	2002	2012
PALO VERDE 1	115	2008	2009	2013
PEACHBOTTOM 2	99	2000	2003	2005
PILGRIM 1	106	1995	2004	2006
POINT BEACH 1	120	1996	2002	2006
PRAIRIE ISL 1	235	1994	2003	2014
ROBINSON 2	190	1990	2004	2013
RVR BEND 1	48	2007	2009	2013
SAN ONOFRE 1	511	1996	2008	2021
SEABROOK 1	40	2011	2012	2016
SEQUOYAH 1	209	2000	2007	2020
ST LUCIE 1	276	1988	2005	2019

TABLE A.8. (contd)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
SUSQUEHANNA 1	166	2004	2007	2010
WASH NUCLEAR 2	150	2002	2008	2020
ZION 1	<u>277</u>	1996	2003	2008
TOTAL	8,310			

(a) Same as Draft 1988 Mission Plan Amendment.

TABLE A.9. Storage Requirements by Site--Schedule 27^(a)

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
ARK NUCLEAR 1	30	1997	1999	2004
BEAVER VALLEY 1	76	1997	2003	2005
BIG ROCK 1	6	1997	1999	2001
BRAIDWOOD 1	506	1996	2007	2031
BRUNSWICK 1	290	1991	2001	2014
CALVERT CLF 1	265	1992	2001	2005
CLINTON 1	19	2005	2007	2009
COOK 1	130	1997	2001	2004
COOPER STN	48	2000	2002	2005
CRYSTAL RVR 3	132	1989	2001	2007
DAVIS-BESSE 1	53	1998	2002	2006
ENRICO FERMI 2	260	1997	2006	2029
FITZPATRICK	10	2000	2000	2001
FORT CALHOUN	32	1996	1999	2001
HADDAM NECK	32	1998	1999	1999
HOPE CREEK	9	2002	2002	2002
INDIAN PT 1	74	1995	1999	2003
KEWAUNEE	17	1999	2000	2003
LASALLE CTY 1	675	1991	2005	2031
LIMERICK 1	191	2002	2009	2031
MAINE YANKEE	36	1997	1999	2000
MILLSTONE 1	242	1987	2000	2008
NINE MILE PT 1	29	1998	1998	1999
NORTH ANNA 1	58	2001	2003	2003
OCONEE 1	405	1987	2001	2006
OYSTER CRK 1	12	1997	1997	1999
PALISADES	167	1988	2000	2009
PEACHBOTTOM 2	6	2000	2000	2000
PILGRIM 1	73	1995	2001	2001
POINT BEACH 1	63	1996	1999	2001
PRAIRIE ISL 1	167	1994	2000	2005
ROBINSON 2	151	1990	2001	2010
SAN ONOFRE 1	329	1996	2005	2013
SEQUOYAH 1	109	2000	2004	2009
ST LUCIE 1	223	1988	2002	2016
SUSQUEHANNA 1	53	2004	2005	2005
WASH NUCLEAR 2	75	2002	2004	2009
ZION 1	184	1996	2000	2003
TOTAL	5,240			

(a) MRS Systems Study Task A, Schedule 27.

TABLE A.10. Storage Requirements by Site--Schedule 31

<u>Pool Name</u>	<u>Site Peak (MTU)</u>	<u>First Year</u>	<u>Peak Year</u>	<u>Last Year</u>
ARK NUCLEAR 1	4	1997	1997	1997
BEAVER VALLEY 1	38	1997	1999	2001
BRAIDWOOD 1	378	1996	2027	2031
BRUNSWICK 1	169	1991	1998	2003
CALVERT CLF 1	162	1992	1998	2001
COOK I	32	1997	1998	1999
CRYSTAL RVR 3	101	1989	1998	2001
DAVIS-BESSE 1	27	1998	2000	2000
ENRICO FERMI 2	161	1997	2003	2028
FORT CALHOUN	7	1996	1997	1997
INDIAN PT 1	14	1995	1995	1998
LASALLE CTY 1	513	1991	2003	2031
LIMERICK 1	155	2002	2027	2030
MILLSTONE 1	176	1987	1995	2001
OCONEE 1	300	1987	1996	2001
PALISADES	117	1988	1996	2000
PILGRIM 1	31	1995	1995	1997
PRAIRIE ISL 1	80	1994	1997	2000
ROBINSON 2	113	1990	1998	2007
SAN ONOFRE 1	175	1996	2001	2005
SEQUOYAH 1	6	2000	2000	2000
ST LUCIE 1	192	1988	1998	2008
WASH NUCLEAR 2	24	2002	2002	2002
ZION 1	34	1996	1997	1998
TOTAL	3010			

APPENDIX B

METHODOLOGY FOR ESTIMATING STORAGE COSTS AT REACTORS SLATED FOR DECOMMISSIONING

APPENDIX B

METHODOLOGY FOR ESTIMATING STORAGE COSTS AT REACTORS SLATED FOR DECOMMISSIONING

The costs of continued spent fuel storage at shutdown reactor sites awaiting decommissioning were estimated based on current projections of at-reactor spent fuel generation and pool storage capabilities, and on annual storage cost estimates that were derived from past studies and adapted to specific reactor conditions (number of reactors at a site, use of out-of-pool storage facilities, etc.) The estimates of annual costs were based upon the projection of storage needs and locations. In developing the unit storage costs, it became evident that the costs of maintaining fuel storage at a site following shutdown were independent of the quantity of fuel stored. To a very close approximation, the operation and maintenance costs are the same for a near-empty pool or dry storage facility as for a full one.

B.1 DEVELOPMENT OF COSTS OF AT-SITE SPENT FUEL STORAGE

The principal categories of costs for long-term storage of spent fuel at shutdown reactors awaiting decommissioning are security coverage, operations required to maintain the reactor pools, and operation of any dry storage facilities. Direct staffing by the utility is assumed for these functions; required support functions including maintenance services, health physics coverage, and environmental monitoring, are assumed to be subcontracted to others and are separately costed. The bases and rationale for estimation of costs associated with required activities are discussed in the following sections. Components of the costs as developed are summarized in Table B.1 at the end of this appendix and are grouped in that table into applicable annual costs for varying situations relating to storage at a site.

In the following paragraphs, site costs associated with maintenance of a storage facility are discussed for a single-reactor site; modifications are then discussed to accommodate multiple-reactor sites, maintenance of an on-site storage field, and other variants.

B.1.1 Site Security Costs

NRC regulations require the presence of a five-person (minimum) armed response team on site at all times while spent fuel is present. At least one supervisor is also needed at all times. Thus, the minimum security force required at a single-reactor station is six persons per shift. To provide adequate coverage for four shifts including allowance for illness and vacations, a total of 23 guards and five supervisory personnel is required. This includes four standard shifts of five guards and one supervisor each, plus three guards and one chief of security added to the day shift. The annual costs for this security coverage are shown below and are summarized in Table B.1. The burdened salary costs (salaries plus appropriate overheads) used are based on estimated costs for the WNP-2 site in Richland, Washington.

B.1.2 Site Operating Costs

As previously mentioned, the operating utility is assumed to provide the minimum full-time staff required for plant operations and security; the staff is augmented by contracting for support services which require less than full-time staffing. Fees and prorated capital replacement allowances must be added to the total. Expected costs are detailed below.

Security Force Annual Costs

<u>Classification</u>	<u>No. Req'd.</u>	<u>Avg. Annual Salary^(a)</u>	<u>Total Annual Cost</u>
Guards	23	\$43,260	\$994,980
Supervisors	4	\$56,392	\$225,568
Chief	1	\$64,117	<u>\$ 64,117</u>
Total annual security cost (rounded)			\$1,285,000

(a) Salaries as listed are burdened (i.e., overheads are included).

Operating Staff - The main operational duties of the remaining utility staff are to monitor and control the largely automatic pool heat removal and radwaste treatment systems, and to routinely monitor radiation levels in the

pool and pool environment. These tasks are assumed to require a minimum staff of five operators (one per shift plus one relief operator) and one site supervisor.

Costs of maintaining this minimum staff are:

Operations Staff Annual Costs

<u>Classification</u>	<u>No. Req'd.</u>	<u>Avg. Annual Salary^(a)</u>	<u>Total Annual Cost</u>
Site Supervisor	1	\$67,980	\$67,980
Power Operators	5	\$60,255	<u>\$301,275</u>
Total annual staff cost (rounded)			\$370,000

(a) Salaries as listed are burdened (i.e., overheads are included).

Contractor Costs, Fees, etc. - The estimated costs from contracting of maintenance and surveillance tasks, licensing support, insurance, and capital replacement are:

Additional Site Operations Costs

<u>Cost Element</u>	<u>Annual Cost</u>
Environmental Surveillance (Contractor)	\$ 33,000
Maintenance (Contractor)	33,000
Health Physics (Contractor)	20,000
NRC License and Safeguards Inspections	20,000
Nuclear Liability Insurance	400,000
Equipment Replacement (prorated) ^(a)	10,000
Structural Maintenance (prorated) ^(a)	10,000

(a) Equipment replacement and building structural maintenance costs are estimated as prorations of equivalent periodic costs of \$50,000 every 5 years and \$200,000 every 20 years, respectively.

Taxes and state/local permitting or business license fees are not included in the above.

B.1.3 Costs With Differing Site Conditions

The costs discussed above are for quiescent pool storage (no activities involving fuel movement) at a single-reactor site with no dry storage. Additional cost factors were estimated to cover other circumstances; these are discussed below.

Out-of-Pool Storage - The concept of shutting down a site storage pool and storing all fuel in dry storage was not considered for this analysis, but could be preferred by some utilities if a long period of storage were anticipated. In this option, only one operator and a site supervisor would be required (day shift) for monitoring; costs for maintenance, health physics, and site refurbishment would also be considerably reduced, although a full security contingent would be needed. Estimated costs for this storage option are about \$1.89 million per year, somewhat lower than the costs for in-pool storage. However, the cost difference must be balanced against the cost of constructing the storage facility and subsequent addition of storage modules (casks or alternatives).

Operation of a dry storage facility as a supplement to in-pool storage at a site involves only the incremental costs directly required for storage operations. Essentially this requires one additional operator for monitoring the field and the casks or other storage modules; costs, from the above data, would be about \$60,000 plus a \$2000 allowance for maintaining the cask (or module) transporter in operable condition.

Costs at Multi-Reactor Sites - At multi-reactor sites, costs of maintaining storage facilities can be shared among the facilities, with the same or only slightly increased operations and security forces. For a two-reactor site, no increase is envisioned to be required; for three-reactor sites, additions of four security guards and four operators (one each per shift) is assumed to be needed. In addition, costs of regulatory inspections are assumed to increase at about \$2,500 per pool (all on-site facilities are assumed to be covered in a single inspection), and the replacement and refurbishing allowances are assumed to increase linearly with the number of

pool facilities at the site. Thus, total annual costs for sites with differing numbers of pools will vary slightly, as follows:

<u>Number of Storage Pools</u>	<u>Annual Cost</u>
One pool	\$2.18 million
Two pools	\$2.20 million
Three pools	\$2.70 million

In general, at multi-reactor sites the individual reactors are projected to reach end-of-life at different dates. Thus, one or more pools may be maintained for shutdown storage at an active site containing operating reactors. In such cases, only the direct costs of operating these pools are attributable to shutdown storage costs. These costs are estimated at \$414,000 annually for a single on-site pool, or \$621,000 for maintaining two shutdown pools at a site with a third reactor still operational.

Costs from the above discussion that were used in the analysis are summarized in Table B.1.

B.1.4 Costs of Outloading of Stored Fuel

At the end of a period of "quiescent" storage, the fuel must be shipped away from the site before final decommissioning can occur. Additional operating staff will be required for these activities. For a typical pool, the additions might involve five to six added crew, of which at least two must be licensed operators. Annual costs could range from about \$270,000 to \$350,000 per site. These crew members must, for any utility, be 1) maintained on the staff during the shutdown period, or 2) hired, trained and certified before unloading can commence. It is uncertain which option a utility might follow; equally uncertain is the degree to which such costs might be considered chargeable to DOE and which would be considered normal utility operations costs since the pool must be unloaded eventually, with or without delays. The added costs attributable to the unloading operations were not included in this analysis. If such costs were fully chargeable to the Waste Fund, the costs derived from this analysis would be low by about 10% to 15%.

TABLE B.1. Summary of Annual Cost Estimates for Maintaining Spent Fuel Storage in Shutdown Reactors Following End-of-Life^(a)

Situation at Reactor Site	Cost Element	No. of Reactors at Site		
		1	2	3
One reactor shut down	Shutdown pool only		414	414
Two reactors shut down	Shutdown pools only			621
All reactors shut down	Storage operations			
	Security	1285	1284	1457
	Supervisors	68	68	67
	Power Operators	301	301	603
	Envir. Surveillance	33	33	33
	Maintenance	33	33	33
	Health Physics	20	20	20
	NRC Inspections	20	23	25
	Nuclear Liab. Ins.	400	400	400
	Equipmt. Replacement	10	20	30
	Structural Maint.	10	20	30
	Total	2180	2202	2699
Storage field used (no pools operating)	Storage operations			
	Security	1284		
	Supervisor	68		
	Operator/Monitor	60		
	Envir. Surveillance	33		
	Maintenance	10		
	NRC Inspections	20		
	Nuclear Liab. Ins.	400		
	Equip/struct. repl.	10		
	Total	1886	1886	1886
Storage field used at shutdown reactor (other reactors in operation)	Incremental storage operations for field			
	Operator/Monitor	60		
	Transporter maint.	2		
	Total	62	62	

(a) Costs in thousands of 1987 dollars.

APPENDIX C

NWPAA PROVISIONS CONSTRAINING AN MRS

APPENDIX C

NWPAA PROVISIONS CONSTRAINING AN MRS

In amending the Nuclear Waste Policy Act of 1982 regarding the disposal of spent nuclear fuels and high-level radioactive wastes, the Nuclear Waste Policy Amendments Act (NWPAA) of 1987 establishes several constraints on a potential monitored retrievable storage (MRS) facility.

Section 142.(b) of the NWPAA authorizes the Secretary of Energy to site, construct and operate one MRS, subject to conditions enumerated under Sections 143 through 149. Section 148.(d)(1)-(4) includes the following explicit operating constraints to the MRS:

"(1) construction of [an MRS] may not begin until the [Nuclear Regulatory] Commission has issued a license for the construction of a repository...

"(2) construction of [an MRS] or acceptance of spent nuclear fuel or high-level radioactive waste shall be prohibited during such time as the repository license is revoked by the [Nuclear Regulatory] Commission or construction of the repository ceases;

"(3) the quantity of spent nuclear fuel or high-level radioactive waste at the site of [an MRS] at any one time may not exceed 10,000 metric tons of heavy metal until a repository under this Act first accepts spent nuclear fuel or solidified high-level radioactive waste; and

"(4) the quantity of spent nuclear fuel or high-level radioactive waste at the site of [an MRS] at any one time may not exceed 15,000 metric tons of heavy metal."

To determine the need for an MRS, the NWPAA establishes the MRS Commission (Section 143) and directs it to report on the need for an MRS, including a comparison of an MRS with the alternative of at-reactor storage. In its report on the comparison of the MRS with at-reactor storage, the MRS Commission is directed to take into consideration the impact on:

"(A) repository design and construction;

"(B) waste package design, fabrication and standardization;

"(C) waste preparation;

"(D) waste transportation systems;

"(E) the reliability of the national system for the disposal of radioactive waste;

"(F) the ability of the Secretary [of Energy] to fulfill contractual commitments...

"(G) economic factors...."

While the NWPAA establishes the MRS Commission and directs its report, the NWPAA does not make the establishment of an MRS facility dependent on the MRS Commission report (see Section 142). However, the Secretary of Energy is constrained by the NWPAA from site surveys and evaluation until the MRS Commission has made its report (Section 144 and 145).

APPENDIX D

SERVICE, FAILURE, AND REPAIR TIME ASSUMPTIONS FOR PROCESS SCHEDULING STORAGE SIMULATIONS

TABLE D.1. MRS Simulation Experiment Description and Process Data

Process Number	Process Function	Process Time (hr)	Mean Failure Time (hr)	Mean Repair Time (hr)
<u>MRS and Repository Facilities</u>				
1, 15	Move casks to pick up wastes	(a)	--	--
2, 16	Load Wastes into casks at site	22.84	--	--
3, 17	Move casks to MRS or repository	(a)	--	--
<u>MRS Facility</u>				
4, 5	Identify and inspect casks and send to cask lag storage			
	Rail	2.33	2,200	1
	Truck	1.83	2,200	1
6	Move cask into facility and prepare for unload			
	Rail	6.00	--	--
	Truck	4.91	--	--
6, 7	Unload contents of cask to HC lag storage and inspect	0.25/unit unloaded	2,000	24
	SF rail (21 PWR/48 BWR)			
	SF truck (3 PWR/7 BWR)			
	Consolidated rail (14 PWR/36 BWR)			
	Consolidated truck (1 PWR/3 BWR)			
8	Consolidate spent fuel			
	PWR (2/canister)	2.2	500	8
	BWR (5/canister)	5.4	500	8
8a	Volume-reduce NFBH (50% PWR 37.5% BWR)	0.375	5,000	8
9, 10	Canister waste and place in lag storage			
	PWR (MRS consolidated)	3.32	1,000	8
	BWR (MRS consolidated)	3.32	1,000	8
	PWR (reactor consolidated)	3.32	1,000	8
	BWR (reactor consolidated)	3.32	1,000	8
	PWR (intact-defective)	3.32	1,000	8
	BWR (intact-defective)	3.32	1,000	8
	NFBH	0.77	2,000	8
11	Bring in storage cask, load cask, and move to storage yard (18 canisters per cask)	7.91	8,760	120

TABLE D.1. (contd)

<u>Process Number</u>	<u>Process Function</u>	<u>Process Time (hr)</u>	<u>Mean Failure Time (hr)</u>	<u>Mean Repair Time (hr)</u>
<u>MRS Facility (continued)</u>				
11	Retrieve storage cask and prepare for unload	4.75	8,760	120
11	Unload storage cask (18/cask)	0.10/unit	8,760	120
12	Load MRS/Repository Rail Cask 28 canisters per cask	26.5	2,000	24
12	Move train to repository	(a)	--	--
<u>Repository Facility</u>				
18, 19	Identify and inspect shipments and move to lag storage			
	Western spent fuel--rail	2.33	2,200	1
	Western spent fuel--truck	1.83	2,200	1
	HLW--rail	2.33	2,200	1
	MRS canisters--rail	2.33	2,200	1
20	Move casks from lag storage and prepare for unload			
	Rail	6.00	--	--
	Truck	4.91	--	--
20, 21 22	Unload casks into lag storage (same SF capability as MRS casks) DHLW (5 canisters/cask) WVHLW (5 canisters/cask)	0.25/unit	2,000	24
23, 24 25	Move wastes to canning stations containerize and move to vault storage MRS waste (3 canisters per container) Intact PWR (4 assemblies per container) Consolidated PWR (4 canisters per container) Consolidated BWR (10 canisters per container)	3.00	1,000	8
26	Pick up containers from vault storage, transport canisters underground, emplace waste and return transporter	3.42	1,000	16

TABLE D.1. (contd)

Process Number	Process Function	Process Time (hr)	Mean Failure Time (hr)	Mean Repair Time (hr)
<u>Cask Servicing</u>				
13	Routine--at MRS			
	Rail	11.25	2,000	24
	Truck	7.82	2,000	24
27	Routine--at repository			
	Rail	11.25	2,000	24
	Truck	7.82	2,000	24
14	Fleet Maintenance (once every 10 trips)	10.00	2,000	24

- (a) Transport times to ship empty and full casks between waste sites and federal facilities vary because of distance, shipping mode and other factors. Cask shipment times are modelled in PNL's WASTES model. For this analysis cumulative probability distributions of shipping times were developed from WASTE runs for the MRS and No-MRS systems by waste type and shipment mode. The FASIT model randomly samples these distributions in order to develop shipping times. These probability distributions are shown below.

Shipments to MRS							
Eastern PWR--Rail		Eastern PWR--Truck		Eastern BWR--Rail		Eastern BWR--Truck	
Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)
0.019	84.95	0.049	2.22	0.105	134.84	0.195	10.82
0.072	112.17	0.124	5.36	0.214	159.88	0.311	21.85
0.142	118.77	0.224	21.85	0.265	160.48	0.572	27.58
0.188	140.71	0.341	24.80	0.353	175.41	0.669	34.62
0.387	159.50	0.423	25.17	0.490	180.93	0.794	35.80
0.563	172.88	0.704	35.74	0.535	188.54	0.802	38.09
0.682	182.41	0.795	35.99	0.645	204.37	0.840	42.93
0.759	208.83	0.825	38.11	0.646	211.56	0.912	43.21
0.876	249.17	0.988	41.67	0.951	220.35	0.944	45.45
1.000	313.06	1.000	45.81	1.000	266.48	1.000	46.92

TABLE D.1. (contd)

Shipments to Repository (Yucca Mountain, Nevada)							
Western PWR--Rail		Western PWR--Truck		Western BWR--Rail		Western BWR--Truck	
Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)
0.488	26.11	0.311	129.15	0.000	236.76	0.000	45.10
0.761	30.98	0.750	167.06	0.500	246.76	0.500	46.10
1.000	46.10	1.000	300.46	1.000	256.67	1.000	47.10

DHLW--Rail		WVHLW--Rail		Dedicated Rail from MRS	
Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)
0.375	186.33	0.000	489.0	0.000	80.50
0.516	273.10	0.500	539.0	0.500	85.50
1.000	520.0	1.000	589.0	1.000	90.50

TABLE D.2. No-MRS Simulation Experiment Description and Process Data

Process Number	Process Function	Process Time (hr)	Mean Failure Time (hr)	Mean Repair Time (hr)
<u>Repository Facilities</u>				
1	Move casks to sites to pick up waste	(a)	--	--
2	Load wastes into casks at site	22.84	--	--
3	Move casks to repository	(a)	--	--
4, 5	Identify and inspect casks and send to cask lag storage			
	Rail	1.25	2,200	1
	Truck	1.25	2,200	1
	Move cask into facility and prepare for unload			
6	WHB 1	4.5	--	--
11	WHB 2	4.5	--	--
<u>WHB 1</u>				
6, 7	Unload HLW into HLW lag storage (5 canisters/cask)	0.08/unit	2,000	24
	Move HLW to containerization cell, containerize and move to vault storage	5.25	1,000	8
10	Remove HLW container from vault storage, transport underground, emplace container and return transporter	3.42	1,000	16
<u>WHB 2</u>				
11, 13	Unload spent fuel into lag storage carts			
	Intact fuel--rail (21 PWR/48 BWR)	0.17/unit	2,000	24
	Intact fuel--truck (3/7)	0.2/unit	2,000	24
	Reactor consolidated fuel (14/36 rail) (1.3 truck)	0.17/unit	2,000	24
12	Containerize defective and consolidated fuel in unloading hot cell and move canisters to vault storage (3 PWR/canister, 6 BWR/canister)	6.33	1,000	8

TABLE D.2. (contd)

Process Number	Process Function	Process Time (hr)	Mean Failure Time (hr)	Mean Repair Time (hr)
<u>WHB 2 (continued)</u>				
14	Move lag storage carts to process hot cells and consolidate fuel			
	PWR (6/canister)	9.0	500	8
	BWR (18/canister)	21.0	500	8
15, 16	Containerize consolidated fuel and move to surface vault storage			
	PWR	6.33	1,000	8
	BWR	6.33	1,000	8
10	Unload waste from surface vault storage, transport underground, emplace container in vertical borehole and return transporter	3.42	1,000	16
<u>Cask Servicing</u>				
17	Routine at repository, all casks	5.0	2,000	24
18	Fleet maintenance (once every 10 trips)	10.0	2,000	24

(a) Transport times to ship empty and full casks between waste sites and federal facilities are calculated using the distributions below.

Shipments to Repository (Yucca Mountain, Nevada)

<u>PWR--Rail</u>		<u>PWR--Truck</u>		<u>BWR--Rail</u>		<u>BWR--Truck</u>	
Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)	Cumulative (%)	Time (hr)
0.080	398.40	0.142	59.76	0.168	610.56	0.111	102.72
0.125	538.08	0.192	67.20	0.201	619.44	0.156	122.64
0.178	590.16	0.216	74.88	0.389	646.80	0.204	134.40
0.436	618.00	0.231	119.28	0.434	688.32	0.263	143.76
0.459	656.16	0.274	139.20	0.532	702.00	0.371	154.80
0.572	679.92	0.339	156.72	0.588	709.92	0.384	172.56
0.843	704.40	0.376	168.48	0.967	711.84	0.670	191.76
0.899	717.60	0.518	180.96	1.000	731.04	1.000	197.28
0.973	733.68	0.735	191.76				
1.000	746.16	0.861	198.00				
		0.946	204.96				
		1.000	213.12				

TABLE D.2. (contd)

<u>DHLW--Rail</u>		<u>WVHLW--Truck</u>	
<u>Cumulative</u>	<u>Time</u>	<u>Cumulative</u>	<u>Time</u>
<u>(%)</u>	<u>(hr)</u>	<u>(%)</u>	<u>(hr)</u>
0.375	186.33	0.00	489.0
0.516	273.10	0.50	539.0
1.000	520.0	1.00	589.0

APPENDIX E

ACCEPTANCE-RELATED STORAGE REQUIREMENTS
AT THE MRS

TABLE E.1. Acceptance-Related Storage Requirements at the MRS

Schedule Number (a)	Maximum MRS Inventory (MTU)		Years of Peak Inventory	Total Storage Required (MTU-yr)		Total Duration of Storage (yr)	Maximum Spent Fuel Inventory as Fraction of MRS Design Capacity (%)
	Spent Fuel	HLW		Spent Fuel	HLW		
1	NA						
2	5,200		18	110,740		24	35
3	13,300		15	283,600		27	89
4	14,050		15	300,850		28	94
5	13,300		15	283,600		27	89
6	21,400		12	456,460		30	143
7	22,150		12	473,710		31	148
8	NA						
9	5,200		18	110,740		24	35
10	13,300		15	283,600		27	89
11	14,050		15	300,850		28	94
12	26,800		10	571,700		32	179
13	34,900		7	744,560		35	233
14	21,400		12	456,460		30	143
15	35,650		7	761,810		36	238
16	22,150		12	473,710		31	148
17	NA						
18	5,200		18	110,740		24	35
19	13,300		15	283,600		27	89
20	14,050		15	300,850		28	94
21	40,300		5	859,800		37	269
22	48,400		2	1,032,660		40	323
23	34,900		7	744,560		35	233
24	49,150		2	1,049,910		41	328
25	35,650		7	761,810		36	238
26	5,200		18	110,740		24	35
27	14,200		15	299,800		27	95
28	14,950		15	317,050		28	100
29	14,200		15	299,800		27	95
30	23,200		12	488,860		30	155
31	23,950		12	506,110		31	160
32	5,200		18	110,740		24	35
33	14,200		15	299,800		27	95
34	14,950		15	317,050		28	100
35	29,200		10	614,900		32	195
36	38,200		7	803,960		35	255
37	23,200		12	488,860		30	155
38	38,950		7	821,210		36	260
39	23,950		12	506,110		31	160
40	5,200		18	110,740		24	35
41	14,200		15	299,800		27	95
42	14,950		15	317,050		28	100
43	44,200		5	930,000		37	295
44	53,200		2	1,119,060		40	355
45	38,200		7	803,960		35	255
46	53,950		2	1,136,310		41	360
47	38,950		7	821,210		36	260
48	5,200	0	18	110,740	0	24	35
49	13,300	1,200	15	283,600	20,940	27	89
50	14,050	1,200	15	300,850	20,940	28	94
51	13,300	1,200	15	283,600	20,940	27	89
52	21,400	2,400	12	456,460	41,880	30	143
53	22,150	2,400	12	473,710	41,880	31	148
54	5,200	0	18	110,740	0	24	35
55	13,300	1,200	15	283,600	20,940	27	89
56	14,050	1,200	15	300,850	20,940	28	94
57	26,800	3,200	10	571,700	55,840	32	179
58	34,900	4,400	7	744,560	76,780	35	233

TABLE E.1. (contd)

Schedule Number ^(a)	Maximum MRS Inventory (MTU)		Years of Peak Inventory	Total Storage Required (MTU-yr)		Total Duration of Storage (yr)	Maximum Spent Fuel Inventory as Fraction of MRS Design Capacity (%)
	Spent Fuel	HLW		Spent Fuel	HLW		
59	21,400	2,400	12	456,460	41,880	30	143
60	35,650	4,400	7	761,810	76,780	36	238
61	22,150	2,400	12	473,710	41,880	31	148
62	5,200	0	18	110,740	0	24	35
63	13,300	1,200	15	283,600	20,940	27	89
64	14,050	1,200	15	300,850	20,940	28	94
65	40,300	5,200	5	859,800	90,740	37	269
66	48,400	6,400	2	1,032,660	111,680	40	323
67	34,900	4,400	7	744,560	76,780	35	233
68	49,150	6,400	2	1,049,910	111,680	41	328
69	35,650	4,400	7	761,810	76,780	36	238
70	5,200	0	18	110,740	0	24	35
71	14,200	1,200	15	299,800	20,940	27	95
72	14,950	1,200	15	317,050	20,940	28	100
73	14,200	1,200	15	299,800	20,940	27	95
74	23,200	2,400	12	488,860	41,880	30	155
75	23,950	2,400	12	506,110	41,880	31	160
76	5,200	0	18	110,740	0	24	35
77	14,200	1,200	15	299,800	20,940	27	95
78	14,950	1,200	15	317,050	20,940	28	100
79	29,200	3,200	10	614,900	55,840	32	195
80	38,200	4,400	7	803,960	76,780	35	255
81	23,200	2,400	12	488,860	41,880	30	155
82	38,950	4,400	7	821,210	76,780	36	260
83	23,950	2,400	12	506,110	41,880	31	160
84	5,200	0	18	110,740	0	24	35
85	14,200	1,200	15	299,800	20,940	27	95
86	14,950	1,200	15	317,050	20,940	28	100
87	44,200	5,200	5	930,000	90,740	37	295
88	53,200	6,400	2	1,119,060	111,680	40	355
89	38,200	4,400	7	803,960	76,780	35	255
90	53,950	6,400	2	1,136,310	111,680	41	360
91	38,950	4,400	7	821,210	76,780	36	260
MRS Proposal	14,700	N/A	16	333,900	N/A	30	98

(a) MRS Systems Study Task A report.

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R. W. McKee
D. R. Payson
M. R. Shay
R. I. Smith
M. G. Woodruff
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