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Introduction

The Laser Inertial Confinement Fusion Fission Energy (LIFE) Engine [1] combines a neutron-rich but energy-poor inertial fusion system with an energy-rich but neutron-poor subcritical fission blanket. Because approximately 80% of the LIFE Engine energy is produced from fission, the requirements for laser efficiency and fusion target performance are relaxed, compared to a pure-fusion system, and hence a LIFE Engine prototype can be based on target performance in the first few years of operation of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). Similarly, because of the copious fusion neutrons, the fission blanket can be run in a subcritical, driven, mode, without the need for control rods or other sophisticated reactivity control systems. Further, because the fission blanket is inherently subcritical, fission fuels that can be used in LIFE Engine designs include thorium, depleted uranium, natural uranium, spent light water reactor fuel, highly enriched uranium, and plutonium. Neither enrichment nor reprocessing is required for the LIFE Engine fuel cycle, and burnups to 99% fraction of initial metal atoms (FIMA) being fissioned are envisioned.

This paper discusses initial calculations of the thermal behavior of spent LIFE fuel following completion of operation in the LIFE Engine [2]. The three time periods of interest for thermal calculations are during interim storage (probably at the LIFE Engine site), during the preclosure operational period of a geologic repository, and after closure of the repository.

Interim Storage Period

During the *interim storage period*, which is at least the first five years after removal from the operating LIFE Engine, the thermal power from the fission product decay in the pebbles will require immersing the pebbles in a heat-transfer medium. The vessel under the LIFE engine, designed to cool the pebbles during a loss of coolant situation, could be used. If the LIFE power plant is being decommissioned, interim storage in that vessel would be appropriate. If the LIFE power plant is being refurbished with new hardware for a second generation of LIFE power production, that vessel or a similar vessel could be used at an on-site location for the interim storage.

For calculation purposes, the interim storage thermal system was conceptualized as packing the pebbles into cylindrical containers the same size as the Transportation, Aging, and Disposal (TAD) containers developed for the Yucca Mountain repository. The 40% of the volume that is between the pebbles would be filled with a static heat transfer fluid during the interim storage period (with the fluid having the same thermal conductivity as the pebbles for the initial calculations). The interim storage containers (10.47 of them for a 40 metric-ton depleted-uranium LIFE engine) would be lined up in a circular conduit (with the conduit and container centerlines coincident). The conduit would be cooled with forced air ventilation, at a rate in which the air temperature would increase from 25ºC at the inlet to 60ºC at the exit of the conduit. A cooling air velocity of 1 m/s was arbitrarily chosen for the 5-year power, allowing sizing of the flow channel (4.2 m diameter). The air flow rate will be high initially, but can be reduced as the spent LIFE fuel thermal power decays (from an initial value 28.7 kW/m^3 to a 5 year value of 5.2 kW/m^3). The air flow rate is calculated from the heat capacity of the air, the desired inlet and exit air temperatures, the power of the line of containers, and the surface area of the cylindrical sides of the containers. For the initial calculation, the air velocity decreased from an initial value of 12 mph to only 2 mph after 5 years.

The calculation assumes quasi-steady-state at each time (0, 1, 2, 3, 4, 5, and 10 years). The convective heat transfer, $q''_{r=a}$, from the container surface (at $r = a$) to the air is

$$q''_{r=a} = h_{air} (T_{od} - T_{air})$$

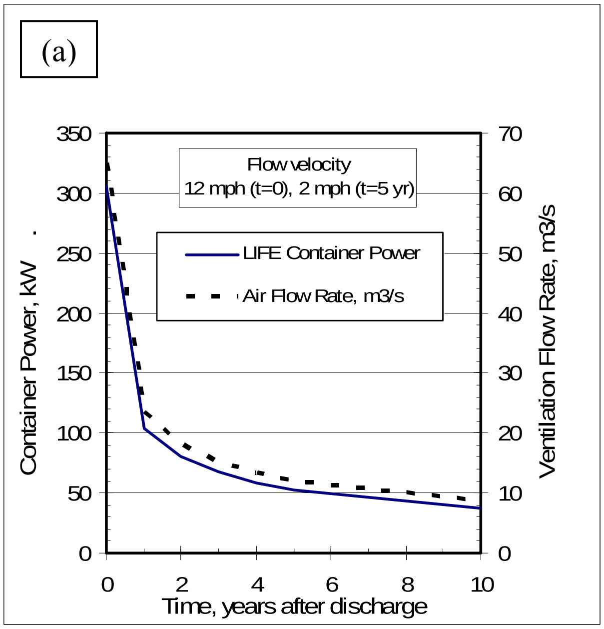
The heat transfer coefficient is taken from the Nusselt Number ($Nu = h_{air} D_h / k_{air}$) where D_h is the hydraulic diameter of the annulus and k_{air} is the thermal conductivity of the air. The Nusselt Number is taken from the Dittus-Boellter correlation ($Nu = 0.023 Re^{0.8} Pr^{1/3}$). The Reynold's Number, Re, is $[(4/\pi)\, m_{air} / (D_h\, \mu_{air})]$ where m_{air} is is the air flow rate in kg/s and μ_{air} is the dynamic viscosity of air. The Prandtl Number, Pr, for air is 0.707. Conservatively using the exit temperature for the air (rather than the local temperature at the position of each container), the container surface temperature can be calculated from the heat transfer coefficient, the container power, and the surface area of the cylindrical shell of the container. Radiation to the conduit and then convection into the air or conduction to the surrounding environment is conservatively not included in this initial model.

The quasi-steady-state temperature profile across the container shell thickness and through the static fuel plus heat transfer fluid to the centerline can be calculated by combining the well-known solutions to the steady-state radial transport equations for heat transfer (across an annulus and across a cylinder) [3]. The result of combining these equations is

$$T_{\max} = T_{od} + \left\{ \frac{q''_{r=a}}{k_{metal}} \right\} \times \left\{ a \ln\left(\frac{a}{b}\right) \right\} + \left\{ \frac{q'''b^2}{4k_{fuel}} \right\}$$

The quantity $q''_{r=a}$ is the heat flux (W/m^2)on the outer surface of the container, which was calculated above from the container power and surface area, k_{metal} is the thermal conductivity of the metal container shell, q''' is the power density in the volume occupied by the fuel (W/m^3), k_{fuel} is the effective thermal conductivity of the fuel mass, a is the outer radius of the container, and b is the outer radius of the fuel mass (inner radius of container).

The results of the calculation are shown in Figure 1. The required ventilation rate is reasonable, and will decrease as the spent LIFE fuel decays. Peak container temperatures are below 450°C, and peak spent fuel temperatures are below 500°C. The fuel is well within its thermal limit, which will be in the 700-1400°C range, with the location in this range still being determined. The container temperature is higher than the current limit for Yucca Mountain, and hence it is likely that the interim storage container will not be a TAD that can be emptied of the static heat transfer fluid (which may not be suitable for the duration of repository performance period). Rather, at the end of interim storage, the spent LIFE fuel will be removed from the (high-temperature-tolerant) interim storage container and emplaced in a TAD, with air or inert gas filling the 40% of the container volume between the pebbles. The TAD can then be shipped to the repository, mated with a waste package, and emplaced underground.



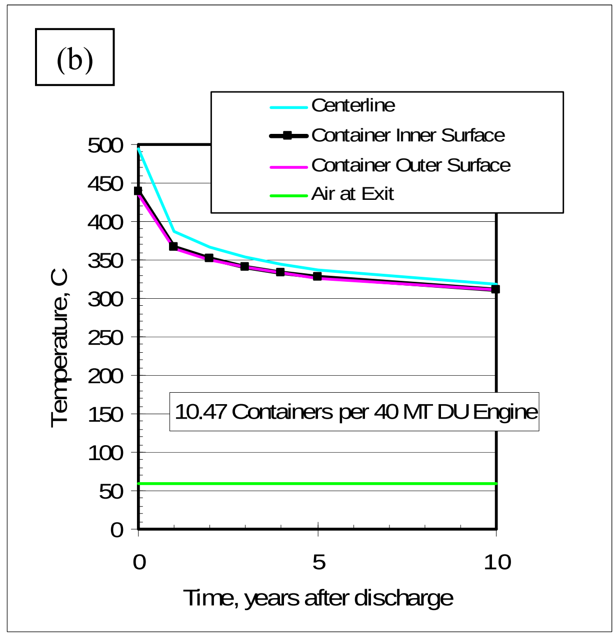


Figure 1 – (**a**) Container power and ventilation rate for interim storage of LIFE spent nuclear fuel with in a static heat transfer fluid (**b**) Temperatures at the container centerline, fuel:container interface, container surface, and air exit (the curves are in the sequence shown in the legend).

Preclosure Period in a Geologic Repository

When the spent LIFE fuel has aged 5 years, it can be placed in the repository, in waste packages filled with inert gas, and with external cooling of the waste packages by active ventilation. The ventilated period is termed the *preclosure period* for a repository. For the purpose of scoping calculations for spent LIFE fuel, and to allow comparison to established spent LWR fuel thermal modeling at Yucca Mountain, the design and setting of the proposed Yucca Mountain repository were used in LIFE repository calculations. The actual location for disposal of LIFE waste could be at Yucca Mountain if its LWR waste is removed and incinerated in LIFE Engines, or it could be elsewhere.

An artist's conceptualization of the Yucca Mountain Repository design for LWR SNF is shown in Figure 2. When completed, the repository will have 108 parallel drifts with a centerline spacing of 81 meters. In order to maintain the performance of the repository system, four temperature limits have been imposed on the Yucca Mountain design:

1) The drift wall temperature must be kept below 200°C to minimize deleterious mineral transformations and swelling.

2) The mid-pillar temperature, at a distance of 40.5 meters from the drift centerline, must be kept below 96°C to permit drainage of the ambient and thermally-mobilized percolating water through the elevation of the waste packages.

3) The container, which will be fabricated from austenitic nickel-based Alloy C-22, must be maintained below 300°C to minimize formation of deleterious (P, σ and μ) intermetallic phases that deplete the matrix of the constituents (Cr, Mo and W) responsible for the outstanding corrosion resistance of this alloy.

4) The temperature of the Zircaloy cladding of the SNF cannot exceed 350°C. For spent LIFE fuel, this limit will be replaced by a limit on the temperature of the TRISO fuel in the pebbles. That limit is still being investigated, but will likely be in the 700-1400°C range.

These four temperature limits apply to both the preclosure and postclosure periods. Because of the time constants of the heat transfer processes involved, the mid pillar temperature is the dominant limit during the postclosure period, and the other limits are more important during the preclosure period.

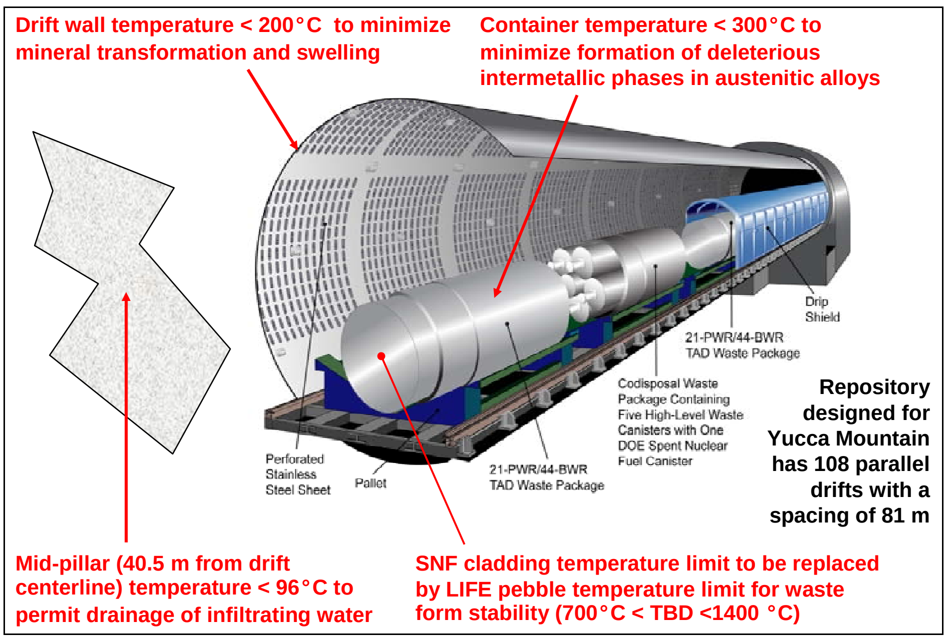


Figure 2 – Artist's conceptualization of the Yucca Mountain repository showing various temperature limits for its operation.

Five-year-old spent LIFE fuel has a thermal power (per meter, when packaged in Yucca Mountain Style waste packages) that is about six times the power of the LWR waste to be emplaced in Yucca Mountain (Figures 3 and 4). Note that spent LWR fuel has an average age of about 23 years since discharge, and has therefore had some chance to decline in thermal output compared to the conservative five-year age assumed for spent LIFE fuel. Nevertheless, the power output of 5-year-old LIFE fuel can be accommodated by a combination of ventilation (at the 15 m^3/s rate per disposal drift of Yucca Mountain) and phased emplacement in the repository drifts. In phased emplacement, twenty-one waste packages from two LIFE engines would be emplaced each decade, filling a drift in five such phases over a period of 50 years. For a higher-volume waste stream, the repository operator would fill multiple drifts simultaneously, maintaining a 10-year in-drift cooling period between phases for each drift.

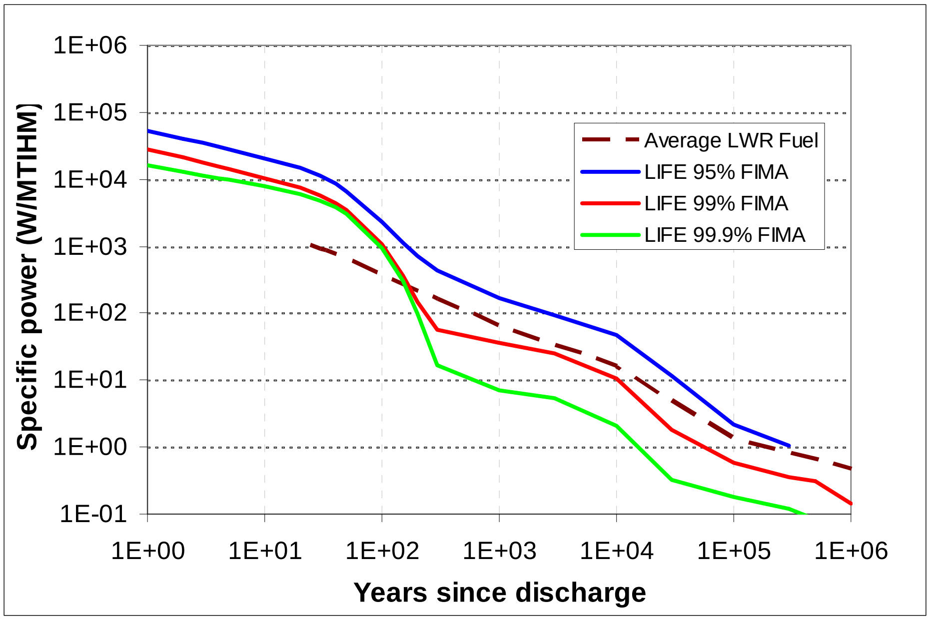


Figure 3 – The thermal power of spent fission fuel from LIFE Engine compared with spent LWR fuel as a function of time. Three potential burn-up conditions are shown for the LIFE fuel, corresponding to 95%, 99% and 99.9% FIMA. After a few hundred years, the thermal power of both LWR fuel and LIFE fuel is dominated by the decay of the actinides. The differences in the thermal powers of LIFE fuels with different burnups are a reflection of the decreasing actinide content of the fuel as burnup increases (the solid curves are in the sequence shown in the legend).

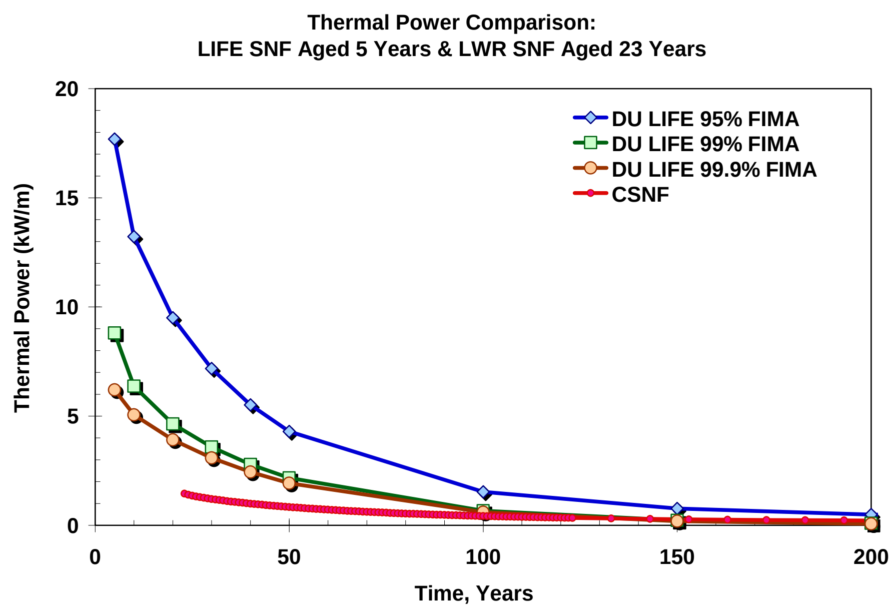


Figure 4– The thermal power of LIFE SNF at 95, 99 and 99.9% FIMA compared to that of a typical commercial LWR SNF (the curves are in the sequence shown in the legend).

The ventilation model for Yucca Mountain [4] was adapted for phased emplacement. The ventilation model includes thermal radiation from the surface of the waste package to the drift wall, convection to the ventilation air from the surfaces of the waste package and the drift wall, and conduction within the rock mass surrounding the emplacement drift. These processes were modeled using analytical techniques that assume quasi-steady-state at each time step, a series of well-mixed volume elements along the repository drift, and the principle of superposition to calculate the temperature response of the rock mass due to a heat flux. The use of the quasi-steady-state approximation allows the energy balance equations to be written without time derivatives, resulting in algebraic solutions to the various components of the thermal energy balance. The progress of the calculation through time is like that of integrating a function using Euler's method of numerical integration, summing a "stair-step" approximation. The drift is divided along its length into volumetric elements, and the properties are assumed to be well-mixed in each volume element such that the variables of interest (*i.e.*, temperature) are the everywhere the same within the element. Application of the superposition technique for the heat transfer within the surrounding rock mass is based on scaling and time-shifting of a single temperature response of the drift wall to a short-duration constant flux. The single temperature response is the higher of the temperature increases for two analytical solutions (for a region bounded internally by a circular cylinder and for the semi-infinite slab. The cylinder solution is higher for the first twenty years. The single temperature response is scaled using the heat flux from the waste package at the time of interest, and the response is combined with the responses for the prior time steps. A convective heat transfer coefficient of 5.7 W/m^2K, indicative of mixed natural and forced convection, is used in the model. Both the natural and forced convection components of the heat transfer fall within their respective turbulent regimes.

Figure 5 shows the results of the thermal calculation. The location for this graph is near the air exit of the drift, which is the hottest end. Peak emplacement drift (tunnel) wall temperatures under *normal preclosure operations* would be at least 25°C below the 200°C limit imposed by mineral stability of Yucca Mountain tuff. Peak waste package surface temperatures are at least 100°C below the 300°C limit imposed by phase stability of the nickel-based alloy (C-22) used as the corrosion-resistant outer shell of the waste package.

A model similar to the interim storage model was developed for the pebble temperatures after emplacement in a repository. The repository model does not include a heat-transfer fluid between the pebbles. Because the pebbles have only a small contact area with each other, radiation between pebbles will contribute significantly to the heat transfer. Natural convection of the gas in the 40% of the volume of the TAD that is between the pebbles is another potential heat transfer mode. The bounding model developed for initial calculations consists of a series of 2-cm-thick cylindrical annuli composed of the pebble material. The annuli are separated by narrow gaps across which radiation must carry the heat. This configuration, although geometrically different than pebbles with minimal surface contact, is expected to bound the centerline temperature because radiation heat transfer is in series, rather than in parallel with conduction. For the convection heat trarnsfer contribution, the centerline and surface temperature results from the radiation:conduction model (at each selected time for the quasi-steady-state calculation) were used in a bounding natural convection model. This two step approach demonstrated that natural convection will not carry a significant fraction of the heat flux from the centerline to the inside surface of the TAD.

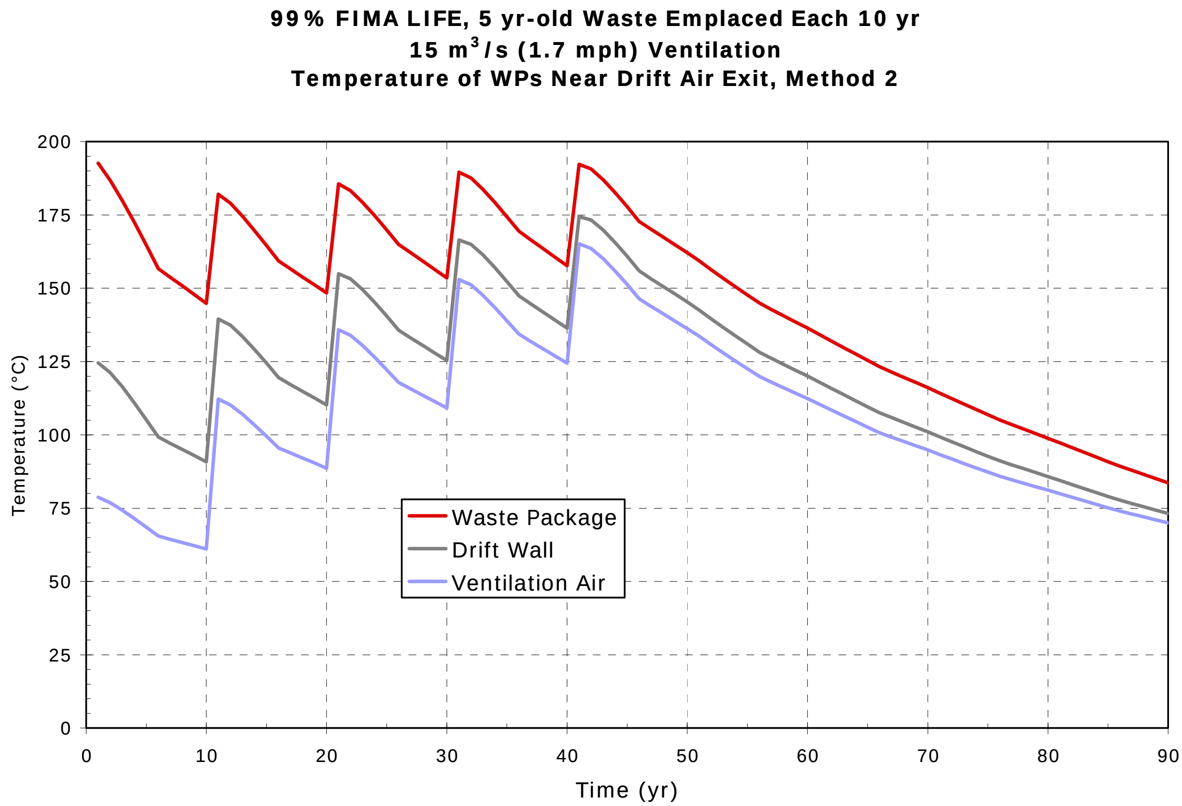


Figure 5 – Temperature of LIFE waste packages, the drift wall, and the ventilation air, for the waste package nearest the air exit, which is the hottest waste package (the curves are in the sequence shown in the legend).

The results of the pebble temperature model are shown in Figure 6, based on a boundary condition of 200ºC at the TAD inner surface. Most of the temperature increase is across the gaps, with the outermost gap having the largest temperature increase (because it carries the thermal power of all of the fuel rings and because it is at the coolest temperature due to the external cooling). Peak pebble temperatures at the centerline at five years fuel age are about 915°C. The temperature limit for the pebbles has not been finalized; however, it is likely to be between 700 and 1400°C. If the pebble temperature limit is at the low end of this range, interim storage of spent LIFE fuel would need to be extended to about 25 yr, similar to the *de-facto* operational scenario for LWR waste in Yucca Mountain. Alternatively, the ventilation rate could be increased, and/or a conductive filler could be added to the waste packages.

Most *off-normal repository events* (flooding, high-magnitude earthquakes, volcanism, meteor impact) are of sufficiently low probability that they can be screened out of the safety analysis for the preclosure period. The most significant off-normal repository event to be considered for the preclosure period is a loss of ventilation power. The thermal time constants for the repository are sufficiently long that a loss of ventilation can be tolerated for over a month for the existing Yucca Mountain scenario. Because of the higher thermal power of young spent LIFE fuel, the allowable period of non-ventilation will be shorter than for 23-yr-old LWR waste. If appropriate, the LIFE repository design would include emergency generators and redundancy for the ventilation fans to ensure the waste package temperature will not exceed the 300°C limit for a significant period.

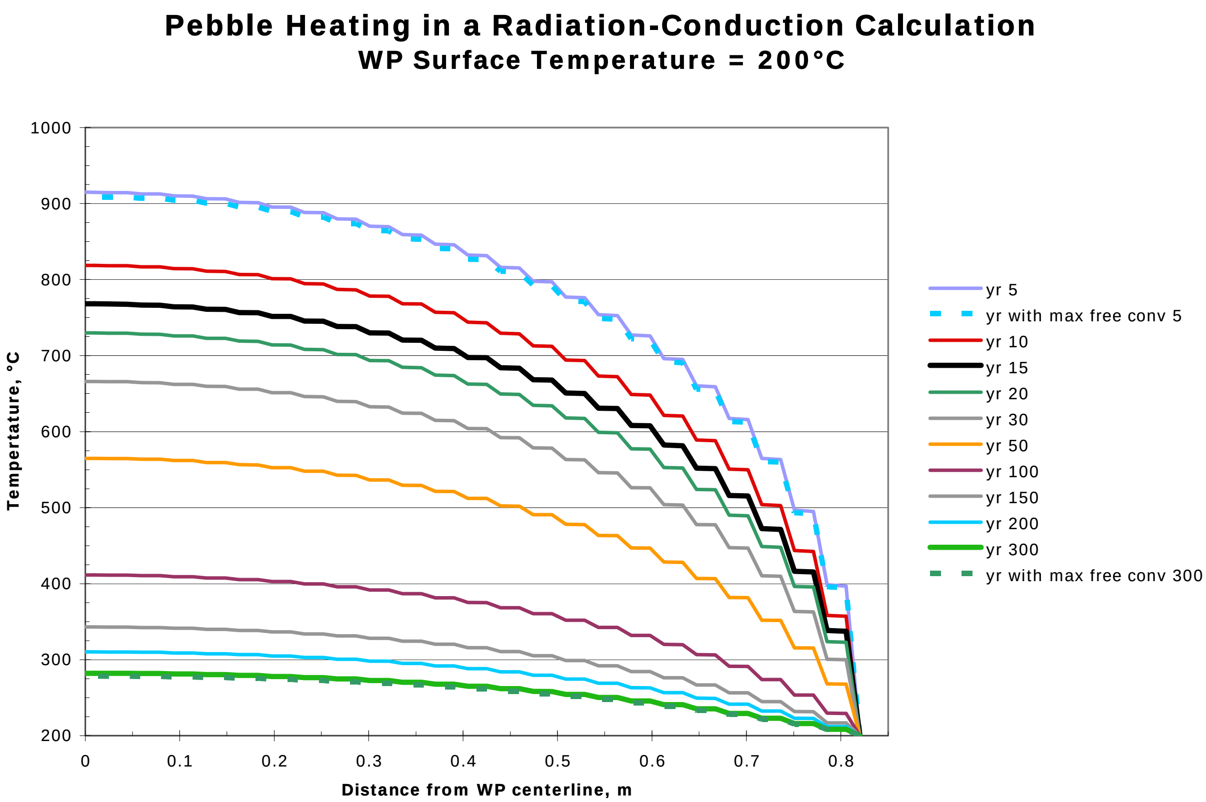


Figure 6 – Temperature of the interior of a LIFE waste package for normal operations during the preclosure period (the curves are in the sequence shown in the legend).

The model developed for normal operations is suitable to calculate WP interior temperatures during off-normal situations, by simply changing the boundary condition at the inside surface of the TAD (it should be noted that the temperature at the inside surface of the TAD is within a few degrees of the outside surface of the waste package due to the high thermal conductivity of the TAD and two waste package layers). The results of the off-normal calculation are shown in Figure 7. The peak pebble temperature is about 925°C, only about 10°C higher than for normal operation.

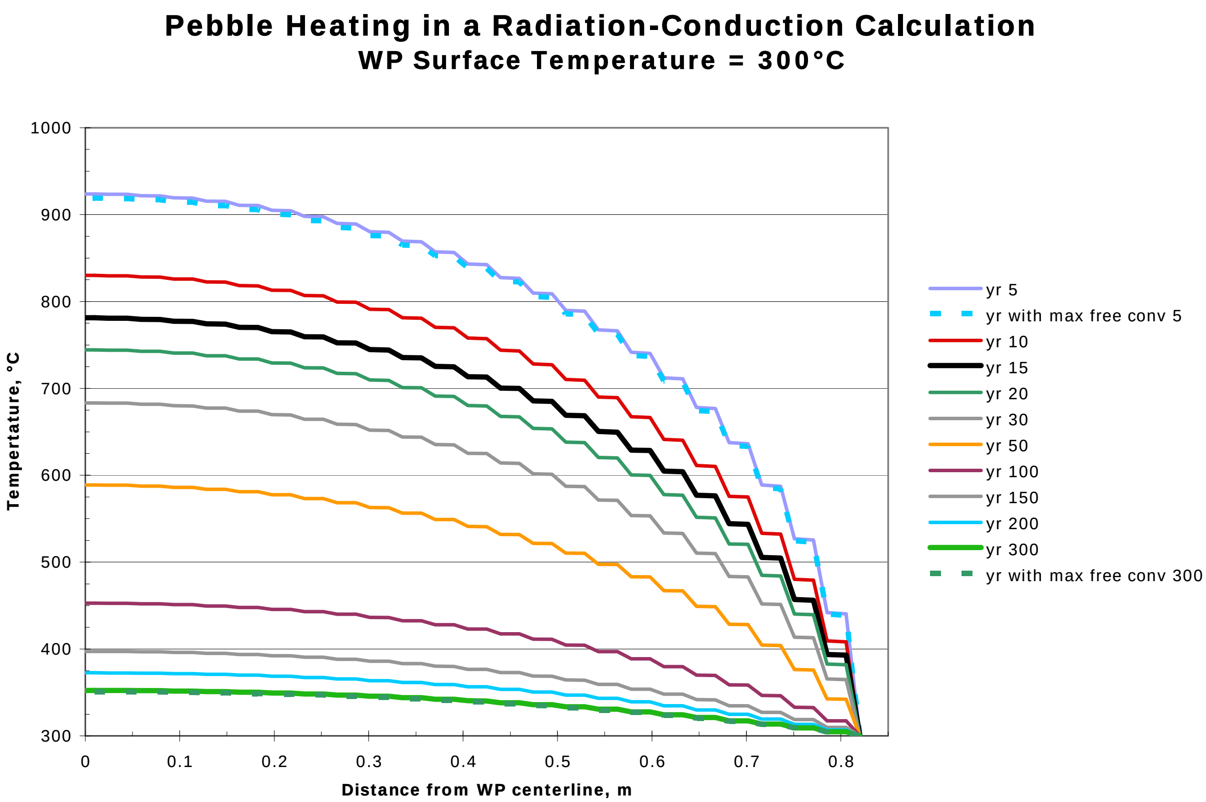


Figure 7 – Temperature of the interior of a LIFE waste package for off-normal operations during the preclosure period (the curves are in the sequence shown in the legend).

Postclosure Period in a Geologic Repository

Postclosure thermal performance of the repository relies solely on the heat sink of the repository rock (and ultimately of the mountain surface and water table). At about 115 yr age, spent LIFE fuel and LWR waste have the same thermal power (per meter, in Yucca-Mountain-style waste packages). After that time, spent LIFE fuel requires less cooling than LWR waste to stay within the four repository thermal limits. The pebble, waste package surface, and drift wall limits have been discussed above; the mid-pillar (midway between the repository emplacement drifts) temperature is the remaining limit, and is the controlling limit for postclosure thermal performance. To avoid impeding drainage of percolating water through the repository horizon, the mid-pillar temperature should not exceed the boiling point of water (96°C at the repository elevation) for significant periods of time (and for extended lengths of the mid-pillar). At Yucca Mountain and for LWR waste, the mid-pillar temperature reaches ~70°C about a century after repository closure (waste age ~175 yr), and peaks near the boiling point of water about five centuries after repository closure. Because most (80-90%) of the preclosure thermal power from spent LIFE or LWR fuel will be removed from the repository by the ventilation air, it is the postclosure thermal power that will drive the temperature history at the mid-pillar. The spent LIFE fuel thermal power will be less than that of LWR waste almost immediately after closure; therefore, it is not expected that the mid-pillar temperatures in a LIFE repository will exceed those in a Yucca Mountain LWR repository.

Conclusions

Spent LIFE fuel will have a higher thermal power than spent LWR fuel. Plausible designs for interim storage containers and cooling configuration can remove the heat without exceeding fuel temperature limits. During the repository preclosure period, temperature limits will not be exceeded if the spent LIFE fuel is emplacement in five phases (one per decade) in each Yucca-Mountain style drift, and the drift is ventilated at the same flow rate as for Yucca Mountain.

The thermal calculations shown in this paper indicate that a spent LIFE fuel repository will perform within the limits established for the proposed spent LWR fuel repository at Yucca Mountain. Because spent LIFE waste represents more than an order of magnitude higher amount of generated electricity (shown in the companion paper), the repository costs and the need for additional repositories are minimized compared to the LWR fuel cycle.

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