THE EFFECT OF WASTE AGE ON THE DESIGN OF A GEOLOGIC REPOSITORY[a]

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ABSTRACT

Spent fuel from civilian power reactors has been accumulating since 1969, and will be as old as 29 years out-of-reactor in 1998, when the first U.S. repository for commercial radioactive waste is scheduled to begin operation. In an oldest-waste-first scenario, the first heat-producing waste committed to a repository will be 29 years old at the time of emplacement. Age at emplacement will decrease as the inventory of old waste is depleted, and will vary throughout the operating life of the repository.

The age of the waste influences the deposition of decay energy in the waste packages themselves and in the geologic medium in which the waste packages are emplaced for disposal. In the short term, there is a local temperature pulse that is the principal consideration in the design of waste canisters--which, of course, are tailored to the individual waste forms to be emplaced. In the longer term, and on a more regional scale, the thermomechanical response of the host rock to areal energy deposition determines the design of the disposal arrays within the repository.

This report is concerned with the latter problem. It is shown that the effect of waste age variability on the thermomechanical stability of the host geology can be minimized by the proper choice of waste canister spacings.

INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) project, managed by the Nevada Operations Office of the U.S. Department of Energy (DOE), has been initiated to study the feasibility of locating a radioactive waste repository in the tuff formations at Yucca Mountain, in Nye County, Nevada. As a participant in this program, Sandia National Laboratories is responsible for the conceptual design of the repository. The thermomechanical behavior of the rock surrounding the repository is an important consideration in the design of emplacement arrays for canisters of heat-producing waste. This phenomenon is being studied in terms of the areal energy deposition associated with a given disposal scenario.

Areal energy deposition is a function of the decay characteristics of the waste, the thermal power of individual waste canisters at the time of emplacement, and the spacing of the canisters. The repository operator has no control over the first of these variables, and little control over the second. Therefore, the only practical means of limiting areal energy deposition to an acceptable value is by controlling canister spacing.

The essential first step in defining canister spacing is the determination of areal energy deposition for realistic disposal scenarios. This report describes Sandia's approach to that problem. It is emphasized that the purpose here is to illustrate a method, and not to fix design parameters for the Yucca Mountain repository.

STATEMENT OF THE PROBLEM

In the design of repositories for civilian power reactor wastes, it has typically been assumed that the waste is 10 years out-of-reactor at the time of emplacement. Spent fuel has been accumulating since 1969, and will be as old as 29 years out-of-reactor in 1998 when the first U.S. repository for commercial radioactive waste is scheduled to begin operation. Age at emplacement will decrease as the inventory of old waste is depleted and will vary throughout the operating life of the repository. The questions arise as to how the actual age of the waste varies with time, and how that variation affects areal energy deposition.

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WASTE AGE

In this report, spent PWR fuel is taken to be representative of high-level waste in general. Calculations of waste age (but not areal energy deposition) are independent of whether or not the spent fuel is reprocessed, since the reprocessing operation entails a delay of months rather than years

Waste calculations are based on repository capacities of 70,000 MTU for the first two repositories Receipt rates for both repositories are assumed to be 1,000 MTU (total, PWR plus BWR) during the first year of operation. 2,000 MTU during the second year, and 3,000 MTU/year thereafter It is further assumed that there is no significant delay between receipt at the repository and emplacement in the disposal horizon

Two estimates of the availability of spent PWR fuel are considered. The first is taken from DOE/NE-0017/2, and is based on the Energy Information Agency's 1982 "mid-growth" projection of 128.6 GW(e) installed nuclear generating capacity in the year 2000 This projection is terminated in 2020, at which time cumulative PWR plus BWR spent fuel discharges total 148,000 MTU--only slightly more than the combined capacities of the two 70,000-MTU repositories

The second estimate of spent fuel availability is based on an NUS Corporation's "limiting-case" projection of 109.7 GW(e) nuclear generating capacity in the year 2000, as discussed in Appendix C of Reference 1. NUS graciously provided the corresponding year-by-year total (PWR plus BWR) discharge rates in a private communication to the authors. PWR discharge rates were calculated by assuming that the year-by-year PWR/BWR ratios for the 128.6 GW(e) case also apply to the 109.7 GW(e) case; this assumption is valid because the NUS limiting-case projection assumes reactor cancellations (9 PWRs and 4 BWRs) that maintain a nearly constant PWR/BWR ratio. For the 109.7 GW(e) case, the cumulative PWR plus BWR spent fuel discharges in the year 2020 total only 113,000 MTU; two 70,000-MTU repositories could, therefore, accommodate this waste plus a significant amount of defense high-level waste

For each of the two estimates of fuel discharge rates, three different delays in second repository startup are considered The first case is for the 4-year delay--i e., second repository startup in 2002--implied by the Nuclear Waste Policy Act of 1982. The second case is for a 23.3-year delay, which allows the first repository to be completely filled before loading of the second repository begins. Finally, for each of the two rates of growth of nuclear generating capacity, a delay in second repository startup was calculated to assure that no waste less than 10 years out-of-reactor is emplaced in either repository. For the higher growth rate [128.6 GW(e) nuclear generating capacity in the year 2000], the required delay is 12 years, for the lower growth rate [109.7 GW(e) in the year 2000], the required delay is 18 years

Results of the waste age calculations are summarized in Fig. 1. For the 109.7 GW(e) case, a 4-year delay in second repository startup requires that waste approaching zero time out-of-reactor be emplaced in order to maintain a 3,000-MTU/year disposal rate. Even for the more optimistic case of 128.6 GW(e) in the year 2000, a 4-year delay implies transporting, handling, and emplacing waste that is less than 10 years out-of-reactor (unless the emplacement rate is reduced substantially). Given the importance of minimum waste age to repository design, it can be inferred from the other curves that the decisions regarding the construction and startup of the second repository could be delayed to accomodate any uncertainty in fuel discharge rates or design requirements

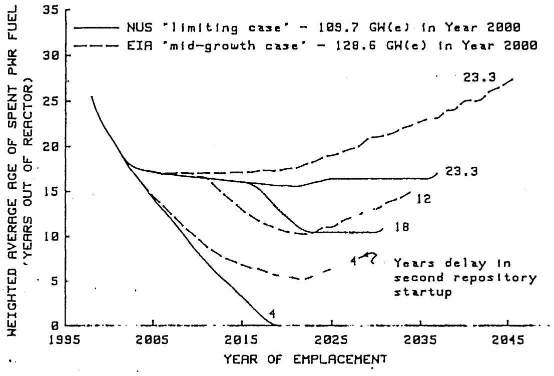

Fig 1 Age of spent PWR fuel

AREAL ENERGY DEPOSITION

Preliminary analysis of the far-field response of the Yucca Mountain geology to repository heating indicates that 10-year-old spent fuel can be emplaced with an initial areal power density (IAPD) of up to 14 W/m^2 The foregoing analysis of waste age shows that, for most disposal scenarios, very little of the fuel is actually 10 years old. There is a question, therefore, as to whether spent fuel should be emplaced at the design value of IAPD, or with the canister spacing determined for the reference 10 year old fuel.

Factors other than age--e.g, uranium loading, ^{235}U enrichment, irradiation history, burnup, etc.,--also influence thermal power and, therefore, areal energy deposition. These variables may be considered in future sensitivity studies, but are considered to be constant in this report so as to isolate the effect of waste age variability.

Qualitatively, one expects that for a constant IAPD, older fuel would deposit more energy per unit area than 10-year-old fuel (because there are more canisters of old fuel per unit area, and because old fuel decays more slowly than 10-year-old fuel). Conversely, fuel that is less than 10 years old would deposit less energy per unit area.

For a constant canister spacing designed for 10-year old fuel, older fuel would deposit less energy per unit area (because the IAPD is smaller for older fuel--although the effect is partially offset by the slower decay of the older fuel). By the same reasoning, relatively new spent fuel would deposit more energy per unit area than 10-year-old fuel.

To provide a quantitative perspective of the problem, calculations of areal energy deposition were made for both configurations--constant IAPD (14 W/m^2) and constant canister spacing (14.8 m on centers, for a hypothetical square array of vertically emplaced 3,050-W canisters). The calculations were carried out for spent PWR fuel ranging in age from 5 to 40 years out-of-reactor, and for periods of emplacement (times over which power is integrated to determine areal energy deposition) from 20 to 50,000 years. The basis for the energy deposition calculations is a reference PWR fuel assembly used by C. W. Alexander, of Oak Ridge National Laboratory, in unpublished ORIGEN2 predictions of spent fuel decay characteristcs. The important characteristics of the reference fuel are listed below:

- Uranium loading -- 0.4614 MTU/assembly
- ^{235}U enrichment -- 3.2 percent
- Burnup -- 32,717 MWd/MTU
- Specific power -- 38.4 MW(t)/MTU
- Three irradiation periods of 284 days each, separated by two 106-day decay periods to account for reactor downtime.

An analytic function for the decay of the reference fuel was derived by curve-fitting Alexander's ORIGEN2 data. For each emplacement configuration, and for 5-year increments in the age of the spent fuel, areal energy deposition was determined by closed-form integration for emplacement periods of 20, 50, 100, 1,000, 10,000, and 50,000 years. Results of the calculations are shown graphically in Fig. 2.

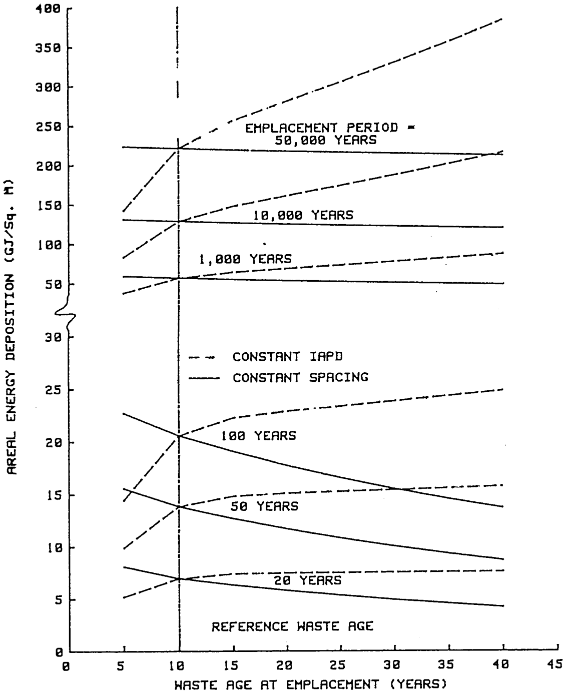

Fig. 2 Areal energy deposition as a function of waste age at the time of emplacement.

The shapes of the curves are as expected, with older fuel depositing more energy for the constant-IAPD case and less energy for the constant-spacing case. For long periods of emplacement, areal energy deposition is markedly higher for old fuel emplaced at the reference IAPD of 14 W/m^2. At 1,000 years, for example, 25-year-old fuel deposits 28% more energy per unit area than does 10-year-old fuel. By contrast, for the same emplacement period, 25-year-old fuel emplaced at the reference canister spacing deposits 9% less energy than 10-year-old fuel.

Solidified high-level waste from reprocessing contains less than 1% of the actinides that dominate the long-term decay characteristics of spent fuel. The magnitude of the effect of waste age variation on areal energy depostion is, therefore, different for reprocessed high-level waste than for spent fuel. For the same 1,000-year emplacement period considered in the above example, 25-year-old high-level waste from reprocessed PWR fuel deposits 27% more energy than 10-year-old high-level waste when emplaced at a constant IAPD (assumed to be 24.7 W/m^2 for reprocessed high-level waste). Emplaced at a constant canister spacing (9.5 m on centers for 2244-W canisters in a square array), 25-year-old PWR high-level waste deposits 18% less energy than 10-year-old waste.

Two generalizations applicable to both spent fuel and high-level reprocessing waste can be made:

1. For the long periods of emplacement that affect far-field rock stability, the areal energy deposition associated with constant canister spacing is less sensitive to variations in waste age than that associated with constant IAPD.
2. Waste that is older than the reference waste used to design a constant-spacing disposal array deposits less energy than the reference waste; thus, a constant-spacing design is conservative for delayed emplacement schedules.

It is concluded that disposal arrays for the Yucca Mountain repository can be conservatively designed with constant canister spacings determined individually for the various waste forms. The actual definitions of these spacings must await a more detailed thermomechanical analysis of the site, based on updated repository design guidelines.

SUMMARY

This report has shown how the age of the waste emplaced in a repository varies in time for realistic disposal schedules. For a constant waste receival rate, early startup of a second repository markedly reduces the age of waste emplaced in the first repository. Recent projections of the growth of nuclear power generation suggest that, from a technical perspective, the decision to build a second repository can be delayed significantly.

Analysis of areal energy deposition shows that disposal arrays for heat-producing waste packages can be conservatively designed on the basis of a constant canister spacing determined for some carefully chosen waste age (which may be different for different waste forms). Such a design minimizes the effect of waste age variation on areal energy deposition and, therefore, on the thermomechanical behavior of the host geology. Constant-spacing arrays have been shown to be conservative for disposal scenarios in which the actual waste is older than the reference waste. Perhaps the most important observation to be made is that the relative insensitivity of areal energy deposition to waste age variations in a constant-spacing design assures efficient utilization of underground space.

REFERENCE

1. U.S. DOE, "Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics," DOE/NE -0017/2 (1983).