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Application of a novel approach to assess the thermal evolution processes associated with the disposal of high-heat-generating waste in a geological disposal facility

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ABSTRACT

The widely accepted solution for the long-term management of higher activity radioactive waste is disposal in a suitably engineered facility, located deep underground. A geological disposal facility (GDF) consists of a series of engineered and natural barriers preventing or inhibiting the release of radioactivity. These barriers include: the radioactive wasteform, the waste disposal container, the buffer material to protect the container and the natural barrier provided by the rocks in which the facility is constructed. This multi-barrier system aims to isolate the waste and contain the harmful effects of the radioactivity on humans and biota in the surface environment. The engineered barrier system (EBS) used in a GDF can include buffers based on cement and clay-based materials. The choice of buffer can have significant implications for the disposal system; the heat must be managed such that the properties of the buffer are not compromised to the extent that it cannot deliver the required level of safety. One of these materials is bentonite, usually rich in sodium montmorillonite, selected for its swelling properties and low hydraulic conductivity when saturated. In the presence of significantly elevated temperatures sodium montmorillonite can undergo mineral alteration, reducing the swelling properties of this material. This paper describes an efficient approach to assess strategies for meeting a maximum temperature constraint placed on either the buffer or geosphere surrounding the waste container. In preparation for designing and building a GDF, it is important, for the purpose of robust planning, to understand the important factors, and uncertainties, affecting the maximum temperature. The objective of this work is to inform the future emplacement strategy to enable: appropriate decay storage times; acceptable waste package loading and spatial configurations of the packages to be determined, to thus enable high-heat-generating waste to be safely disposed in a GDF.
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1. Introduction

In the UK it is government policy that all higher activity waste will be disposed in a geological disposal facility (DECC, 2014). The programme of activities to develop a geological disposal facility (GDF) is at a generic or preparatory stage as the location, and hence the geological setting, for a GDF is not known. In some countries, waste management organisations have made significant progress towards the siting and licensing of a facility to dispose of higher activity waste (Posiva, 2012; SKB, 2011), and in other countries this progress is less advanced (Jove Colon et al., 2013; NUMO, 2015). As part of the planning stage in the UK, a range of disposal concepts have been identified to enable disposal of the wide range of UK's radioactive wastes in a variety of possible geological environments. This is to illustrate the potential types or combinations of engineered and natural barriers that could be used for a GDF upon which an environmental safety case could be developed (NDA, 2010a).

The wastes for geological disposal comprise all radioactive material that has no further use and that cannot be managed under the policy for the long-term management of solid low level radioactive waste in the United Kingdom through, for example, emplacement in the low-level waste repository (LLWR). Included in these higher activity wastes is a number of high-heat-generating wastes (HHGWs) and nuclear materials (spent fuel and plutonium) that are subject to government policy decisions and nuclear plant operating decisions, and therefore may be declared as wastes in the future (RWM, 2015a). The inventory for disposal of high-heat-generating UK wastes and materials therefore potentially includes the following (DECC, 2014):

- Vitrified High Level Waste (HLW) from spent fuel reprocessing;
- Advanced Gas Reactor (AGR) spent fuel (SF) that is not reprocessed;
- Pressurised Water Reactor (PWR) spent fuel;
- Spent fuel from a potential new build programme;

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- "Exotic" fuels (includes a range of fuels from UK research and defence activities);
- Magnox spent fuel (if not reprocessed);
- Mixed-oxide (MOX) spent fuel (from any potential future re-use of UK plutonium);
- Separated (unirradiated) plutonium that is unsuitable for reprocessing as MOX.

The disposal of HHGW in a GDF creates a number of technical questions that need to be addressed in order that a robust and environmentally safe disposal solution can be developed. The work presented in this paper aims to enhance the understanding of the factors affecting geological disposal of HHGW with a view to supporting the development of a robust disposal concept for these wastes and to identify priority areas for research. A full description of the scope of research being undertaken is provided in a project roadmap (Holton et al., 2012) and in the project report (RWM, 2015b).

One important aspect of the investigation, reported here, is to understand the consequences of placing a maximum temperature constraint on the buffer material (or host rock), to ensure the key safety functions (e.g. the ability of the buffer to protect the container) are not unduly impaired. The process of exploring the waste package loading and the separation of the HHGW packages to ensure these limits are not exceeded, is termed thermal dimensioning (Hökmark et al., 2009). This analysis is an important aspect of determining the size, schedule and cost of a GDF.

2. The inventory of high-heat-generating waste

The UK government's framework for "Implementing Geological Disposal" (DECC, 2014) defines the inventory for disposal in a geological disposal facility (GDF) in terms of types of higher activity radioactive wastes (and nuclear material that could be declared as waste). Radioactive Waste Management (RWM), a wholly owned subsidiary established by NDA to manage the delivery of a GDF, has developed a more detailed description of this inventory (a 'Derived Inventory') for use in generic GDF design and assessment work to support the implementation process. This inventory includes projections for future waste arisings made by the organisations that operate sites where radioactive waste is generated, based on assumptions as to the nature, scale and timing of future operations and activities. The various assumptions relevant to future arisings of HHGW and materials underpinning the 'Derived Inventory' are given in Table 1. For each type of material the estimated masses of unpackaged material is given.

Table 1
Key assumptions for each high-heat-generating waste and material type in the 'Inventories for assessment purposes'.

Waste/material type	'Inventories for assessment purposes' tonnes of uranium (tU), tonnes of heavy metals (tHM)
HLW[a]	All 2013 UK RWI HLW from reprocessing 55,000 tU Magnox SF and 5000 tU AGR SF
Spent fuel (SF)	4500 tU advanced gas-cooled reactor (AGR) SF 1050 tU pressurised water reactor (PWR) SF 740 tU Sellafield legacy ponds SF 10 tHM prototype fast reactor (PFR) SF 8260 tU EPR SF (PWR new build) 6030 tU AP1000 SF (PWR new build) 1460 tHM Mixed oxide fuel (MOX) SF Submarine SF included but not quantified.
Pu	5.75 tHM separated plutonium residues from civil SF reprocessing (representing 5% of 115 tHM UK-owned plutonium unsuitable for reuse as MOX fuel)[b].

[a] Note that a small portion of HLW created from reprocessing UK spent fuel will be returned to overseas customers under waste substitution arrangements.
[b] There is potential for this quantity to change, for two reasons: the assumption is based on predictions of the final reprocessing outturn; and Government policy allows the UK to take title to overseas plutonium under commercial terms.

3. Disposal concepts for high-heat-generating waste (HHGW)

There is a wide range of designs that could be considered when developing a disposal concept for HHGW. At this generic stage, RWM has identified three illustrative concepts for HHGW; one in each of three generic geological environments, higher strength rocks (HSR), lower strength sedimentary rocks (LSSR) and evaporites (NDA, 2010a). However, a number of other, less well-developed concepts could also be considered. For this particular thermal dimensioning analysis study, a wider selection of five different disposal concepts for HHGW are considered, spanning a range of feasible engineering construction methods and waste container deposition configurations. A methodology is developed to consider the consequences of the full range of parameter uncertainties associated with these disposal concepts, including engineering material and geosphere properties, to understand the flexibility and limitations of the designs. To do so, a fast and efficient modelling approach was developed to enable the consequences of those uncertainties to be considered using thermal dimensioning to understand the dependencies between material parameters and the contents and spacings of the waste containers in the disposal concepts, outlined below:

- Concept A1 - Copper waste containers emplaced vertically in boreholes in higher strength rock (as illustrated in Fig. 1)
- Concept A2 - Carbon steel waste containers emplaced horizontally in tunnels in lower strength sedimentary rock (as illustrated in Fig. 2)

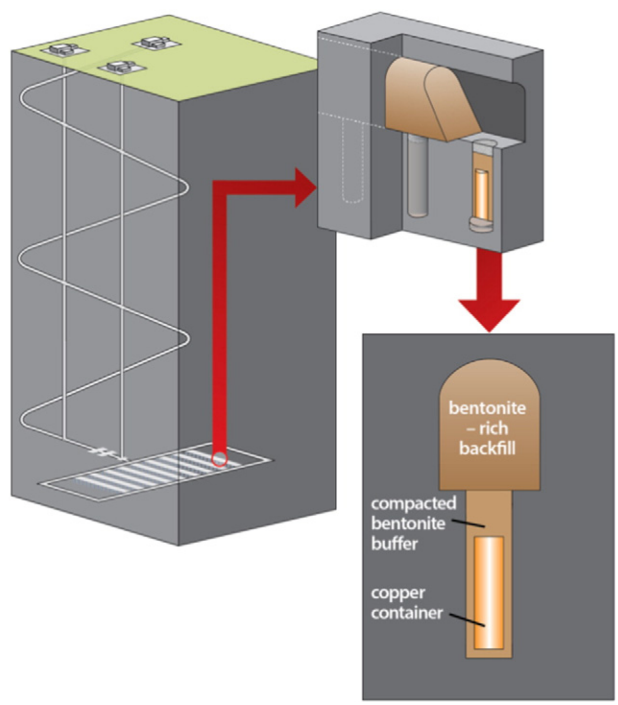

Fig. 1. Copper waste containers emplaced vertically in boreholes in higher strength rock (Concept A1). The illustrative concept for higher strength rock is based on SKB's KBS-3V concept (SKB, 2004) in which the waste containers, consisting of a copper container with a cast iron insert, are emplaced in deposition holes (vertical boreholes). The disposal container design has been developed by Arup on behalf of Radioactive Waste Management (RWM) (Arup, 2014) based on the container design originally developed by SKB of Sweden. These have been designed to relatively small payloads (e.g. up to four LWR fuel assemblies). The waste containers are surrounded by a compacted bentonite buffer. The compacted bentonite buffer leaves small gaps at the interfaces between the waste container and buffer, and between the buffer and host rock. It is assumed that the innermost gap is open at the time of emplacement, and that the outermost gap is filled with bentonite pellets. Deposition holes are separated by a specified distance along deposition tunnels.

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