Mineralogical Magazine, December 2012, Vol. 76(8), pp. 3003–3017

Deep borehole disposal of higher burn up spent nuclear fuels

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[*Received 11 December 2011; Accepted 13 March 2012; Associate Editor: Nicholas Evans*]

ABSTRACT

The heat outputs of higher burn up spent fuels (SF) create problems for disposal in mined repositories, including needs for reduced container loadings and extended pre-disposal cooling. An alternative that is less temperature sensitive is deep borehole disposal (DBD) which offers safety, cost, security and other potential benefits and could be implemented relatively quickly using currently available deep-drilling technology. We have modified our previously proposed version of DBD to be more appropriate for higher burn-up fuels by using smaller (0.36 m diameter) stainless steel containers, a smaller (0.56 m diameter) borehole, and different support matrices. We present the results of new heat-flow modelling for DBD of UO_2 and MOX SF with burn ups of 55 and 65 GWd/t showing how temperatures evolve, especially on the outer surface of the containers. Consequences for the performance of the support matrices and the disposal concept are discussed. The thermal modelling indicates DBD is a viable option for higher burn-up SF and could be a practical disposal route for many combinations of fuel types, burn ups, ages and container loadings. Further, the results suggest that DBD of complete fuel assemblies, a desirable option, would be feasible and require much shorter pre-disposal cooling than necessary for disposal in mined repositories.

Keywords: disposal, used fuel, heat-flow modelling, boreholes, support matrices.

Introduction

The generation III light water reactors likely to be used for new nuclear builds over the next two or three decades will seek to extract more energy from their fuel than did their predecessors, mainly through higher burn ups (>55 GWd/t). Irrespective of whether they use uranium dioxide (UO_2) or mixed oxide (MOX) fuels, the higher radioactivities and heat outputs of the irradiated fuels create problems for spent fuel (SF) management and especially for disposal in mined repositories. Among the latter are constraints on the size and contents of waste packages (and hence on the size, siting and costs of the repository) and on the suitability of certain host rocks and materials (such as bentonite) for the engineered barrier system (EBS). Perhaps even more of a concern is the need for protracted cooling and storage prior to disposal, possibly for over 100 years after removal from the reactor (Nuclear Decommissioning Authority, 2009).

An alternative disposal concept that is much less sensitive to temperature than mined repositories is deep borehole disposal (DBD) (Gibb, 1999, 2000; Chapman and Gibb, 2003; Massachusetts Institute of Technology, 2003; Gibb *et al.*, 2008*b*; Arnold *et al.*, 2010). In the USA the Presidential Blue Ribbon Commission (2012) identified DBD as “a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste

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DOI: 10.1180/minmag.2012.076.8.16

management system and therefore merits further research, development and demonstration." The basic principle of DBD, which places more emphasis on the geological barrier and less on the EBS, can be summarized as follows.

Large diameter (~0.5 m) boreholes over 4 km deep are sunk into a suitable host rock (usually the granitic basement of the continental crust) and waste packages are deployed in their lower reaches. With a geological barrier an order of magnitude greater than mined repositories DBD utilizes the very low hydraulic conductivities found at such depths, even in fractured rocks. It also capitalizes on the likelihood that the highly saline intra-rock fluids at depth will have been out of physical and chemical contact with near-surface mobile groundwaters for many Ma. This isolation arises from long-lived density stratifications that are likely to remain stable far into the future, unaffected by climate change, glaciations, sea-level rises and even tectonic events. Low lateral flow rates and almost non-existent vertical flow across the density stratification ensure that any radionuclides eventually escaping from the near-field containment go effectively nowhere in 1 Ma, the time needed for the SF to decay to a radiologically safe level.

It has been argued (e.g. Chapman and Gibb, 2003; Gibb *et al*., 2008*b*) and supported by a preliminary safety case analysis (Brady *et al.*, 2009) that DBD offers potential technical and other advantages compared to mined repositories, such as safety, cost, dispersed disposal and easier siting. Reiteration of these arguments is beyond the scope of this paper but it may be helpful to emphasize that the safety is based on the combination of greater depth (isolation) with the very low hydraulic conductivities, density stratified saline groundwaters and long groundwater residence times that can be found at the depths in question. Any one of these could provide the long-term containment required of the geological barrier. The most recent study (Beswick, 2009) estimates the cost of the first 4 km borehole (capable of disposing of over 360 tHM of SF) at \$47M reducing to \$31M for subsequent holes. Dispersed disposal can contribute to safety, economic and environmental benefits, especially if transport distances to a mined repository would be long. The extents of such advantages would undoubtedly be site specific and depend on the size of the disposal programme but the concept is relatively new compared to mined repositories and much analysis, especially of safety cases, remains to be done before the two can be compared on an equal basis.

Of particular relevance in the present context, DBD tolerates a wide range of waste compositions and heat outputs and has the potential to be implemented on a relatively short timescale. Using existing technology, boreholes around 0.5 m diameter can be sunk to over 4 km in less than a year (Beswick, 2008, 2009) and could be filled and sealed in less than another two years. The first disposal could therefore be completed three years after a successful full-scale demonstration of the technology (using non-active waste), regulatory approval and the selection and approval of a site, all of which could proceed simultaneously.

We present here the first results from a more sophisticated finite differences heat-flow model than previously for the disposal of UO_2 and MOX fuels with burn ups of 55 and 65 GWd/t using a new version of DBD. We focus on the evolution of temperatures in and around the disposal zone of the borehole, especially at the surfaces of the SF containers, and discuss their significance for the design of the disposal system and strategy.

Disposal concept

Two new versions of DBD have been derived from the one referred to as LTVDD-2 (low temperature very deep disposal - 2) by Gibb *et al*. (2008*a*,*b*). These are more appropriate for higher burn up SF and we designate them LTVDD-2a and 2b (Fig. 1). The main changes are reductions in the diameters of the borehole and SF containers (Table 1) and the introduction of a choice of support matrices depending on the temperatures attained.

After initial cooling in the reactor fuel ponds the fuel pins are removed from the assemblies (using a procedure similar to that for replacing damaged pins) and up to 825[1] of them (equivalent to 3.1 PWR assemblies or 1.7 tonnes of heavy metal (U or Pu)) are placed in a cylindrical stainless steel container (Table 1). This could be done at the reactor or an encapsulation plant. A variant that avoids this step by disposing of whole assemblies is discussed later. In an encapsulation

[1] Up to 1000 pins are used in the modelling but this packing density (= 97% of maximum) may not be achievable in practice.

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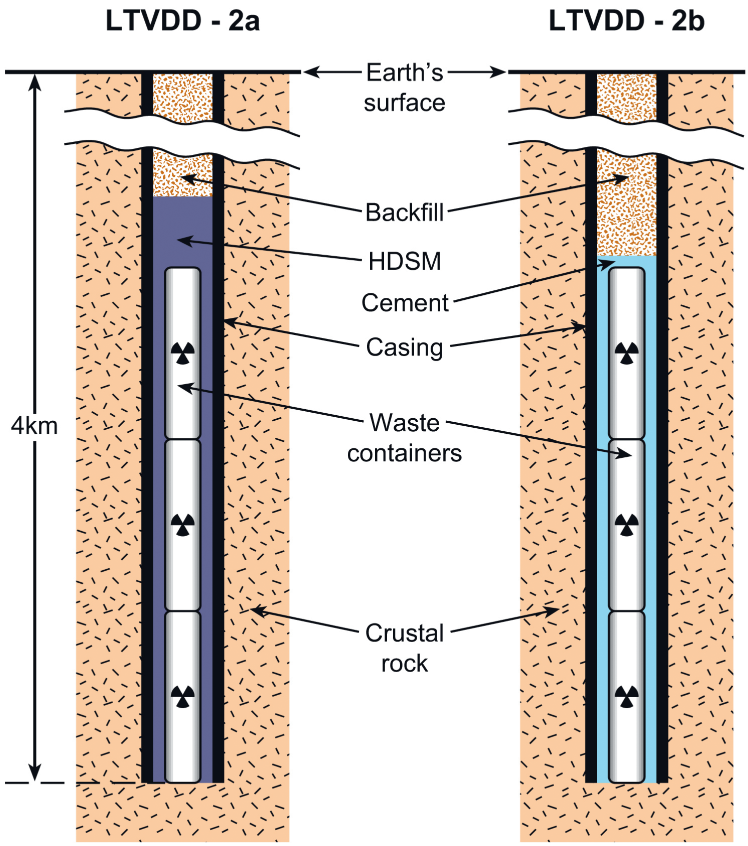

FIG. 1. Deep borehole disposal concepts LTVDD-2a and LTVDD-2b showing alternative support matrices (not to scale).

plant the container and its contents are dried then heated slowly to ~335ºC removing the last traces of H_2O from any microcracks in the Zr alloy cladding (Gibb, *et al.*, 2008*a*). This is done in an inert atmosphere (e.g. N_2) to eliminate possible oxidation of the Zr. The container is then filled with molten lead (Pb), the lid put on, the container sealed and cooled ready for disposal. Among the

TABLE 1. Parameters of disposal system components used in the modelling.

Item	Material	OD* (m)	ID* (m)	Length (m)
Borehole	Granite host rock	0.560		Dependent on well design
Casing	Mild steel	0.454	0.419	>1000
Container	Stainless steel	0.360	0.320	4.640
Fuel pin cladding	Zirconium alloy	0.0095	0.0084	4.583
Fuel pin (upper part)	Various	0.0082		0.173
Fuel pin (central part)	Uranium dioxide	0.0082		4.267
Fuel pin (lower part)	Various	0.0082		0.143

* Abbreviations used are OD, outside diameter and ID inside diameter.

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functions of the Pb infill are support for the pins and prevention of escape of radionuclides from the fuel pins, especially the instant release fraction, should the integrity of the cladding be lost before the borehole is sealed. The infill further reduces the already slight risk of contamination of the borehole fluid during the operational stage. The use of Pb as infill could provide a disposal route for much of the contaminated Pb from the nuclear industry.

The containers are deployed singly or in small batches over the lowermost 1 km or so of a fully cased borehole at least 4 km deep. To prevent possible load damage from the overlying stack (Gibb, *et al.*, 2008*a*) the containers must be supported until the borehole is sealed, and preferably longer. A suitable material for this is a high-density support matrix (HDSM) in the form of a fine Pb alloy shot. Following emplacement of each container a quota of HDSM is released from the drill string just above the container and sinks rapidly through the aqueous deployment fluid into the annulus between the container and casing (Fig. 1; LTVDD-2a). It also finds its way into the gaps between the casing and the borehole wall via weight-reducing perforations in the deployment zone casing (Fig. 2). Soon the decay heat from the SF will generate temperatures sufficient to melt the shot to a dense liquid that will fill all voids between the containers and the wall rock. After emplacement of the last container in a batch, a 'head' of shot is added to compensate for volume reduction in the annulus on melting. Years to decades after deployment the decay heat will decline and the molten alloy will cool and solidify to 'solder' the containers into the borehole, providing permanent support and a barrier to fluid access to the containers and escape of radionuclides. For cases where temperatures in the annulus around the containers are insufficient to melt the Pb alloy, support can be provided by a high temperature cement grout (Fig. 1, LTVDD-2b) pumped down the drill string after each container. This sets normally and no extra 'head' is required. For various practical reasons cements are unlikely to be as good a support or effective a barrier as the HDSM.

Once full, the borehole above the deployment zone must be backfilled and sealed to prevent the hole providing an easier flow path to the biosphere than the rest of the geological barrier. This can be achieved using a variety of materials and technologies (Brady, *et al.*, 2009; Arnold, *et al.* 2010) but our current preference is for a form of 'rock welding' by down-hole electric heating that

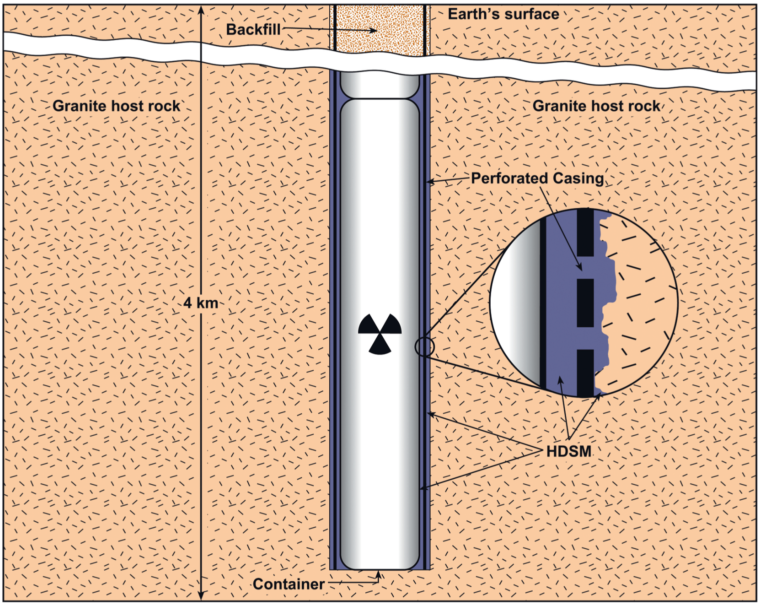

FIG. 2. Deep borehole disposal concept LTVDD-2a with inset showing detail of the high-density support matrix (HDSM) (not to scale).

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partially melts the crushed host rock backfill and adjacent wall rock. For a granitic host temperatures around 800ºC should suffice (Attrill and Gibb, 2003). A major advantage of this method is that it eliminates the engineering disturbed zone (EDZ) of microfractured rock around the borehole by recrystallization. The rock welding would be facilitated by cutting and withdrawing the casing at the top of the deployment zone, although this is not essential. Recovered casing could be re-used to reduce costs.

Modelling

Fuel assemblies for the Westinghouse AP1000 PWR were used for modelling, although those for other Generation III PWRs are very similar. The fuel pins consist of three parts: upper and lower parts containing springs, insulators and gas spaces that generate no heat and the main central portion containing the fuel pellets that is the heat generating part. The dimensions of the fuel pins and the containers, casing and borehole which follow from them are given in Table 1. Four combinations of UO_2 and MOX with burn ups of 55 and 65 GWd/t were modelled and are referred to as UO_2-55, UO_2-65, MOX-55 and MOX-65. The heat output of each (Fig. 3) was calculated using *FISPIN* (Burstall, 1979). Other main variables in the modelling are the post-reactor age of the fuel and the number of pins in the container. The latter can be up to 100% of the theoretical maximum packing density but the practicalities of remote insertion suggest an upper limit around 80%.

Temperatures in the Earth's crust at a depth of 4 km will be controlled by the local geothermal gradient which, for continental crust, tends to be between 20ºC and 30ºC km^{-1} with an average of ~25ºC km^{-1} (Best, 2003). Pressure increases by 100 MPa every 2.73 km (Best, 2003) so at a depth of 4 km is likely to be around 150 MPa. However, this is due largely to the surrounding rocks and while the borehole is open it will be much lower (approximately that of a 4 km column of water). Once the hole is sealed the time required for the pressure to recover to its equilibrium value will depend on local conditions but is likely to take many years. For modelling purposes the ambient conditions in the disposal zone were taken as 80ºC and 40 MPa.

As the waste packages have densities between 8500 and 10,000 kg m^{-3} depending on their contents, we have used a $Pb_{40}Sn_{60}$ alloy as the HDSM. This is close to the eutectic composition in the Pb–Sn system with solidus and liquidus temperatures of 183ºC and 190ºC at 1 atmosphere. We calculate these will rise to 185ºC and 192ºC at

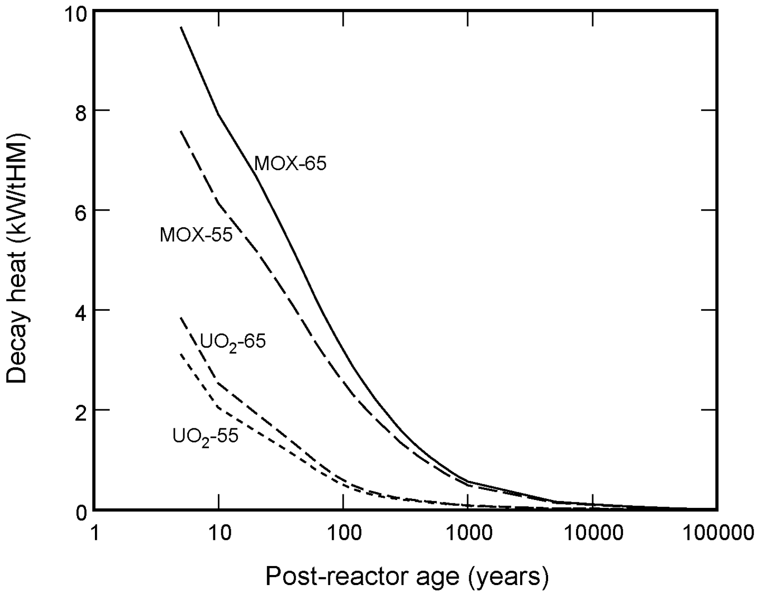

FIG. 3. Decay heat outputs for the four fuel type/burn up combinations used in the modelling.

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40MPa (Gibb *et al*., 2008*a*). This material has a density that is only slightly less than the waste packages so it can provide support and, when it is molten, the packages will have only slight negative buoyancy.

The evolution of temperature at each location in and around the borehole is derived from a finite differences heat flow model using an upgraded version of the Fortran code *GRANITE* (Gibb *et al*., 2008*b*) referred to as *GRANITE-2* in which it is assumed heat transfer is mainly via conduction (Travis *et al*., 2012). Preliminary results from a complementary modelling study indicate that convective transport via both the borehole fluid and the intra-rock fluids is transient and insignificant compared with conduction. Further, given the scale and duration of the thermal anomalies in the host rock (see below) compared to the saline groundwater stratification, the latter is most unlikely to be significantly disrupted by any convection in the host rock. Among the advances in *GRANITE-2* are heat source terms that accurately reflect the heat generation and geometry of the fuel pins, more realistic modelling of heat flow within the containers, flexible mesh sizes and resolution depending on the number of containers in the batch, and temperature dependent thermal properties for all materials involved. The thermal properties used in the modelling are given for selected temperatures in Table 2.

Results

Decay heat from the SF will raise temperatures in and around the borehole by an amount dependent on the number and size of containers and the heat output of their contents. The latter is a function of the type and burn up of the fuel, its age and the number of pins in the container. For the cases reported here all containers in a batch are the same and all the pins in a container are identical, although neither need be so. Varying these merely adds an extra degree of complexity to the modelling that could be accommodated if required. For any location in or around the borehole the initial temperature rise will change to a fall as the decay heat diminishes resulting in a maximum or 'peak' temperature for that location. The most important peak temperatures for the disposal concept are those generated at the outer surfaces of the containers with those at the centres of the containers, at the borehole wall and in the host rock being less significant.

TABLE 2. Thermophysical properties of key materials at selected temperatures as used in *GRANITE 2*.*

Material	Density ($kg\ m^{-3}$)			Specific heat ($J\ kg^{-1}K^{-1}$)			Thermal conductivity ($W\ kg^{-1}m^{-1}$)		
type	T = 25°C	T = 100°C	T = 300°C	T = 25°C	T = 100°C	T = 300°C	T = 25°C	T = 100°C	t = 300°C
Lead	11,300	11,227	11,031	128.6	132.8	142.3	35.035	33.67	30.03
UO_2†	10,955	10,931	10,866	235.9	258.2	290.3	6.443	5.779	4.486
Zircaloy	6551.2	6540.1	6510.5	6551.2	6540.1	6510.5	13.403	13.814	15.406
$Pb_{40}Sn_{60}$‡	8471.5	8425.6	8121.6	188.5	196.8	224.1	54.068	51.495	22.223
Water	1037.2	999.0	822.9	3973.1	4037.4	4393.3	0.6085	0.6783	0.5476
Granite	2630	2630	2630	781.5	867.4	969.2	2.2923	2.1059	1.7306
Mild steel	7860	7839	7784	443.3	487.6	564.7	53.168	50.670	44.010
Stainless steel	7900	7869	7787	526.66	544.42	591.8	14.503	16.002	19.002

* Further details, including data sources, are available from the authors.

† Values for the density and specific heat of MOX were taken to be the same as those for UO_2. The thermal conductivity of MOX was taken to be 1.087 times that of UO_2.

‡ Properties calculated as weighted means of those for solid or liquid Pb and Sn end members; properties in the solidus–liquidus interval calculated by linear interpolation.

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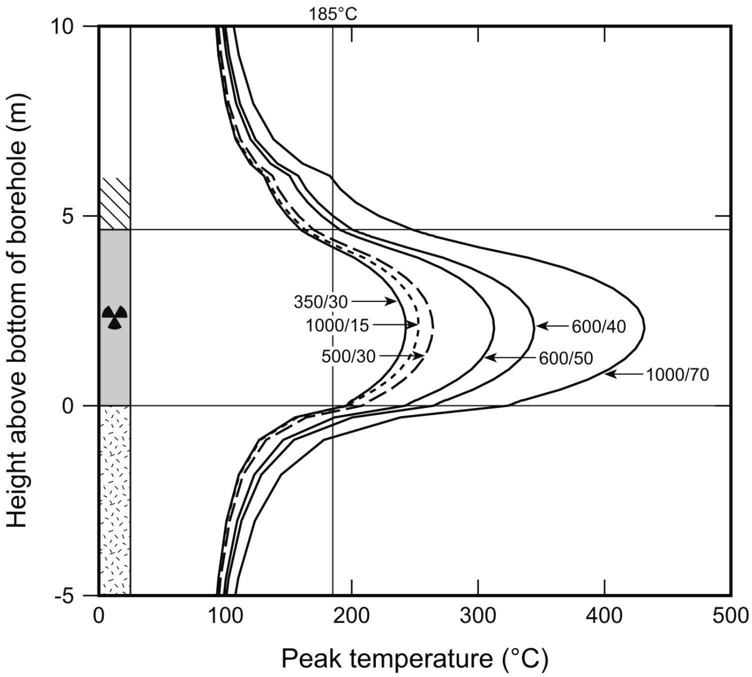

FIG. 4. Examples of peak temperatures at the outer surfaces of single containers. The short dashed line is for UO_2-65, the long dashed line for MOX-55 and the solid lines for MOX-65; arrows indicate the number of pins per container and the age of the fuel (years).

Single containers

The baseline case is that of a single container at the bottom of the borehole. We have modelled many such cases for all four fuel combinations and the main variation in peak temperature at the container surface is always along the length of the container (Fig. 4). The highest value is always just below the middle of the container and peak temperatures at the bottom of the container are always higher than at the top. This is partly due to the asymmetry of the fuel pins but mainly because conduction of heat downwards through the host rock is less efficient than upwards through the overlying materials. Variations in peak temperatures generated along horizontal radii are shown in Fig. 5 for one of the cases in Fig. 4. Most obvious is the rapid decrease in the host rock, such that less than 20 m away from the borehole wall, peak temperature elevations above ambient are only a few degrees. This has obvious implications for the spacing of boreholes in multiple borehole disposal programmes (see Discussion).

The highest peak temperature generated anywhere is on the container axis just below the middle. For the case in Fig. 5 this is 260ºC, only 8ºC higher than the maximum at the outer surface. For the same case the evolution of temperature with time is illustrated in Fig. 6 for points on the outer surface of the container and on the borehole wall at the top, middle and bottom of the container. Apart from the differences in temperature with height, two important points are highlighted by such diagrams. Peak temperatures at the different levels are attained at different times and temperature differences between the container surface and borehole wall at any level are small, usually less than 3ºC. This applies to all cases we have modelled to date and suggests radial thermal gradients within the annulus between the container and wall can largely be ignored from the perspective of the disposal concept.

Batch deployments

It is likely that the waste packages in DBD would be deployed in batches separated by a time interval and/or some physical spacer in the borehole. Some DBD concepts envisage strings

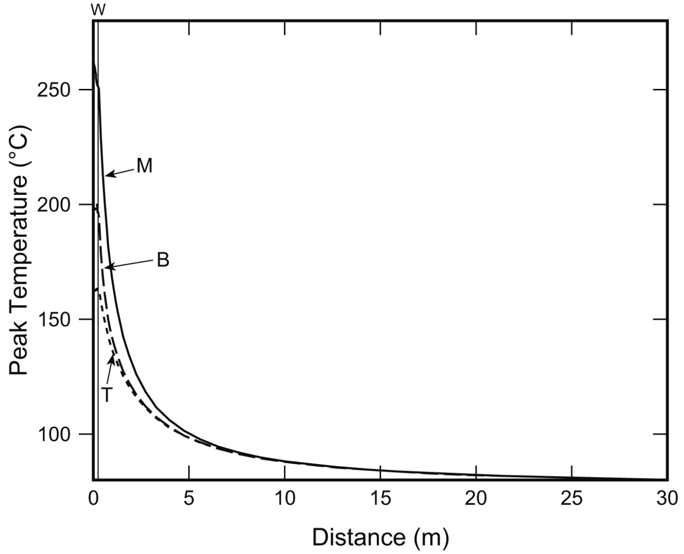

FIG. 5. Peak temperatures along horizontal radii out into the host rock for a single container with 1000 pins of 15 year old UO_2-65. Abbreviations used are T, top of the container; M, middle of the container; B, bottom of the container; and W, borehole wall.

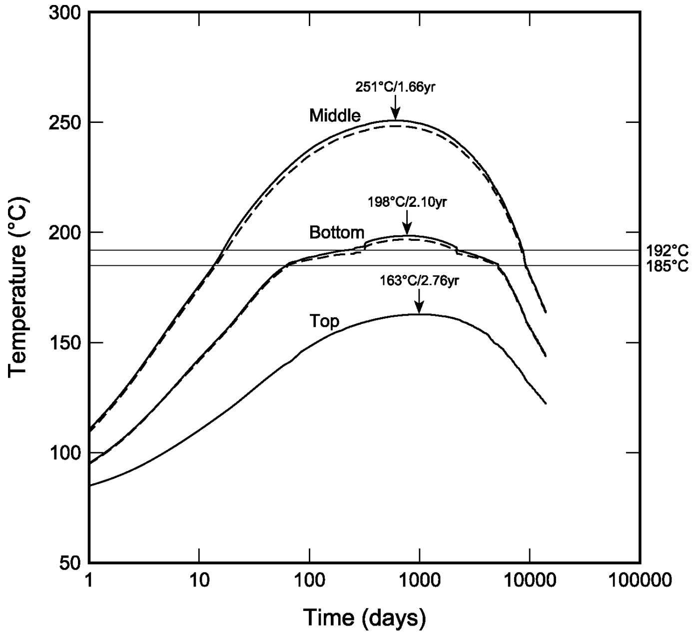

FIG. 6. Evolution of temperatures for a single container with 1000 pins of 15 year old UO_2-65. Solid lines are for points on the outer surface of the container and dashed lines for points on the borehole wall at the top, middle and bottom of the container. Arrows indicate peak temperatures and the times at which they are reached.

of up to 20 packages being emplaced at a time (Brady *et al*., 2009) but for practical reasons it is unlikely that heavy packages such as envisaged here would be emplaced other than one at a time and that the interval between emplacements would be less than one or two days (Beswick, 2008). Consequently, in modelling batch deployments we have assumed the containers are emplaced singly at intervals of one week.

To evaluate the effect of the number of containers in a batch the results for batches of one, five and ten identical containers can be compared as in Fig. 7 for containers with 350 pins of 30 year old MOX-65. As expected, temperatures increase with the number of containers. For the single container a maximum peak temperature at the outer surface of the container of 243ºC is reached 2.27 years after emplacement and occurs just below the middle of the container. For the five-container case the highest peak temperature is 330ºC just below the middle of the third container and is reached 5.62 years after emplacement begins. For the 10-container case the mid-point of the stack coincides with the boundary between two containers resulting in twin maxima at 352ºC just below the mid-points of the fifth and sixth containers. These are reached almost simultaneously 7.62 years after first emplacement.

There will be practical limitations on the size of a batch due to factors such as package availability, well-head buffer store capacity and equipment maintenance and compromise is needed between the need for appropriate container surface temperatures and making the batches too large. Temperature increases are not linearly proportional to the size of the batch. For the case in Fig. 7 increasing from one container to five raises the maximum peak temperature by 87ºC but an increase to 10 only raises it by another 22ºC and further increases lead to even smaller temperature rises. We therefore selected five containers as the 'standard' batch size for our modelling experiments.

Examples of 5-container batch deployments are given in Fig. 8 with maximum peak temperatures at the surface of the stack ranging from 153ºC to 359ºC. However, just as important as the maximum peak temperatures are those attained at the tops and bottoms of the stacks. For four of the cases in Fig. 8 temperature evolution on the outer surface of the containers is given in Fig. 9 for the top, middle and bottom levels of the stack. These exemplify four possible outcomes (A–D) of heat flow modelling from the perspective of the disposal concept. In Fig. 9*a* (outcome A) peak temperatures exceed 185ºC (the HDSM solidus) everywhere on the surface of the stack. In Fig. 9*b*

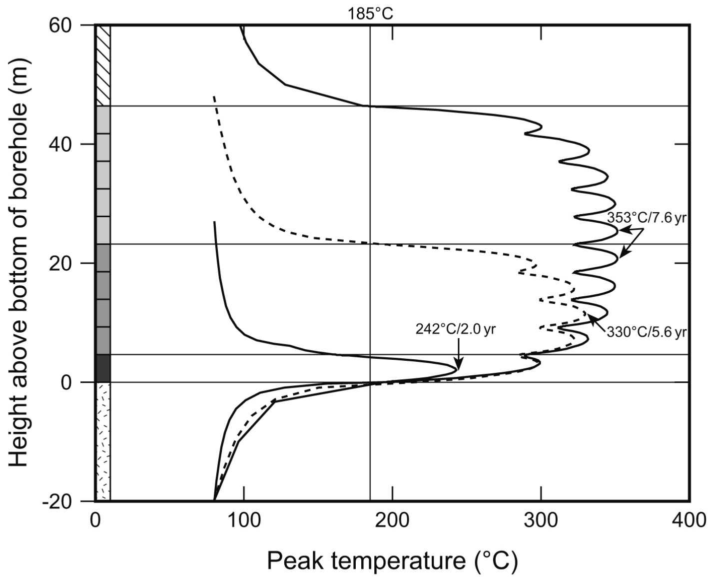

FIG. 7. Comparison of peak temperatures on the outer surface of the stack for 1, 5 and 10 containers with 350 pins of 30 year old MOX-65 emplaced at 7 day intervals.

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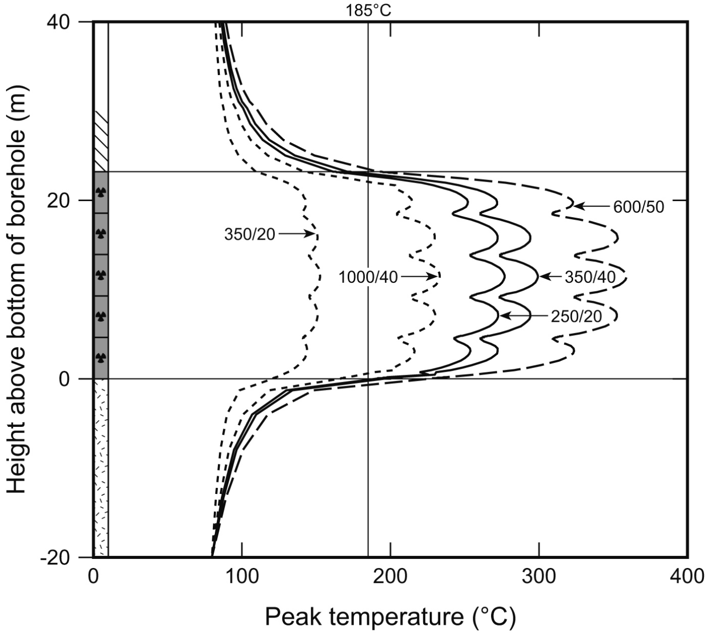

FIG. 8. Examples of peak temperatures at the outer surfaces of the containers in batches of 5 emplaced at 7 day intervals. The short dashed lines are for UO_2-65; long dashed line is for MOX-55 and solid lines are for MOX-65; arrows indicate the number of pins per container and the age of the fuel (years).

(outcome B) the peak temperature at the top of the stack fails to reach 185ºC. In Fig. 9*c* (outcome C) the peak temperature fails to reach 185ºC at both the top and bottom of the stack while in Fig. 9*d* (outcome D) no point on the surface of the container stack reaches 185ºC.

Discussion

The peak temperatures generated in and around the waste packages determine the selection of the support matrix, the design of the disposal strategy, the viability of the concept and could control the spacing of boreholes in multi-borehole disposal programmes.

Limitations

The highest peak temperature attained anywhere will always be on the axis of the borehole/container stack (i.e. inside the containers close to their centres). Ideally this should not exceed the maximum operating temperature of the fuel pins but this may not be crucial. If the temperature inside a container exceeds ~335ºC the Pb infill could melt. Provided the container is intact this should not matter as the Pb will soon re-solidify as the temperature falls. If, however, the container has lost its integrity before the borehole is sealed (e.g. during deployment) and the cladding of any of the fuel pins is damaged, melting of the infill introduces a small potential risk to radionuclide containment. If this is a concern the maximum temperature in the system must be limited to 330ºC but it should be noted that normally the borehole would be sealed long before peak temperatures are reached anywhere in the system (Fig. 9).

Other components of the disposal system such as the containers (stainless steel), borehole casing (mild steel) or host-rock (most likely granite or granitic gneiss) are unlikely to suffer any significant structural or other effects at transient temperatures below 500ºC. As the modelling shows, temperatures would rarely, if ever, reach such levels and would be much less in the wall rock (Fig. 5).

Based largely on the German KTB scientific drilling programme, it has been estimated (J. Beswick, pers. comm.) that the accuracy with which a vertical hole with a diameter of ~0.5 m can be drilled should now be better than 50 m at

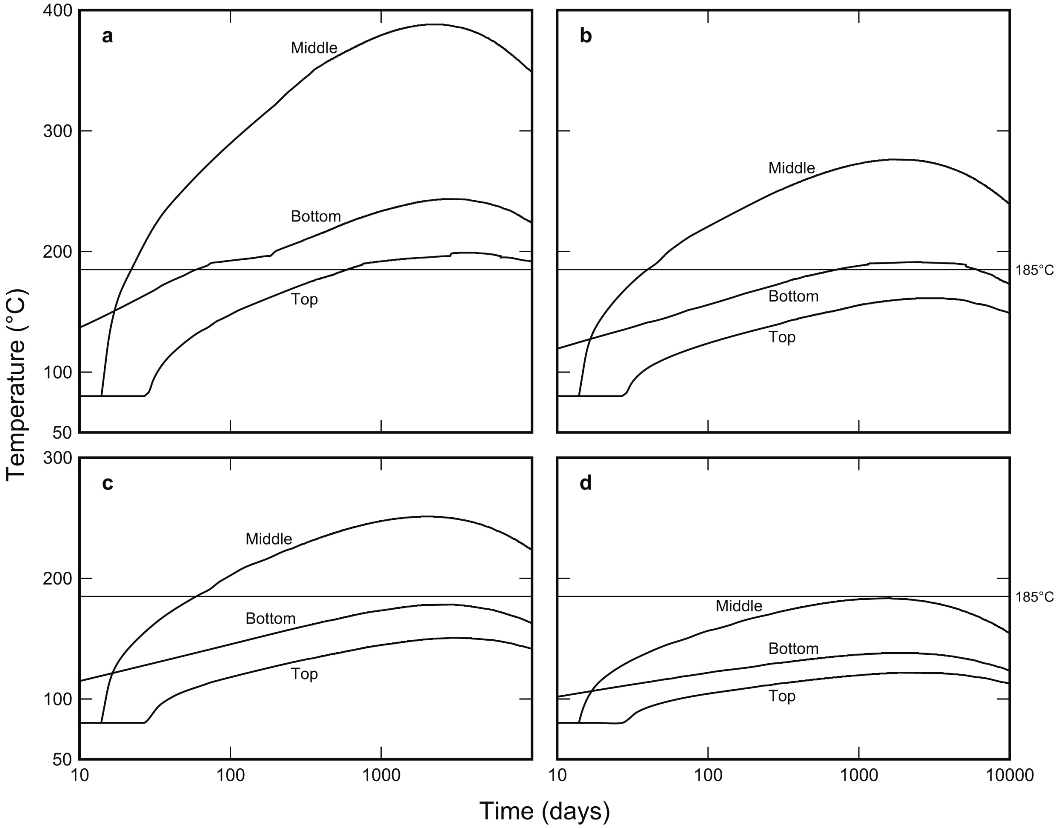

FIG. 9. Evolution of temperatures at the outer surfaces of the containers in batches of 5 emplaced at 7 day intervals: (*a*) 600 pins of 40 year old MOX-55; (*b*) 250 pins of 20 year old MOX-65; (*c*) 250 pins of 30 year old MOX-65; and (*d*) 600 pins of 30 year old UO_2-65. Top, middle and bottom refer to the level in the stack.

4 km. As the boreholes cannot be allowed to intersect and thermal considerations suggest separations of at least 20 m are desirable, a practical target spacing of the holes in a multi-borehole disposal programme of 50 m would seem appropriate. Once a hole is drilled its position is known to within a few metres, thus allowing selection of the location for subsequent boreholes. Any hole that approaches, or looks like approaching, another too closely could be deviated or abandoned before costs become too great.

Choice of support matrix

The preferred support matrix for the waste packages is the $Pb_{40}Sn_{60}$ alloy (Fig. 1, LTVDD-2a). For this to function properly, temperatures attained in the annulus between the container(s) and the borehole wall must be high enough for melting to occur. For the HDSM to melt the temperature only has to reach the solidus. The latent heat of melting of the HDSM affects mainly the amount of melting and the temperatures (and time taken to reach them) beyond the HDSM (e.g. in the wall rock) but as such effects are likely to be small and of only marginal relevance to the present paper this latent heat was not taken into account here. If high enough temperatures cannot be generated, a cement similar to those employed in geothermal energy wells must be used (Fig. 1; LTVDD-2b).

The four possible outcomes (A–D) in Fig. 9 can be used to discuss the behaviour and suitability of the HDSM. Although these cases are for 5-container batches, the outcomes apply equally to single container deployments or any size of batch. In outcome A the peak temperatures

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in the annulus exceed the HDSM solidus (185ºC) everywhere along the length of the stack. For the case illustrated (Fig. 9*a*) melting of the alloy shot begins around the middle of the stack 22 days after emplacement of the first container, after 60 days at the bottom but not until 1.63 years at the top. As the HDSM in the annulus melts the head settles to top it up, eventually all melting itself. Solidification of the HDSM begins first at the top of the stack after 37 years and after 52 years at the bottom with the last of the alloy solidifying around the middle of the stack ~138 years after disposal. These temperatures and times are functions of the actual case and so can be controlled by the choice of pin numbers and the age of the fuel.

In outcome B peak temperatures in the annulus exceed 185ºC everywhere except at the very top of the stack. For the case in Fig. 9*b* melting of the HDSM commences at the mid-point after 40 days and at the bottom after 1.96 years but it would never melt at the top of the stack unless another batch is emplaced directly on top of it (as would normally be the case in practice)[2]. When this occurs the bottom container of the next batch would come to rest on top of a 7 m head of alloy shot (minus what had subsided into the annulus). After less than 40 days (because of heat from the underlying packages) the heat from the new batch would start to melt the head allowing the overlying containers to sink gently through the dense liquid and come to rest on top of the batch below. In time the HDSM would solidify to seal in both batches.

Outcome C is illustrated by the case in Fig. 9*c* in which the HDSM, if used, would begin to melt around the middle of the stack after 60 days and spread to all but the lowermost 0.2 m and uppermost 0.7 m of the 23.2 m high stack. In such cases emplacement of a subsequent batch will raise temperatures in the head between the batches slightly but is unlikely to melt it. Outcome C may therefore give rise to a range of circumstances in which the HDSM could function satisfactorily as a support (as shot or melted then solidified) for the containers but not as a continuous seal along their length. In outcome D the peak temperatures are too low to melt the HDSM anywhere in the annulus, although in the example illustrated in Fig. 9*d* the HDSM at the mid-point just fails to melt at 184ºC, which is reached 4.16 years after emplacement.

Although the Pb alloy shot might provide adequate support in cases with outcomes C and D, it can not provide a barrier to groundwater access to the containers or escape of radionuclides and consideration must be given to the use of the cement support matrix (Fig. 1; LTVDD-2b). Cement grouts are commercially available for sealing geothermal energy wells, but have limitations on the temperature at which they can be used and their survivability, especially in aggressive alkaline or CO_2-rich environments. Such environments are unlikely in DBD and, if they are used only in cases where annulus temperatures are less than 185ºC (outcome D), they should survive until long after the borehole is sealed. However, emplacing cement grouts in boreholes and getting them into all the necessary voids before setting are notoriously difficult and more research into their formulation, design and performance is needed for use in DBD. In the cases of outcomes C and D it may be preferable to re-assess the disposal strategy so the HDSM can be used.

Although $Pb_{40}Sn_{60}$ alloy provides a technically preferable HDSM, such material is not cheap. Filling the annulus between the containers and casing and the gaps between the casing and rock for 1 km of disposal zone could require over 1000 tonnes of HDSM. At current metal prices this equates to ~\$14M worth of Sn and \$0.9M worth of Pb, although the latter could come from waste Pb from the nuclear industry. The use of such expensive HDSM would significantly increase the cost of DBD (by ~50% of the borehole cost for a 4 km borehole with a 1 km disposal zone) and we are currently investigating less costly materials for the HDSM.

Disposal strategy

For each of the four fuel combinations the outcome can be plotted as a function of the number of pins in the container and their age (e.g. Fig. 10). For outcome A annulus temperatures are high enough everywhere for the HDSM to function as intended and the only consideration may be whether maximum temperatures are too high. If so a reduction in the number of pins and/or an increase in the age may be advisable. For outcome B, although the HDSM does not melt at the top of the stack it can still be used if another batch is emplaced within a few years of the first as

[2] Modelling of multiple batch deployments will be dealt with in a separate publication.

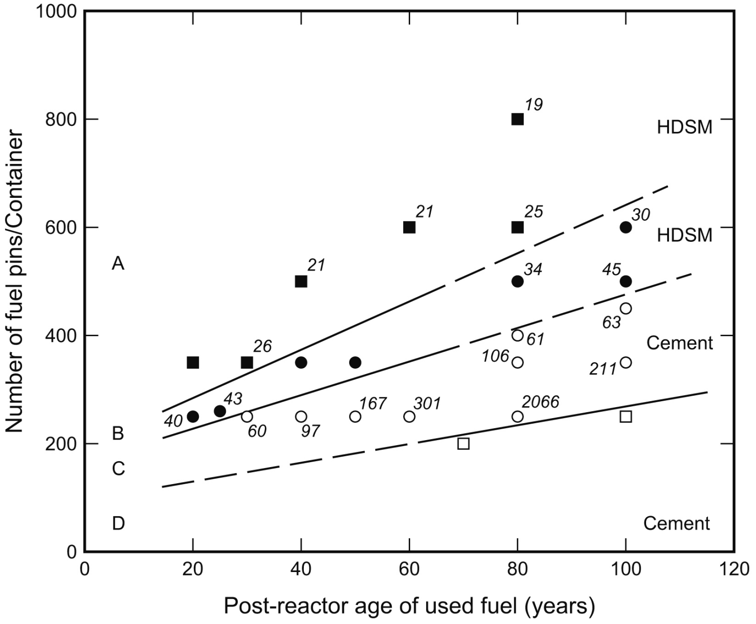

FIG. 10. Outcomes (see text) of temperature modelling for DBD of 5-container batches of MOX-65 as a function of age of the fuel and number of pins per container. Symbols indicate outcome; adjacent numbers indicate time in days to first melting of the HDSM (if used).

explained above. If another batch is not to follow there are two options: (1) replace the top container in the batch by one with high enough heat output to transform the outcome to A; or (2) replace the batch with one giving outcome A. If the HDSM is used in cases with outcome C it would only melt and then solidify around the central parts of the stack. Although providing enough physical support and regular sealing at vertical intervals, the latter may not be deemed enough and a cement support matrix would be preferable. The alternative would be to increase the thermal loading of the packages to avoid outcome C. If a disposal yielding outcome D is to proceed there is no option but to use a cement grout to support and seal the containers into the borehole.

In deciding disposal strategy a further consideration is the time for which elevated temperatures persist in and around the borehole. Of particular importance are the timeframes in which melting and subsequent solidification of the HDSM occur both in absolute terms and in relation to the deployments and sealing of the borehole. Taking as an example a batch of five containers with 600 pins of 40 year old MOX-55 (Fig. 9*a*), melting of the HDSM will commence around the middle of the third container 22 days after emplacement begins, i.e. only 8 days after the third container is emplaced. However, melting will not occur at the bottom of the stack until 60 days and at the top until 16.3 years after emplacement with the result that the effects of melting of the HDSM within the annulus will be negligible above the top of the stack before the next batch is emplaced. Solidification of the HDSM around the five containers will begin at the top of the stack after ~43 years, at the bottom after ~76 years and be complete (at the mid-point) after ~137 years. In none of the cases we have modelled can melting of the HDSM occur at the top of the growing stack before the next container in the batch is emplaced but if this proved possible for a specific case the disposal strategy would need to be revisited and either thermal loading or the deployment interval reduced. It appears unlikely that long periods (hundreds of years) for completion of solidification would necessitate a change of disposal strategy. The main factors affecting the choice of disposal strategy are more likely to be economic with optimization of the balance between making the most efficient use of borehole capacity by disposing of as many fuel pins as possible and

https://doi.org/10.1180/minmag.2012.076.8.16 Published online by Cambridge University Press

the need to keep post-disposal temperatures to an acceptable level. The latter could involve reducing the numbers of pins per container or prolonging pre-disposal cooling.

DBD of complete assemblies

Other versions of DBD (Massachusetts Institute of Technology, 2003; Brady *et. al*., 2009; Arnold *et. al*., 2010), like most mined repositories, look to dispose of whole fuel assemblies as opposed to the pin 'consolidation' approach advocated here. Although it makes inefficient use of expensive borehole space, there can be good reasons for disposing of complete assemblies other than simply avoiding the cost of removing the pins. For example, high burn ups can lead to the fuel cladding becoming embrittled so increasing the risk of damage during removal of the pins and possible escape of the instant release fraction radionuclides into the pond water. It might therefore be deemed desirable to dispose of assemblies from which only the top and bottom nozzles (and possibly the control rods) are removed.

The DBD concept described above allows for disposal of complete assemblies with one per container. We have yet to modify our models and *GRANITE-2* to take account of all the other components in an assembly but a very good approximation of the outcomes can be obtained from the consolidated cases with 260 pins per container, i.e. only four less than in a whole assembly. Two such cases are illustrated in Fig. 11. That for 25 year old MOX-65 gives outcome B and for only slightly younger fuel (~20 years) or more containers in the batch would give outcome A. Either way it is suitable for LTVDD-2a using the HDSM. On the other hand, in the case of UO2-65, container surface temperatures fall well short of those required for the HDSM and whole assemblies would have to be disposed of using a cement support matrix (LTVDD-2b).

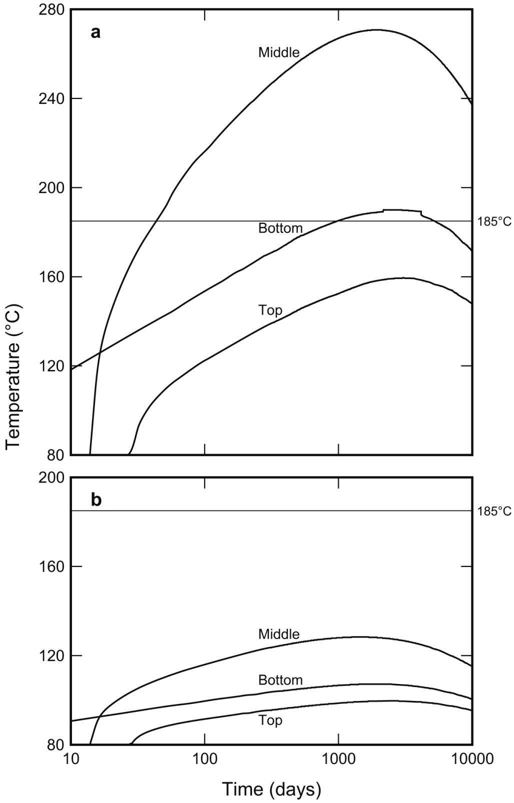

FIG. 11. Evolution of temperature at the outer surfaces of the containers in batches of 5 emplaced at 7 day intervals: (*a*) 260 pins of 25 year old MOX-65; and (*b*) 260 pins of 25 year old UO_2-65.

Conclusions

The heat flow modelling reported above supports the view that, for higher burn up irradiated UO_2 and MOX nuclear fuels of the type likely to be used in new build reactors, deep borehole disposal with fuel pin consolidation is a viable option for most combinations of fuel type, burn up, age and number of pins in a container. The preferred support matrix, a high-density $Pb_{40}Sn_{60}$ alloy shot, may not be appropriate for low pin numbers of older UO_2 fuels and a cement-based grout may have to be used if the disposal strategy cannot be changed. Although not specifically modelled in this paper, there is great scope for mixing both the types and ages of the pins in the containers and for having different contents of the containers in the disposal. This allows considerable flexibility for the disposal strategy to optimize the disposal conditions and benefits. In cases where pin consolidation by dismantling fuel assemblies is considered undesirable, the disposal of complete assemblies is a viable option.

Acknowledgements

We thank Mike Cooper for drafting the figures and Fiona Neall, Ian McKinley and an anonymous referee for helpful reviews.

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https://doi.org/10.1180/minmag.2012.076.8.16 Published online by Cambridge University Press