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THERMAL ANALYSIS FOR A SPENT REACTOR
FUEL STORAGE TEST IN GRANITE

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ABSTRACT

The Lawrence Livermore Laboratory is conducting a test in which spent fuel assemblies from an operating commercial nuclear power reactor are emplaced in the Climax granite at the U.S. Department of Energy's Nevada Test Site. In this generic test, 11 canisters of spent PWR fuel are emplaced vertically along with 6 electrical simulator canisters on 3 m centers, 4 m below the floor of a storage drift which is 420 m below the surface. Two adjacent parallel drifts contain electrical heaters, operated to simulate (in the vicinity of the storage drift) the temperature fields of a large repository. This test, planned for up to five years duration, uses fairly young fuel (~2.5 years out of core) so that the thermal peak will occur during the time frame of the test and will not exceed the peak that would not occur until about ~40 years of storage had older fuel (5-15 years out of core) been used.

This paper describes (briefly) the calculational techniques and summarizes (in more detail) the results of a large number of thermal calculations used in the concept, basic design and final design of the spent fuel test. The calculational techniques ranged from simple analytic solutions of the diffusion equation, through rather extensive superposition of analytic solutions, to detailed 2- and 3-dimensional finite-difference calculations in which the canisters, the storage holes, the storage hole liners, various shield plugs, and

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the drifts, with transport including thermal radiation, natural convection, and forced ventilation through the drifts could be properly modeled. The results of the preliminary calculations show the effects of spacing and spent fuel age. The more detailed finite-difference calculations show a number of interesting results. Either radiation or convection is sufficient to make the drifts much better thermal conductors than the rock that was removed to create them. The combination of radiation and convection causes the drift surfaces to be nearly isothermal even though the heat source is below the floor. With a nominal ventilation rate of $2 \text{ m}^3/\text{s}$ and an ambient rock temperature of 23°C , the maximum calculated rock temperature (near the center of the heat source) is about 100°C while the maximum air temperature in the drift is around 40°C . This ventilation ($1 \text{ m}^3/\text{s}$ through the main drift and $1/2 \text{ m}^3/\text{s}$ through each of the side drifts) will remove about $1/3$ of the heat generated during the first five years of storage.

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INTRODUCTION

A test of retrievable geologic storage of spent-fuel assemblies from a commercial nuclear power reactor is underway at the Nevada Test Site of the U.S. Department of Energy (DOE). This project is part of the DOE Nevada Nuclear Waste Storage Investigations, managed by the Nevada Operations Office of the DOE. The Lawrence Livermore National Laboratory (LLNL) is responsible for the technical direction of this test which is located 420 m below the surface in the Climax granite stock. Eleven canisters containing spent-fuel assemblies approximately 2.5 years out of reactor core have been emplaced in the floor of a storage drift along with six electrical simulator canisters for comparison of very near field effects. Two adjacent parallel drifts contain electrical heaters which will simulate within the test array the thermal field of a large repository. During the test, thermomechanical data will be obtained which may ultimately be useful in designing a spent-fuel repository in granite or other hard rock.

CONCEPT AND BASIC DESIGN

The model used in the early phases of the thermal calculations was very simple. The granite was considered to be homogeneous, isotropic and of infinite extent. The model repository, or the spent-fuel test, was modeled as an array of parallel finite line sources whose length was that of the spent-fuel assembly (~4 m).

The power vs time history of the sources was taken to be

proportional to that for the PWR fuel with a burnup of 33000 MWD/MTU at a specific power of 37.5 MW/MTU.¹

This model, of course, ignores the existence of the mined drifts used to emplace the spent fuel and the drill holes in which they are stored. The neglect of the drifts was considered to be conservative in the sense that temperatures calculated would be higher than the "real world" since the openings would be better conductors than the rock they replaced and any ventilation would remove heat from the system. The use of line sources rather than cylindrical sources only affects early transients.

The calculations used in this phase were also simple, namely the superposition in space and time of the continuous point source solution of the diffusion equation.

$$\Delta T = \frac{Q}{\pi k d} \operatorname{erfc} \sqrt{\frac{d^2}{4kt}}.$$

The Model Repository

The model repository is simple in design. It consists of a large number of long parallel drifts with the spent-fuel canisters placed in vertical holes drilled along the center lines of the drifts. The dimensions used in this model are 15 m, center-to-center, for the drifts with the waste canisters emplaced on 3-m centers along the drifts. The rationale for the 15-m drift spacing was an extraction ratio of 33% using a projected drift width of 5 m.

Thermal calculations have been made for the center of such a repository. The parameters used in these calculations were $k = 3$ W/m-K, $\kappa = 1.25$ mm²/s, $Q = 2$ kW @ 2.5 years out of reactor core, $L = 3.66$ m. Some results of these calculations for the hottest (rock) point in the repository (the rock surface at the fuel assembly midpoint in the center hole of the repository) are shown in Fig. 1. The three curves are for spent fuel that has been out of the reactor core for 2.5, 5, and 10 years, respectively, before emplacement in the rock.

The Spent-Fuel Test

The present spent-fuel-test design calls for fuel that has been out of reactor core for only about 2.5 years. Use of young fuel will allow the assessment of maximum thermal effects in a few years, as opposed to a few decades, and will expose the rock to higher temperatures than might be encountered using older fuel.

Fig. 1. Temperature history of the rock surface at fuel-assembly midpoint in the center hole of a hypothetical spent-fuel repository, calculated for spent fuel emplaced 2.5, 5, and 10 years after removal from the reactor.

Fig. 3. Calculated temperature history of the rock surface at the fuel-assembly midpoint in the center hole of our 17-canister spent-fuel storage array. The spent fuel, electrical simulators, and heaters are deployed as shown in Fig. 2. The guard heater power is a constant 1739 W; it is turned on at 2.8 years.

Fig. 2. Plan view of the Climax granite spent-fuel storage test.

After considerable study involving not only thermal effects, but mechanical and mining considerations as well, a spent-fuel-test design evolved whose physical layout is shown in Fig. 2. In the storage drift (5 by 6 m in cross section) is a linear array of 17 storage holes (on 3-m centers) in which are placed storage canisters, 11 of which contain spent-fuel assemblies and 6 of which contain electric heaters whose power level is varied with time to match the decay of the spent fuel. Thus, for the purposes of most thermal calculations the 17 canisters are identical. In addition, there are two parallel side drifts (3 by 3 m in cross section), each containing a row (10 m from the storage array) of 10 electric heaters in small holes on 6-m centers. The function of these heaters is (1) to provide a means of maintaining higher temperatures in the storage canister array, and (2) to heat a larger mass of granite than would be affected by the storage array alone.

Some results of the thermal calculations pertaining to this design are shown in Fig. 3. A single canister gives a peak rock temperature of $\sim 60^{\circ}\text{C}$, well below the 85°C calculated for the model repository. The 17-canister array peaks within a few degrees of the model repository, but drops to near half the value in 7 years. A number of calculations led to the design of the guard heater power history. When turned on at 0.3 years after the spent fuel is emplaced and maintained at a constant power of 1732 W each, they produced the contribution shown in the lower curve. When this is added to the canister array curve to give the top curve, the result is a peak rock temperature history that is remarkably close (within 1% for the first 7.5 years) to that of the model repository. Additional calculations have shown that the region between the canister row and the heaters experiences a temperature rise a few degrees higher than the region between rows in the repository design.

Thus, the spent-fuel-storage test, as described here, is expected to subject a substantial granitic mass ($\sim 1000\text{ m}^2$ horizontal area) to thermal effects that match or exceed those that might be expected in an actual repository in a similar medium.

FINAL DESIGN

In order to provide additional information for the final design, the decision was made to do more detailed thermal calculations beyond the capabilities of the calculational techniques used above. These calculations were based on a unit cell of the repository or spent-fuel test. This cell contains one canister and is bounded by two parallel vertical planes perpendicular to the drifts and spaced half-way between canisters. For the model repository calculations two additional vertical planes of symmetry parallel to and midway between the drifts also bound the

unit-cell. The four-fold axis of symmetry at the canister center line provides two more vertical planes of symmetry, thus reducing the required calculations to a region comprising one-fourth of the unit-cell.

The mesh typically used contains three basic regions. The innermost region is 20 m wide by 40 m high and is divided into 1600 zones (0.5 by 1 m) to give the desired spatial resolution. To simulate an infinite medium for a long period of time two more regions were added with 5- by 5-m and 20- by 20-m zones giving an overall size of 80 by 160 m. In the regions comprising the drifts the regular zoning was replaced by single zones containing air. For three-dimensional modeling the region beneath the canister drift was three-dimensional with the zoning becoming progressively finer as the source was approached. Additional zones were used to model the canister, liner, shield plugs, railroad tracks, and other details. In all more than 2500 zones were used. For the numerical computations the TRUMP³ computer program was used.

In some repository calculations that we have seen the drifts were considered as non-conductors (voids) and thus gave a large floor-to-ceiling temperature difference and isotherms that were perpendicular to the drift surfaces. This is quite incorrect. Either thermal radiation or convection will make the drifts better conductors than the rock that was removed to create them. When radiation and convection are properly treated, the drift surfaces are nearly isothermal and the nearby isotherms nearly parallel to the surfaces.

Thermal radiation was modeled by straightforward application of the Stefan-Boltzmann equation. An emittance of 0.8 was normally used. One important consideration (often overlooked) is that in models having plane(s) of symmetry (such as occurs in our model) the adiabatic boundary condition at such planes is equivalent to a mirror. Thus, the "half" main drift in our model with 16 radiating surfaces has 185 radiative connections.

Heat transfer from the drift surfaces to the air in the drift may be expressed by $q = h\Delta T$, where h is the convection coefficient (typical units $W/m^2\cdot K$). For the convection coefficient we have used a standard empirical correlation for natural convection in the turbulent regime relating the Nusselt number (N_{Nu}) to the Rayleigh number (N_{Ra}), Ref. 2: $N_{Nu} = 0.13 N_{Ra}^{1/3}$, where the Rayleigh number is the product of the Grashof number and the Prandtl number.

Ventilation

The heat removed from a repository or the spent-fuel test by ventilation can amount to a significant fraction of the heat produced.

Furthermore, the temperature rise of the air as it flows through the drift is nearly a linear function of the flow rate. Thus a careful approach to the calculation of thermal effects of ventilation seems prudent.

One approach is to hold the air, or some external boundary representing it, at the ambient air/rock temperature and then proceed with the calculation using convection coefficients. This ventilation model, while easily incorporated into the unit-cell model, has several serious drawbacks. In the spent-fuel test a fixed amount of air will enter one end of a drift and be removed at the other, picking up heat and rising in temperature as it passes through. The fixed air temperature will overestimate the heat removed, underestimate the rock temperatures (particularly the drift surfaces) and give no estimate of what the actual air temperature will be. On the other hand, physical implementation of the fixed air temperature model would require a very large amount of air.

In order to retain the unit-cell model and still do realistic ventilation effect calculations, we have adopted a "partial-flow" model in which the cell receives only a fraction of the total flow but that partial-flow enters the cell at ambient and leaves at the average air temperature of the cell. The heat removal may then be expressed as: $\Delta q = \rho c \dot{V}' \Delta x T$, where

ρ = air density (kg/m^3)

c = heat capacity (J/kg-K)

$\dot{V}'$ = flow rate per unit length of drift (m^2/s)

Δx = length of calculational cell (m)

T = temperature rise above ambient (K)

The question then arises as to what is the numerical value of $\dot{V}'$? The answer is to use several different values. They all represent different locations.

If the situation that we actually wish to model a constant air flow, $\dot{V}_0$ (m^3/s), passes thru the drift and at some point while traveling a distance Δx the temperature increases by an amount ΔT . The heat removal is then: $\Delta q = \rho c \dot{V}_0 \Delta T$. By equating this equation and the previous one and passing to the limit as Δx becomes infinitesimal we obtain:

$$\frac{dT}{dx} = \frac{\dot{V}' T}{\dot{V}_0}$$

Thus, by using different values of $\dot{V}'$ in the (complete) model and calculating the resulting air temperatures at a time or times of interest, a functional relationship between $\dot{V}'$ and T may be obtained. The above differential equation may then be integrated to give the desired result, air temperature rise as a function of distance along the drift. In practice we find that the product $\dot{V}' T$ is adequately approximated as a linear function of T .

Fig. 4. Three-dimensional TRUMP code calculations of temperature vs time at indicated locations in the storage drift (no ventilation effects are considered).

Fig. 5. Three-dimensional TRUMP code calculations of temperature vs time at indicated locations in the storage drift (ventilation effects included). Note the significant cooling compared with Fig. 4.

FIG. 6 Temperature for various ventilation rates as a function of distance along the storage drift.

RESULTS

Over a period of about one and one-half years, approximately 100 TRUMP calculations were made in the development and use of the above models. The spent fuel to be stored had been identified (from Turkey

Point Unit #3, discharge date 19 November 1977) and the power level purported to be 2.4 kW at 1.9 years out-of-core. This is equivalent to 1.8 kW at 2.5 years. The first of the 11 spent-fuel canisters was emplaced on 18 April 1980, the last on 28 May.

The ventilation rate, a new parameter at this stage, was varied over a wide range (25 to 50 fold) to assess the air temperature as a function of flow rate and position in the storage drift. However, for a majority of the calculations, a single value of the "partial-flow" was used. This flow was derived by the simple expedient of distributing the total flow uniformly along the active length of the drift (essentially cross-flow as opposed to thru-flow).

The three-dimensional version of our model was developed primarily to study details in the near vicinity of the storage holes. It does, of course, retain all of the features of the two-dimensional version. Shown in Figs. 4 and 5 is an interesting set of results that include items that require 3-D and some that could just as well have been done in 2-D. In both figures we see temperature histories of five locations. They are (from top to bottom)

- the steel shield plug at the top of the canister assembly
- the bottom of the concrete plug directly above
- the railroad tracks
- the floor surface
- the air.

The only difference between the two calculations was ventilation and it makes a significant difference. After five years of storage the air temperatures differ by 30°C.

Results of a series of calculations to determine the spatial distribution of the air temperature are shown in Fig. 6. The heat removed by the ventilation is significant. During most of the test the air will be leaving the storage drift $\sim 10^\circ\text{C}$ hotter than it entered (at a flow rate of $1 \text{ m}^3/\text{s}$). With $pc \sim 1000 \text{ J/m}^3\text{-K}$, this amounts to a heat removal rate of 10 kW. When this is compared to the total heat input, (initially 30 kW but decreasing with time) it is apparent that more than one-third of the heat input will be removed by ventilation over a few-year period.

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