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Modelling Deep Borehole Disposal of Higher Burn-up Spent Nuclear Fuels

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ABSTRACT

Higher burn-up (> 50 GWd/t) spent nuclear fuels (SNF) present problems for long-term management and disposal in mined repositories, principally because of their higher heat output. Here we present results from heat flow modeling of an alternative scheme for disposing of SNF - deep borehole disposal (DBD). We focus on how temperatures on the outer surface of the containers evolve, affect the melting and re-solidification of the high density support matrix (HDSM) and their consequences for the feasibility of this disposal concept. We conclude that not only is DBD a viable option for higher burn-up SNF, but it could be a practical disposal route for a range of combinations of SNF ages and number of fuel pins per container.

INTRODUCTION

The reactors deployed in new nuclear builds over the next two or three decades are most likely to be Generation III light water reactors (LWR). Irrespective of whether they use uranium dioxide or mixed oxide (MOX) fuels, they will seek to extract more energy from the fuel than their predecessors through higher burn-ups, i.e. 55 GWd/t or greater. From a used nuclear fuel (UNF) disposal management perspective this creates problems, especially those arising from the higher radioactivity and heat outputs. One disposal concept that is relatively insensitive to radiation and temperature and so could overcome these problems is deep borehole disposal (DBD). Deep borehole disposal [1] places more emphasis on the geological barrier and less on the engineered barriers. Its basic principle is illustrated in figure 1 and can be summarized as follows. Large diameter boreholes at least 4 km deep are sunk into a suitable host rock, usually the granitic basement of the continental crust, and waste packages are deployed in the lower reaches of the hole. With a geological barrier an order of magnitude greater than most mined repositories, DBD takes advantage of the very low bulk hydraulic conductivities (< 10^{-11} m/s) that can be found at such depths even in fractured rocks. In addition to improved safety, cost-effectiveness, security, flexibility and environmental impact [1], DBD offers important advantages over mined repositories for disposal of SNF and other HLW. Among these are tolerance of a wide range of compositions and heat outputs, relative ease of siting, shorter implementation timescales and the option of dispersed disposals DBD is also earthquake proof. In this paper we introduce a new variant designed to dispose of higher burn-up spent UO_2 and MOX. First we discuss the physical model and give details of our improved and refined computational model. We then present the results of modeling “experiments” to explore the large parameter space including: the number of fuel pins per container, the type of fuel and its burn-up (55 & 65 GWd/t), the post-reactor age of the fuel and the number of containers per batch to determine the temperature. We then discuss the consequences for the viability of the concept and the design of the disposal system.

THEORY

Physical Model

The variants of DBD presented in this paper are based on the consolidated disposal of fuel pins in stainless steel containers with a lead infill. We have chosen to model the pins from a Westinghouse AP1000 PWR fuel assembly. Each pin is 4.583 m long with a diameter of 9.5 mm and consists effectively of three parts. The upper and lower parts (0.173 m and 0.143 m long respectively) contain springs, insulators and gas spaces and generate no heat. The central part (4.267 m long) contains the fuel pellets within the cladding and is the heat generating part of the pin. The size of the pins governs the dimensions of the other components such as the containers, the borehole and casing, although we have selected the last two to correspond with commercially available drilling sizes. The physical model is illustrated in figure 1 and the parameters used in our modeling are as follows: borehole diameter = 0.56 m; container (316 stainless steel) ID = 0.32 m, OD = 0.36 m, height = 4.6 m; borehole casing (mild steel) ID = 0.419 m, OD = 0.454 m. We assume that the fuel pins are homogenously packed inside the containers and the remaining space is occupied by lead.

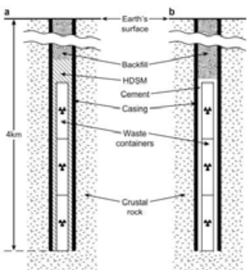

Figure 1. Details of the DBD concept showing alternative support matrices (not to scale): (a) HDSM + Head, (b) cement, no Head.

We refer to the 4 combinations arising from the 2 fuel types (UO_2 and MOX) and 2 burn-ups (55 GWd/t and 65 GWd/t) as UO_2-55, UO_2-65, MOX-55, MOX-65 and their heat outputs have been calculated using FISPIN [2]. In addition to the type and burn up of the fuel, the other main variables in our modeling are the number of pins in the container and the post-reactor age of the pins. The former is normally less than 80% of the theoretical maximum to allow for the practicalities of remote insertion. The age is never less than 10 years; that being the minimum amount of cooling necessary for further operations in practice.

A lead-tin alloy high-density support matrix (HDSM) [3] is emplaced in the borehole in the form of a fine shot The HDSM serves two different purposes: first, it protects the containers it surrounds from mechanical stresses generated by the ones above, and second, it acts as an additional engineered barrier. Decay heat will melt the alloy which, when it eventually cools and re-solidifies, will effectively solder the containers into the borehole. Full details of the HSDM are given in [3]. In this work we choose a 40% lead composition which will begin to melt at a temperature of 185˚C at a pressure of 40 MPa (the estimated pressure at 4 km when the borehole is open). After each container is emplaced, further HDSM shot is introduced into the borehole to compensate for the reduction in volume that will occur once melting has begun. The composition has been chosen so that the HDSM has a specific gravity (SG) of 8.47, slightly less than that of the lightest container we use (SG = 8.5).

We have modeled both a single container within a borehole to establish a baseline result, and also a borehole in which up to ten containers have been emplaced at 7-day intervals. In all cases, we assume that water fills the borehole above the excess HDSM on top of the final container in the batch. For multiple batches (not explored in this paper), a spacer of crushed rock could be added above the HDSM of the batch before the first container of the next batch is emplaced. For cases deemed unsuitable for HDSM (those in which insufficient heat is generated to melt the alloy), a cement grout is used instead (see figure 1b).

Computational Model

Our computational model assumes heat is transferred mainly by conduction. The main object of our calculations is to determine the temperature at any position in and around a container and/or borehole as a function of time. To this end we have solved the heat conduction equation in cylindrical polar coordinates (exploiting the symmetry of the problem which assumes the containers are perfect cylinders). Full details of our model can be found in our earlier papers [4]. We use the method of Finite Differences, together with a fully implicit integration scheme to advance the temperature in time, and in this work, we have used a time step of 100 seconds. For the source term, we have used FISPIN data to determine the heat output arising from the fuel pellets within the pins. The "source" itself is then a cylindrical section consisting of lead infill and smaller cylinders which themselves comprise the fuel pellets and Zr alloy cladding. The height of this cylinder is that of the fuel component in an individual pin. The heat output from these fuel components is distributed over the cylindrical volume. A composite thermal conductivity for this source is obtained by combining the thermal conductivity of the fuel pellets and cladding as two thermal resistances in series and then combining this composite value with the thermal resistance of the lead and the other fuel elements as thermal resistances in parallel. The density of the source is the combined mass of all of the source components divided by the cylindrical volume. The specific heat of the source term is obtained from the mass fraction weighted sum of the component specific heats.

For the HDSM the temperature dependent thermal conductivity is calculated as follows: if the temperature at a HDSM mesh point is below the temperature at which the alloy begins to melt (185˚C), we use a mass-weighted average of the pure metal thermal conductivities. If it is above the temperature at which the alloy is fully molten (192˚C), a weighted average of the liquid state thermal conductivities is used. For temperatures between these limits we use linear interpolation. Temperature dependent thermophysical properties are employed for all other materials in our model. We also use an ambient (disposal depth) temperature of 80 ˚C.

RESULTS AND DISCUSSION

For a single container, the variation of peak temperature vertically up the container surface has been calculated for several combinations of fuel type, pin number and age of the waste. Representative examples are shown in figure 2. The highest temperatures are always generated at a point just below the midpoint of the container while ambient temperature is approached at distances of as little as 5 m above and below the container. For all cases the peak temperature at the bottom of the container is significantly higher than at the top. This is partly due to the asymmetry of the non-heat generating parts of the pins but also due to the fact that the rock below the container is a better insulator than the HDSM and borehole fluid above the container. There is a noticeable inflection in each curve ~ 1.4 m above the top of the container corresponding to the junction between the HDSM and the aqueous borehole fluid. While the general form of these temperature profiles is similar, it is evident from figure 2 that varying the fuel type, pin number and age of the fuel can generate a wide variety of temperature profiles. Excessive heating, as shown by the curve corresponding to young, spent MOX-65 can be tamed by resorting to older waste or by reducing the number of fuel pins. We have also calculated peak temperatures along radii from the vertical axis of the borehole. Ambient temperature is approached within 30 m of the centerline of the container and is only a few degrees higher at a distance less than 20 m, even for 1000 pins of very young UO_2-65. This result has a positive and significant bearing on the proximity of adjacent boreholes in a multiple borehole disposal site.

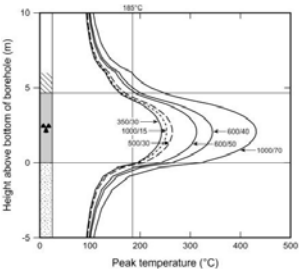

Figure 2. Peak temperatures along the vertical outer surface of a single container of UO_2-65 (short dashed line), MOX-55 (long dashed line) and MOX-65 (solid lines). Labels on the curves indicate the number of pins in the container and the age of the fuel in years.

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Temperature-time curves are shown in figure 3 for the case of 1000 pins of 15 year old UO_2-65. The three pairs of curves relate to temperature evolution at the top, middle and bottom of a container at its outer surface and at the borehole wall. In all cases, the temperature rises to a maximum and then falls off with time. The hottest temperatures are at the midpoint of the container while the coolest are at the top.

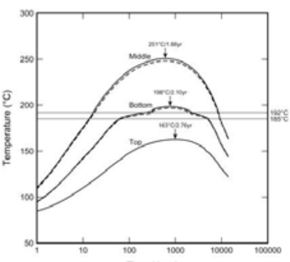

Figure 3. Evolution of temperature with time for a single container of UO_2-65 (1000 pins/15 years). Solid lines are for points on the outer surface of the container and dashed lines are for points on the borehole wall.

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These plots are of great utility since they enable determination of which type of support matrix should be employed: HDSM or cement grout. In this example the surface temperature at the mid-point of the container peaks at 250 ºC 1.66 years after emplacement; at the bottom at 197 ºC after 2.08 years and at the top at 163 ºC after 2.72 years. These temperatures and times are functions of the specific case. Differences between temperatures at the container surface and at the borehole wall are only 0-2.5 °C and radial thermal gradients can effectively be ignored. This particular case shows that more than enough heat is generated to completely melt an HDSM matrix at the bottom and middle of a single container but it is too cool at the top to cause melting. In practice, containers would be deployed in batches and heat from the next container would be conducted to the top of the container immediately below it, so melting the HDSM. The single container modeling is useful to determine a baseline case and rapidly scope out potentially useful combinations of pin numbers and fuel age for each type of SF. In practice it would be preferential to deploy several containers in a batch, with each container being emplaced after an interval of a few days. We explored the option of deploying batches of 5 and 10 containers, comparing peak temperatures in these cases with those obtained for a single container. We find that increasing the number of containers increases the peak temperature obtained as one would expect, but 5 containers increases the peak temperature proportionally more than the difference between the same 5 containers and a stack of 10. Based on this, we concentrated the rest of our modeling on batches of 5 containers and explored the parameter space for this configuration. Five typical examples are shown in figure 4 with the maximum in peak temperature at the surface of the stack ranging from 153ºC to 359ºC, just below the middle of the third container.

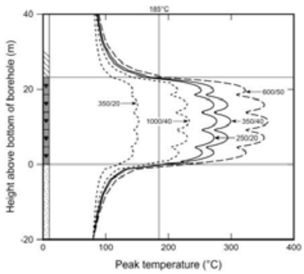

Figure 4. Peak temperatures along the vertical outer surface of the container stack (5 containers at 7 day intervals) of UO_2-55 (short dashed lines), MOX-55 (long dashed lines) and MOX-65 (solid lines). Labels on the curves indicate the number of pins in the container and the age of the fuel in years.

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We have begun extensively mapping out the parameter space by varying the number of pins per container between 250 (almost equivalent to a whole AP1000 PWR assembly) and 1000 (close to the theoretical maximum packing density) and the age of the spent fuel between 15 years and 100 years for all four fuel types. From the data, we have extracted the time taken to reach the temperature at which the HDSM starts to melt (185˚C), and can also obtain the time required for it to re-solidify. In some cases, insufficient heat was generated to melt the HDSM and for these cases, we would use a cement grout. The lower burn-up spent UO_2 combinations require cement except for those with high numbers of very young fuel pins. The results from such a study are most conveniently displayed as a 'field' diagram, which defines a feasibility envelope for DBD of these higher burn-up spent fuels. Figure 5 shows such a diagram constructed from the data we have obtained so far. The lines are used to separate four possible outcomes, labeled A, B, C and D. The different plot symbols correspond to the different outcomes for that fuel type and the 'coordinates' are the number of fuel pins per container and the age of the waste. Outcome A represents those cases where there is sufficient heat generated to melt the HDSM in the annulus between the containers and the borehole wall everywhere along the length of the stack, those labeled as B result in melting of the vertical annulus of HDSM everywhere except at the very top of the stack, those labeled C result in incomplete melting at both the top and bottom of the stack while D captures those cases in which the there is insufficient heat generated to melt the HDSM anywhere in the annulus.

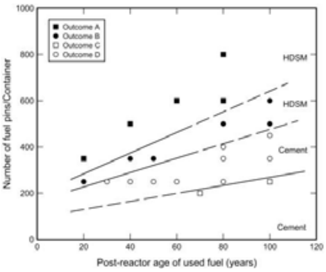

Figure 5. Outcomes of temperature modeling for selection of support matrix for MOX-65.

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CONCLUSIONS

We have conducted numerical heat flow modeling to determine the temperatures reached in and around a deep geological borehole containing higher burn-up spent fuels of the type likely to be produced in new-build reactors. The use of a computational model has allowed us to explore a large parameter space that includes the number of fuel pins per container, the number of containers per batch, and the fuel type, burn-up and age. The results of our study clearly demonstrate that DBD is a viable and highly flexible means of disposing of a wide range of spent fuel combinations.

Two different support matrices have been discussed, and the outcome of a systematic series of heat flow calculations has been used to generate a ‘field’ diagram from which the best matrix can be chosen for a particular combination of pin number and fuel type and age. Looking ahead, we aim to widen our study to consider the possibility of disposing of entire fuel assemblies, expand our field diagrams to the other fuel types and to explore the outcome of disposing of containers with a mixture of different fuel pins.

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