Conf-911040--16

DISCLAIMER

PNL-SA--19194

DE92 015151

EFFECTS OF SPENT NUCLEAR FUEL AGING ON DISPOSAL REQUIREMENTS

R. W. McKee
K. I. Johnson
H. D. Huber
M. C. Bierschbach

October 1991

For presentation at the
1991 Joint International Waste Management Conference
October 21-26, 1991
Seoul, Korea

Work Supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

EFFECTS OF SPENT NUCLEAR FUEL AGING ON DISPOSAL REQUIREMENTS

R. W. McKEE
Pacific Northwest Laboratory
P.O. Box 999, K6-25
Richland, WA 99352
(509) 376-1309

K. I. JOHNSON
Pacific Northwest Laboratory
P.O. Box 999, K5-22
Richland, WA 99352
(509) 376-2241

H. D. HUBER
Pacific Northwest Laboratory
P.O. Box 999, K6-25
Richland, WA 99352
(509) 376-1309

M. C. BIERSCHBACH
Pacific Northwest Laboratory
P.O. Box 999, K6-25
Richland, WA 99352
(509) 376-7254

ABSTRACT

This paper describes results of a study to analyze the waste management systems effects of extended spent fuel aging on spent fuel disposal requirements. The analysis considers additional spent fuel aging up to a maximum of 50 years relative to the currently planned 2010 repository startup in the United States.

As part of the analysis, an equal energy deposition (EED) methodology was developed for determining allowable waste emplacement densities and waste container loading in a geologic repository.

Results of this analysis indicate that substantial benefits of spent fuel aging will already have been achieved by a repository startup in 2010 (spent fuel average age will be 28 years). Even so, further significant aging benefits, in terms of reduced emplacement areas and mining requirements and reduced number of waste containers, will continue to accrue for at least another 50 years when the average spent fuel age would be 78 years, if the repository startup is further delayed.

INTRODUCTION

A study has been carried out at Pacific Northwest Laboratory (PNL)[1] to analyze waste management system effects of extended spent fuel aging on spent fuel disposal requirements. The study results indicate significant as well as unexpected benefits. The most significant impacts relate to the repository.

As a result of radionuclide decay, spent fuel aging reduces the amount of heat generated from the waste, which in turn, can reduce the repository mined areal requirement (that is, the actual underground area required for waste disposal). Alternatively, this could permit reduced peak temperatures to be specified. Although the general effect is well known, the magnitude of the benefit of additional aging for spent fuel already aged more than 20 years has not been recognized.

DELIVERED SPENT FUEL CHARACTERISTICS

Two key spent fuel characteristics that vary with age are important to the repository. These are the heat release rate at the time of emplacement in the repository, referred to as thermal power (kW/MTU), and the thermal energy (kW-yr/MTU) released over a period of time. The thermal power declines as the radioactive elements in the spent fuel decay, and the thermal energy release is determined by integrating the thermal power release over a specified period of time. These characteristics can vary substantially over the entire inventory of spent fuel as it is delivered to the repository.

Thermal Power

The thermal power generated by any batch of spent fuel depends on both its exposure (MWd/MTU) in a nuclear reactor and its age since reactor discharge. It varies almost linearly with fuel exposure at any specific spent fuel age over much of the range from 10 to 60 GWd/MTU and over an age range from 5 to 200 years, as shown in Figure 1.[1]

Thermal Energy

Thermal energy release is a particularly important property because much of the thermal effect of spent fuel on the repository environment is controlled more by the integrated thermal energy deposited in the repository over a period of time than by the initial thermal power at the time of emplacement.

Spent fuel continues to release heat energy, but at continuously declining rates, over hundreds and thousands of years. Thus, the integrated energy release continues to increase the longer the integration period. However, with respect to a repository in tuff, a 100-year energy release period was found in this study to be an important characteristic. Just as exposure directly increases thermal power, so does exposure directly increase the integrated thermal energy release. This is illustrated in Figure 2 for

[1]Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

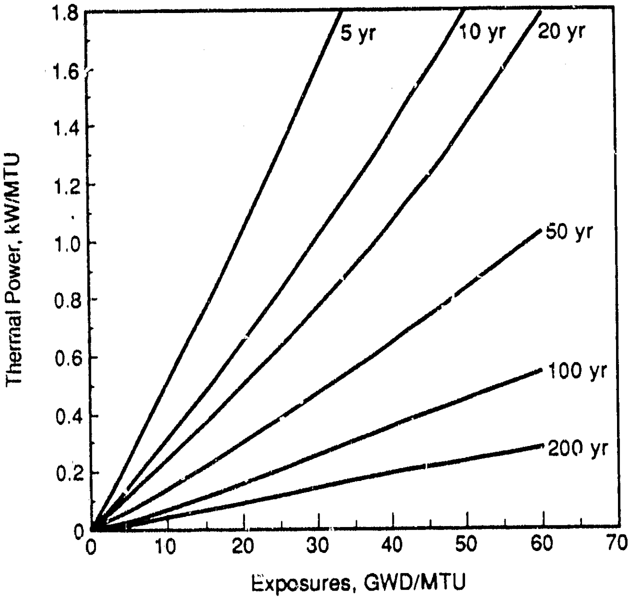

Fig. 1 Effect of fuel exposure on spent fuel thermal power at several specified ages[1]

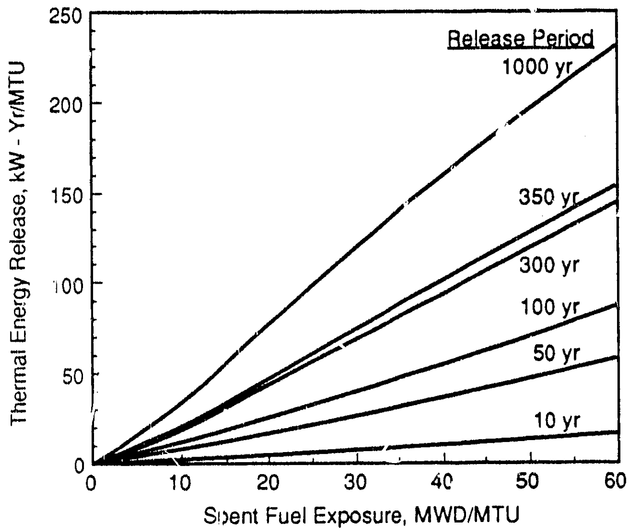

Fig. 2 Effect of fuel exposure on thermal energy release from 20-year-old spent fuel over a range of energy release periods[1]

an example 20-year-old spent fuel. The effect of spent fuel age on thermal energy release is illustrated in Figure 3 for an example spent fuel exposed to 35,000 MWd/MTU.

The relationship between thermal energy release and spent fuel exposure above 10,000 MWd/MTU is approximately linear (Figure 2), and the relationship between thermal energy release and spent fuel age is close to linear over the limited age span of 20 to 50 years in spent fuel mixtures. Because of these relationships, use of average age and exposure to calculate energy release from complex mixtures of

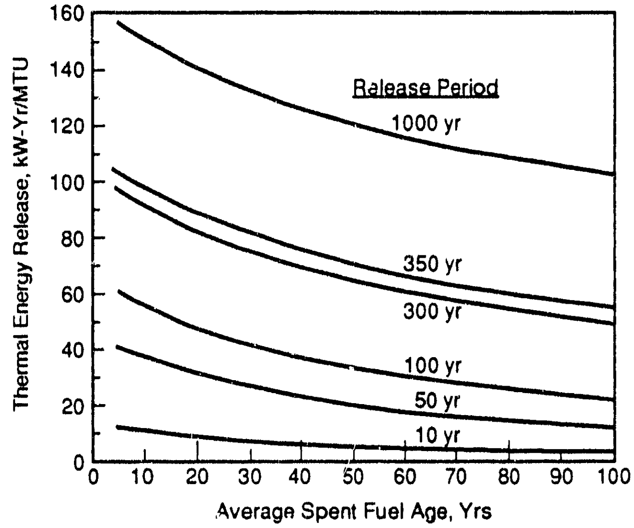

Fig. 3 Effect of spent fuel age on thermal energy release from spent fuel exposed to 35,000 MWd/MTU over a range of energy release periods[1]

spent fuel characteristics produces an energy value very close to this actual weighted average energy release value for these mixtures.

Delivered Spent Fuel Characteristics

The characteristics of spent fuel delivered to the repository will vary over time and will depend on its irradiation history during power production, on the time when the repository opens, on the rate of spent fuel deliveries, and on the spent fuel delivery sequence. Consideration here is limited to the current 120 nuclear reactors in the United States either operating, in startup, under construction, or shut down. The spent fuel irradiation histories as developed by the U.S. DOE's Energy Information Agency (EIA) for their No-New-Orders Case spent fuel discharge projection[2] and described in DOE's Spent Fuel Storage Requirements Report[3] were used as the basis for determining spent fuel characteristics at the time of reactor discharge.

Spent fuel is assumed to be received at the first repository at a rate of 3,000 MTU/yr, following an initial startup phase, and receipts are limited to 63,000 MTU out of a total of 83,800 MTU of projected life cycle discharges from the 120 power reactors. The 63,000 MTU is the commercial spent fuel share of the 70,000 MTU capacity of the first repository. The other 7,000 MTU is allocated for vitrified high-level waste (HLW), which is mostly defense program wastes. The spent fuel is delivered over a 25-year period. With these factors fixed, the effects on spent fuel characteristics of repository startup date and spent fuel selection sequence were examined using the WASTES[4] model which tracks projected spent fuel discharges and characteristics through the waste management system.

By selecting a mix of young and old, high- and low-exposure spent fuel each year, a nearly uniform or energy-levelized spent fuel stream can be delivered, either directly from the reactors or from the MRS. As a result of levelizing, the repository emplacement requirements can be more nearly uniform each year and this will mitigate any limitations that could otherwise develop with respect to requirements for emplacing either very cold or very hot spent fuel. It is assumed here that agreement can be reached between DOE and the utilities on such a delivery sequence, that benefits efficient use of the repository, as long as the rights for the quantities of annual spent fuel deliveries are determined on an oldest fuel first (OFF) basis.

Several different energy-levelizing techniques are available and many different spent fuel mixtures will yield reasonably levelized mixtures. As an example, the annual delivered 100-year energy release for two different levelizing scenarios is compared in Figure 4 with results for an OFF scenario. The average age, exposures, and average 100-year energy release for the same three spent fuel delivery scenarios are compared in Table 1. This table shows that these average characteristics are similar whether levelized or not and that, as discussed previously, the weighted average energy release is close to the energy release value that is calculated based on average age and exposure.

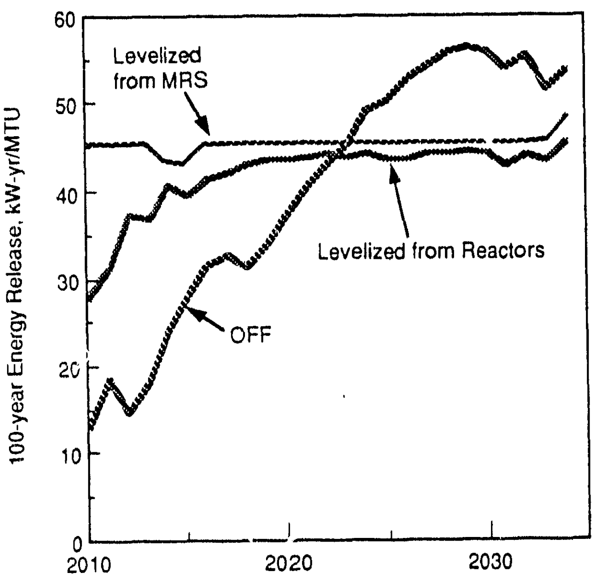

Fig 4. Effect of selection scenario on 100-year energy release from annual spent fuel deliveries for a 2010 Repository Startup

Table 1 Effect of spent fuel selection scenario on weighted average characteristics (2010 repository)

	Strict OFF	Levelized from Reactors	Levelized from MRS
Average SF Age, year	28.7	27.3	27.7
Average SF Exposure MWd/MTU	35,600	34,000	35,600
100-yr Energy Release			
Weighted Average	43.9	43.1	45.4
Based on Average Age and Exposure	43.0	41.8	44.3

Averaging Assumption

As a result of the relationships just discussed, and to simplify the analysis of spent fuel age effects, it was assumed 1) that the energy-levelized mixtures of spent fuel that could be delivered to the repository at 10-year aging intervals from 2010 to 2060 could be represented by the average age and exposure values shown in Table 2, and 2) that the average energy release from the spent fuel could be determined from these average age and exposure values.

Table 2 Assumed spent fuel characteristics for this analysis

Repository Start Date	Average Spent Fuel Age, year	Average Spent Fuel Exposure GWd/MTU	Average 100-yr Energy, kW-yr/MTU
2010	28.0	35.0	42.6
2020	38.0	35.0	37.8
2030	48.0	35.0	33.9
2040	58.0	35.0	30.6
2050	68.0	35.0	28.0
2060	78.0	35.0	25.9

REPOSITORY THERMAL CONSTRAINTS

Because of the variability in the rock properties in the proposed repository, there are significant uncertainties in evaluations of thermal loadings imposed by spent fuel emplacement. The thermal properties of the rock, especially its thermal conductivity, its variability with temperature, and its dependence on the degree of pore-water saturation, are not yet known with certainty. In addition, the possibility of two-phase heat transfer through vaporization and condensation of pore water adds additional uncertainty. To compensate for these uncertainties, temperature limits have been conservatively developed. The determination of waste emplacement requirements is the subject of continuing investigations.

Current Thermal Loading Goals

It has been determined[5] that a gross thermal loading or areal power density (APD) of 57 kW/acre for design-basis spent fuel, i.e., 10-year-old pressurized water reactor (PWR) spent fuel exposed to 33,000 MWd/MTU, will satisfy all current thermal goals for the proposed repository. However, recent work at Sandia National Laboratory has indicated that it may be possible to meet thermal constraints with APDs as high as 80 kW/acre for design basis spent fuel.[6]

The significant repository thermal goals considered in this analysis are the same goals used in developing the underground layouts for the Yucca Mountain Site Characterization Plan.[5,7] These include a peak borehole temperature limit of 235°C, a 200°C temperature at 1 meter into the rock from the borehole, a 115°C limit at the Calico Hills strata interface a minimum of 60 meters below the repository, and a performance goal of ensuring that the borehole wall temperature remains above the boiling point of water for at least 300 years.

This last goal appears to be somewhat at odds with any possible benefits of spent fuel aging, but this analysis has shown that this is not necessarily the case.

Equivalent Peak Temperature Rise Concept

A concept identified as the "equivalent peak temperature rise concept" (EPTR)[5] has been developed by the Yucca Mountain Project for adjusting the design basis APD limit of 57 kW/acre for the varying age and burnup characteristics of spent fuel that would be received by the repository. This EPTR concept is based on the assumption that, when emplacing spent fuel with different age and exposure characteristics, "if the peak temperature rise at the center of the repository region for both cases was equivalent, the thermo-mechanical effects would be the same."[8]

Tables are provided in the DOE draft Yucca Mountain Reference Information Base (YM RIB), based on the EPTR concept, that provide adjustments for age and exposure for spent fuel loadings in the repository in terms of MTU/acre over a range of ages from 5 to 30 years and a range of exposures from 5,000 to 60,000 MWd/MTU. However, with a currently planned repository startup in the year 2010, the average waste age is already approaching 30 years. Thus, the YM RIB tables do not provide a basis for estimating the repository loading requirements for any significant additional spent fuel aging.

Equal Energy Deposition Concept

To provide for estimating possible increased repository waste loadings for aged spent fuel that would extend farther than the 5- to 30-year age tables in the YM RIB, a method defined as an EED concept was utilized. It was postulated that equal energy deposition from the spent fuel over equal time periods should equate to equal thermal affects. For example, if a 100-year period is required to reach a constraining peak temperature for a reference repository waste loading, then any other waste loading that deposits the same thermal energy over a 100-year period should produce a comparable peak temperature. Because of differences in heat decay characteristics with spent fuel age, this relationship is not exact; however, a very good first approximation of the effect of spent-fuel aging on allowable repository waste loadings can be made using this EED concept.

To use this EED methodology, it is necessary to know the approximate time period required to reach the limiting peak temperature for a reference condition. As a guide, time ranges to reach critical peak temperatures are provided in Table 3. For loadings of substantially aged spent fuel, these time periods are generally longer.

Table 3 Approximate times to reach maximum repository temperatures (with vertical waste emplacement)

Critical Temperatures	Time to Maximum Temperature, Year
Canister Centerline	1 to 10
Emplacement Borehole Wall	5 to 30
One Meter from Borehole	10 to 50
Strata Interface (Calico Hills/Topapa Springs)	300 to 1000
Average at Center of Repository	50 to 120

To illustrate the leverage that spent fuel age at repository emplacement can have on energy deposition values, and thus inferentially the effect on peak temperatures or repository loadings, the plot in Figure 5 is provided. The ratio of energy deposition

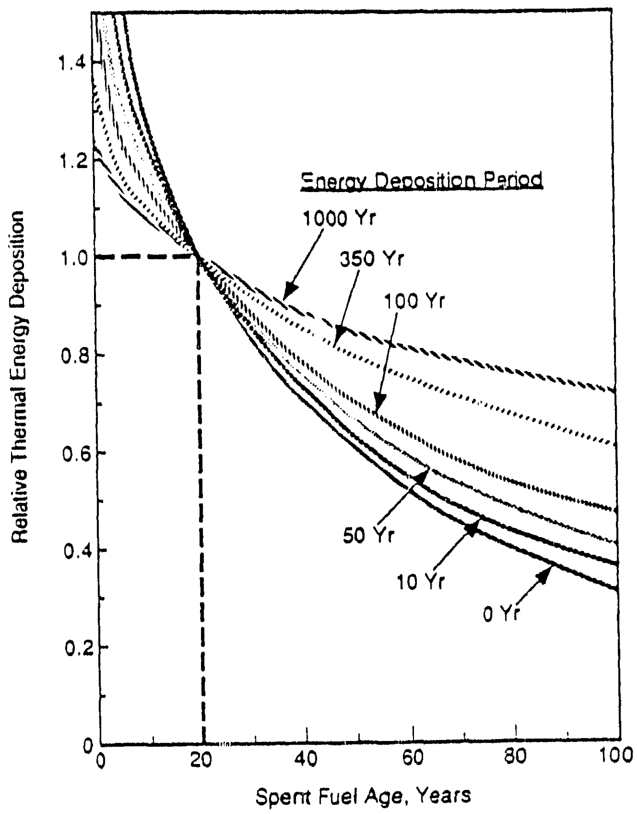

Fig. 5 Effect of age at emplacement on thermal energy deposition ratios relative to deposition from 20-year-old spent fuel for selected energy deposition periods

relative to energy deposition from 20-year-old spent fuel is plotted against spent fuel age for several selected deposition periods ranging from 0 to 1,000 years. It was found that these ratios, over the ranges of 10 to 60 GWd/MTU and 5- to 100-year-old spent-fuel, are essentially indifferent to exposure.

The relative decline in the thermal energy deposition values in Figure 5 is a measure of the achievable increased repository loadings possible as spent fuel ages. For example, if one uses the average peak temperature at the center of the repository as the criterion for waste loading limits as in the EPTR concept, and assumes that this peak temperature is reached in about 100 years, an additional 50 years aging of 20-year-old spent fuel would reduce the 100-year energy deposition by more than 40% and would indicate about a 70% increase in allowable areal waste loadings or substantial reductions in peak temperatures. Considering some of the shorter times required to reach maximum temperatures shown in Table 1, even larger gains would be indicated if the critical limiting temperature is taken to be either the borehole wall temperature or the canister centerline temperature, or even the temperature one meter from the borehole wall.

Another important observation with respect to the EED concept is that, if waste is emplaced to achieve an equal energy deposition at, say 100 years, the energy deposition over longer time periods for older waste will always be greater, thus inferring that the longer-term temperatures will be higher.

This is an important consideration relative to achieving the goal of maintaining long-term repository temperatures above the boiling point of water.

Comparison of the EED and EPTR Procedures

To check the validity of the EED procedure relative to the EPTR procedure for estimating allowable repository loadings, allowable spent fuel loadings based on a constant 100-year energy deposition were calculated and compared with the results of the EPTR method as presented in the YM RIB tables. The 100-year period was used because this is the approximate time after waste emplacement when the calculated average temperature at the center of an emplacement panel reaches a peak. The results using the EED method agree with the results from the EPTA method very closely. Over the entire range in the YM RIB tables, for both PWR and BWR spent fuel, none of the values differed by more than 4.4%, and most values differed by less than 1%. Thus, the EED method using a 100-year energy deposition period, is equivalent to the EPTR method, at least over the 0 to 30-year range for which EPTR results were available. However, results of the repository loading and heat transfer calculations presented in the following discussion indicate that this 100-year EED methodology produces quite conservative loading results relative to borehole wall peak temperature limits.

REPOSITORY CONCEPT

The underground layout of the conceptual repository is based on information provided in the Yucca Mountain Site Characterization Plan (SCP).[5,7] Both horizontal emplacement in the emplacement room walls and vertical waste emplacement in the emplacement room floors were considered in the SCP. This analysis is based on the layout for vertical emplacement of spent fuel containers.

The conceptual repository consists of a series of waste emplacement panels containing waste emplacement drifts or rooms and an area dedicated to support and test facilities. The total conceptual repository area is about 1420 acres of which approximately 180 acres is required for support and test facilities, main drifts and the unused standoff areas between the main drifts and emplacement drifts. This leaves approximately 1240 acres of panel area available for waste emplacement. A minimum emplacement borehole spacing of 7.5 feet has been established for structural integrity.

The reference spent fuel disposal containers assumed for this analysis are based on the containers defined in the 1988 MRS System Studies[9] for intact spent fuel assembly containerization at the repository. The principal container is the one that holds three PWR and four boiling-water reactor (BWR) intact assemblies. This ratio of PWR to BWR assemblies is close to the overall average for spent for fuel deliveries. To take care of any leftover PWR or BWR assemblies, either a 4 PWR or 10 BWR assembly container is used. The overall average weight of contained initial uranium is 2.0 MTU. All three containers have 28-inch diameters.

REPOSITORY LOADING CALCULATIONS

Repository loading limits for repository startups from 2010 to 2060 were calculated at 10-year intervals based on the 100-year EED methodology and disposal of 63,000 MTU of spent fuel. The total repository waste inventory also includes 7,000 MTU equivalent of vitrified HLW. However, the heat output from these containers is very low, no more than 0.1 to 0.2 kW/container, and it is assumed here that these HLW containers can be co-emplaced in horizontal boreholes in the same rooms as the vertically emplaced spent fuel.

The results indicated a significant reduction in emplacement area requirements as spent fuel ages. The repository delay from 1998 to 2010 has already reduced the emplacement area requirement to 1060 acres. A delay to a 2030 startup would reduce the areal requirement by another 200 acres, and a delay to 2060 would reduce the required panel area by more than 400 acres relative to the 1060 acres waste emplacement area required for a 2010 repository.

Reductions in the emplacement area can have two benefits: 1) it can allow for an increased repository capacity, or 2) it can reduce the mining requirement, or some combination of these. Reductions in the mining requirement can be a significant cost consideration but can only be achieved if emplacement borehole spacing can be reduced. Starting with the 126-foot emplacement room pitch specified in the SCP/CDR design concept,[5,7] the required borehole and room pitch for these repository delay cases was calculated. The results in Table 4 show that mined volume reductions could not be achieved with the 2.0 MTU reference waste package assumption for delays beyond the year 2030. At that point, the 7.5-foot minimum allowable borehole pitch would be reached and an approximate 20% reduction in mined volume relative to a 2010 startup would be realized. Mined volume reductions might be achieved for delays beyond the year 2030 if a higher waste package loading could be used.

Another potential benefit of the aging delay was indicated by the last column of Table 4 where the

Table 4 Effect of spent fuel aging on the waste emplacement configurations

Startup, yr	SF Age,	Area Required, Acres[1]	Emplacement Room Pitch, ft	Borehole Pitch, ft	300-yr Energy kW-yr/Acre
2010	28	1059	126	9.2	4520
2020	38	939	126	8.2	4700
2030	48	842	123	7.6	4870
2040	58	761	111	7.5	5050
2050	68	696	102	7.5	5210
2060	78	643	94	7.5	5350

[1]Area determined by the 100-year EED.

areal energy deposition at 300 years is shown. Although the 100-year energy deposition is held constant, the 300-year energy deposition increases. This results because the 300-year energy is not reduced proportionately as much with aging as the 100-year energy deposition (see Figure 5). This is an indication of higher near field temperatures after 300 years and infers improved prospects for maintaining borehole region temperatures above the boiling point of water for at least 300 years.

Confirming Heat Transfer Calculations

To test the validity of emplacement densities based on the 100-year EED methodology, the transient thermal analysis capabilities of the ANSYS finite element code[10] were used to model the conduction of heat from the waste package through the host rock and to estimate critical temperatures over time.

A three-dimensional, transient, heat conduction model was constructed to estimate temperatures related to a single borehole through time, and a one-dimensional transient heat conduction model was constructed to estimate average temperature at the center of the repository through time.

The results showed borehole wall temperatures ranging from 194°C for a 2010 startup to 177°C for a 2060 startup, thus indicating substantial potential for higher container loadings relative to the 235°C goal. The temperature 1 meter into the rock was also well below its limit. However, the strata interface temperature 60 meters below the repository exceeded its 115°C limit for startup dates of 2030 and later, indicating that all of the repository area reductions shown in Table 4 might not be achievable. The borehole wall temperature at 300 years increased as the startup was delayed, confirming that it would be easier to maintain temperatures above 97°C to 100°C for well beyond 300 years through the higher emplacement densities made possible by aging spent fuel.

These results suggested that a more optimum repository loading for aged spent fuel should consider higher waste container loadings to minimize the number of waste packages and somewhat lower areal loadings for startup years of 2030 and later to avoid exceeding a 115°C strata interface temperature limit.

Higher Waste Container Loadings

To provide for long-lived waste containers, high nickel and nickel-copper alloys are now being considered for the repository container material. These are anticipated to be at least a factor of two more costly than the stainless steel containers previously specified. Thus, higher container loadings may be quite important since costs for the stainless-steel containers amount to about $1 billion. These higher loadings could be achieved either through spent fuel rod consolidation or by use of larger containers for intact assemblies. However, rod consolidation would be the most container efficient approach. With a two-to-one volume reduction, more than 6 MTU of spent fuel rods could be placed in a 28-inch-diameter container for a three-fold reduction in container requirements. Cladding temperature constraints for central fuel rods might be a limitation, but with aged spent fuel, this is unlikely.

To develop a set of cases that takes advantage of higher container loadings, spent fuel loadings were developed using EED methodology. The waste package loading was determined on the basis of maintaining a constant 100-year energy deposition from each waste package relative to an SCP[5] reference package. (The reference package was loaded with consolidated 10-year-old spent fuel producing 3.0 kW of thermal power.) The 100-year energy deposition basis is a conservative waste container loading approach since, temperatures near the waste package peak after only 20 to 30 years.

To limit the 60-meter strata interface temperature to 115°C or less, the local area loading for 2030 and later startup cases was reduced to conserve a constant 1000-year energy deposition relative to the 2020 case, since that is the time period when the 60-meter temperature peaks are reached. The area loadings for cases up through a 2020 startup were held to the same values as before.

Results are shown in Table 5. Emplacement area benefits, relative to 2010 requirements, were reduced. A 160-acre area reduction is gained for a delay from 2010 to 2030, and a 250-acre area reduction is achieved for a delay to 2060 as compared to the previous calculations of 200 and 400 acres, respectively. However, waste container loadings are all well above the previous 2.0 MTU, and the 2060 loading is almost three-fold greater. The number of spent fuel containers will be inversely proportional to the container loadings; thus, substantial reductions in container requirements appear to be achievable. When container size differences are factored in, the cost savings will be reduced somewhat if intact spent fuel is containerized (approximate container diameters for intact spent fuel are also shown in Table 5). Even so, substantial container cost savings should be possible for aged spent fuel since container material costs should increase in proportion to the container

Table 5 Achievable waste package and area loadings

Repository Startup, year	Spent Fuel Age, year	Waste Pkg. Loading, MTU	Approx. Container Diameter for Intact SF, in.	Emplacement Requirements[1] Area, Acres	Pitch, ft
Ref.	10	2.55	-	1366	15.2
2010	28	3.29	34	1059	15.2
2020	38	3.71	36	938	15.2
2030	48	4.14	40	899	16.2
2040	58	4.58	42	863	17.2
2050	68	5.01	43	832	18.2
2060	78	5.42	44	807	19.0

[1]All emplacement rooms spaced at 126 feet apart.

diameter, while container capacity will increase in proportion to the diameter squared.

Heat transfer calculations were again carried out with the ANSYS code to confirm that temperature limits were not exceeded. These results are presented in Table 6, and show that all temperature constraints are satisfied.

The adjustment in areal loading resulted in meeting the strata interface limit in all cases. Both the average peak temperatures at the repository center and the borehole wall temperature at 300 years held nearly constant for 2030 and later repository startup. Although the 300-year borehole wall temperature no longer increases for spent fuel ages beyond 58 years, neither does it decline, thus indicating the potential benefit of maintaining elevated temperatures over very long time periods that can be achieved by aging the spent fuel. The 300-year temperatures appear to be quite high relative to the boiling point of water. However, this is a calculation for a centrally located borehole, and this temperature drops off sharply near the edges of an emplacement panel.

SYSTEM COST IMPACTS OF SPENT FUEL AGING

The impact of spent fuel aging on system facility and operating costs was developed using system cost modeling capabilities developed under DOE's Office of Civilian Waste Management's System Integration Program. This includes a recently developed computer model named SECAM (System Engineering Cost Model),[11] the WASTES model[4] and cost estimates consistent with costs developed for DOE's 1989 MRS System Studies.[9] The conceptual system includes transportation facilities, MRS facilities and repository facilities. A reference case was developed based on a 2007 MRS startup and a 2010 repository startup. Repository container costs were based on intact spent fuel disposal as in Table 5. The reference case spent fuel container was 28 inches in diameter and had an estimated cost of $79,000 for a high nickel alloy material. Costs for the larger capacity containers were scaled in proportion to their diameter. Results are presented in Table 7.

The results in Table 7 show that the added costs of storing spent fuel for a 2030 or 2060 repository startup amount to $1.3 to $1.6 billion. These costs are partially offset by reduced mining and reduced container costs. However, when costs are discounted at 3% per year, to the currently planned repository startup year, the effect of the long delays on the repository costs overshadows all other cost considerations. A 3% discount rate may be somewhat high considering the long time periods involved. Over long time periods, the historical return (net after inflation) on government securities averages close to 2%.

CONCLUSIONS

The principal conclusions of this study can be summarized as follows:

1. Results of this analysis indicate that substantial benefits of spent fuel aging will already have been achieved by a repository starting up in 2010 (when the average spent fuel age will be 28 years). Even so, further significant aging benefits in terms of reduced emplacement area and mining requirements and reduced number of waste containers, will continue to accrue for at least another 50 years when the average spent fuel age would be 78 years, if the repository startup is further delayed.
2. Contrary to a conclusion of the MRS Review Commission (December 20, 1989, letter to Senator Bennett Johnson) with respect to spent fuel aging where they concluded that "extended cooling of the spent fuel may, in fact, be disadvantageous to the repository," this analysis found that with the higher emplacement density possible with extended aging, the energy deposition at 300 years actually <u>increases</u>. This increase benefits the objective of maintaining dehydrating temperatures for more than 300 years in the spent fuel borehole emplacement regions of the repository. Maximum borehole wall temperatures are lower but elevated temperatures are maintained for longer time periods.
3. An analysis of spent fuel aging cost impacts, assuming extended storage in an MRS facility, indicates that a significant portion of the extended storage costs can be offset by savings resulting from reduced mining requirements and reduced requirements for high-cost disposal containers. However, the most significant cost impact shows up when costs are compared on a discounted present-worth basis, in which case substantial savings are indicated.
4. This analysis has demonstrated that the EED methodology developed here provides a simple and effective means for estimating the effects of varying spent fuel age and exposure on

Table 6 Maximum temperatures and approximate time to reach the maximum for adjusted waste container and area loadings

		Calculated Maximum Temperatures, °C				
Repository Startup, year	Average SF Age, year	Borehole Wall[1]	One Meter	Average at Repository Center	Strata Interface 60 Meters Below Repository	Borehole Wall at 300 year
2010	28	210 @ 20 yr	173 @ 30 yr	109 @ 100 yr	107 @ 800 yr	152
2020	38	201 @ 20 yr	170 @ 30 yr	111 @ 120 yr	113 @ 900 yr	161
2030	48	188 @ 20 yr	159 @ 40 yr	113 @ 500 yr	113 @ 1000 yr	162
2040	58	177 @ 30 yr	152 @ 60 yr	113 @ 500 yr	114 @ 1000 yr	163
2050	68	169 @ 40 yr	147 @ 100 yr	113 @ 500 yr	114 @ 1000 yr	163
2060	78	164 @ 50 yr	149 @ 500 yr	113 @ 500 yr	115 @ 1000 yr	163

[1] Borehole wall temperatures are based on the large-diameter containers for intact spent fuel. If spent fuel is consolidated into smaller-diameter containers, the peak borehole wall temperatures will be 10 to 20°C higher.

Table 7 Cost impacts of spent fuel aging, $ billions[1]

	Repository Startup Year and Spent Fuel Container Type			
	2010 Reference	2010 Large	2030 Large	2060 Large
Transportation	1.02	1.02	0.98	0.93
MRS				
Storage	0.17	0.17	1.07	1.08
Site Support	0.51	0.51	0.85	1.00
All Other	0.50	0.50	0.62	0.65
Subtotal	1.18	1.18	2.54	2.73
Repository				
Containers	3.30	2.67	2.61	2.27
Underground	2.60	2.42	2.18	2.15
All Other	2.85	2.85	2.84	2.86
Subtotal	8.75	7.94	7.63	7.28
Total System	10.94	10.13	11.17	10.94
Present Worth in 2010 @ 3%/yr[2]	8.36	7.76	5.61	3.48

[1]Constant 1989 dollars.
[2]Costs discounted to 2010.

repository emplacement area and/or waste container loading limits. It can be used to design both waste package loading and areal loading to meet more than one thermal goal simultaneously. However, it will always be necessary to fine tune results using EED methodology with actual heat transfer calculations. The key to successful application of the EED methodology is to use a deposition period that represents the approximate time to reach a peak temperature at a specific location.

5. This analysis has also confirmed the feasibility of delivering an energy-levelized mixture of spent fuel each year either directly from the reactors or from an MRS. In addition, it has demonstrated the validity of representing the complex mixture of spent fuel receipts by average age and average exposure.

Other benefits of aging include reduced radiation fields to deal with in handling the spent fuel containers.

In the final analysis, however, the potential benefits of deliberate aging must be balanced against the more intangible problem of delaying the demonstration of nuclear waste disposal and the associated problem of public acceptance of the nuclear option in the absence of such a demonstration.

REFERENCES

1. U.S. Department of Energy. "Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which may Require Long-Term Isolation." DOE/RW-0184, Vol. 2, Washington, D.C. (1987).
2. U.S. Department of Energy. "World Nuclear Fuel Cycle Requirements 1989." DOE/EIA-0436(89), Energy Information Agency, Washington, D.C. (1989).
3. U.S. Department of Energy. "Spent Fuel Storage Requirements 1989-2020." DOE/RL-89-30, Washington, D.C. (1989).
4. Ouderkirk, S. J. "WASTES II: Waste Systems Transportation and Economic Simulation - Release 24 Users Guide." PNL-5714-1, Pacific Northwest Laboratory, Richland, Washington (1988).
5. U.S. Department of Energy. "Site Characterization Plan. Yucca Mountain Site, Nevada Research and Development Area, Nevada." DOE/RW-0199, Washington, D.C. (1988).
6. Hertel, Jr., E. S., and E. E. Ryder. "Areal Power Density: A Preliminary Examination of Underground Heat Transfer in a Yucca Mountain Repository and Recommendation for Thermal Design Approaches." SAND-1989. Sandia National Laboratories, Albuquerque, New Mexico (1989).
7. MacDougall, H. R., et al. "Site Characterization Plan - Conceptual Design Report." SAND-2641, 6 Volumes, Sandia National Laboratories, Albuquerque, New Mexico (1987).
8. Mansure, A. J., and S. V. Petney. "Determination of Equivalent Thermal Loading as a Function of Waste Age and Burnup." SAND-87-2909. Sandia National Laboratories, Albuquerque, New Mexico (1988).
9. U.S. Department of Energy. "MRS System Study Summary Report." DOE/RW-0235, Washington, D.C. (1989).
10. Swanson Analysis Systems, Inc. "ANSYS - Engineering Analysis System, Revision 4.4." Houston, Pennsylvania (1990).
11. Humphreys, K. K., et al. "System Engineering Cost Analysis Capability, Technical Reference Manual." PNL-7443. Pacific Northwest Laboratory, Richland, Washington (1991).

DATE FILMED

7/23/92