Development of Understanding of Disposability of High-Heat-Generating Wastes in the UK - 15359

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ABSTRACT

The inventory of radioactive wastes planned for geological disposal in the UK is diverse. This inventory includes a range of high-heat-generating wastes and potentially some other nuclear materials (some spent fuel, uranium and plutonium) that are subject to government policy decisions and therefore may be declared as wastes for geological disposal in the future. To ensure that safe disposal solutions can be developed, it will be necessary to understand the influence of this heat on engineered barrier systems for the range of generic disposal concepts being considered in the UK. Furthermore, waste producers need to develop packaging solutions for these materials that take account of any thermal constraints.

For these reasons, RWM has established the High-heat-generating Wastes Project (Project Ankhiale), a dedicated project to enhance understanding of the factors affecting geological disposal of high-heat-generating wastes with a view to supporting future decision making and concept selection. The project has been established around a multi-disciplinary Integrated Project Team (IPT), comprising members of RWM, Amec Foster Wheeler and external experts, to provide a comprehensive approach across a range of technical disciplines.

Phase 2 of the project, which comprises a series of specific technical activities, commenced in March 2013 and, since then, progress has been made across the following five broad categories:

- Compilation of the inventory of UK high-heat-generating wastes;
- Waste package performance work;
- Development of a better understanding of thermal constraints for different buffer materials;
- Exploration of the range of disposal parameters using a thermal dimensioning modelling tool; and
- Concept engineering design work.

INTRODUCTION

The Nuclear Decommissioning Authority (NDA) is responsible for planning and implementing geological disposal in the UK and has established the Radioactive Waste Management Limited (RWM) (a wholly owned subsidiary) for this purpose. The RWM work programme is currently at a generic stage as the geological environment for a geological disposal facility (GDF) is not yet known. A range of possible disposal concepts have therefore been identified to enable disposal of the wide range of radioactive wastes in the range of possible geological environments. This is to illustrate the potential range of engineered and natural barriers that could be used for a GDF in the UK, upon which generic safety cases can be developed.

The inventory of radioactive wastes planned for geological disposal in the UK is diverse. This inventory includes a range of high-heat-generating wastes and potentially some other nuclear materials (some spent fuel, uranium and plutonium) that are subject to government policy decisions and therefore may be declared as wastes for geological disposal in the future. The inventory of high-heat-generating UK wastes and materials therefore potentially includes the following:

- Vitrified High Level Waste (HLW) from spent fuel reprocessing;
- Advanced Gas Reactor (AGR) spent fuel (SF) that is not reprocessed;
- LWR SF from Sizewell B (currently the UK's only LWR);
- SF from a potential LWR new build programme;
- "Exotic" fuels (includes a range of fuels from UK research and defence activities);
- Magnox[1] SF (if not reprocessed);
- Mixed-oxide (MOX) SF (from any future re-use of UK plutonium);
- Separated (unirradiated) plutonium.

For the purpose of robust planning, the materials above are assumed to be declared as waste and plans for its disposal in a GDF must therefore be developed.

The disposal of high-heat-generating wastes in a GDF creates a number of technical questions that need to be answered in order that safe disposal solutions can be developed. For these reasons, RWM has established the High-heat-generating Wastes Project (Project Ankhiale), a dedicated project to enhance understanding of the factors affecting geological disposal of high-heat-generating wastes with a view to supporting future decision making and concept selection. The Project aims to enhance understanding of the factors affecting geological disposal of high-heat-generating wastes with a view to supporting the development of the disposal system specification (i.e. the disposal system requirements) and spent fuel life cycle options (e.g. supporting the development of packaging solutions). This will be achieved through a series of activities that will develop understanding and create UK expertise in the geological disposal of high-heat-generating wastes.

The project has been established around a multi-disciplinary Integrated Project Team (IPT), comprising members of RWM, Amec Foster Wheeler and external experts, to provide a comprehensive approach across a range of technical disciplines.

The project was split into two distinct phases: a preparatory period, referred to as Phase 1, followed by a series of specific technical activities that are being executed in Phase 2.

During Phase 1 of the Project, a methodical approach was used to identify how high-heat wastes could affect the performance of the barrier systems employed in the various disposal concepts. This exercise informed the scope of work to be carried out in Phase 2 of the project, as set out in the Project Roadmap [1]. Phase 2 commenced in March 2013, and having run for about 2 years will be consolidating results into a final report due for publication in June 2015. The information obtained will be used to support concept design and to advise waste producers on packaging and storage requirements for their heat-generating wastes, as well as to define future research needs.

This paper provides an overview of the work that has been carried out within Phase 2, with particular emphasis on the work carried out on the influence of heat on buffer materials.

PHASE 1 – SCOPE DEFINITION

The RWM work programme is currently at a generic stage as the geological environment for a GDF is not yet known. A range of possible disposal concepts have therefore been identified to enable disposal of the

[1] Magnesium-alloy clad metallic uranium fuel used in the UK's first generation of commercial gas-cooled power reactor.

wide range of radioactive wastes in the range of possible geological environments. During Phase 1 of the Project, a methodical approach was used to identify how high-heat wastes could affect the performance of the barrier systems employed in the various disposal concepts.

For the purposes of the Project, a range of concept options was selected that is focused on the most likely combinations of waste type, container type and material of construction, buffer material, backfill material, geology and concept geometry. The options have been developed around three basic container types: disposal canisters, multi-purpose containers (MPCs) and supercontainers [2]:

- **Concept A1** (Fig. 1a) – Concept A1 describes the emplacement of copper disposal containers in vertical deposition holes. The disposal containers are surrounded by a compacted bentonite buffer. A higher-strength host rock is assumed.
- **Concept A2** (Fig. 1b) – Concept A2 describes the emplacement of carbon-steel disposal containers horizontally along the centre of emplacement tunnels. A pelleted bentonite backfill is assumed. It is assumed this is applicable to a lower-strength sedimentary host rock.
- **Concept A3** (Fig. 1c) – Concept A3 describes the emplacement of disposal containers vertically in a mined borehole matrix of deposition holes. The disposal containers are of smaller diameter than the standardised designs, for consistency with international precedents for this concept. A number of disposal containers are emplaced in each deposition hole, separated from each other. The assumed host rock is an evaporite. A backfill of crushed host rock would be used.
- **Concept B** (Fig. 2a) – Concept B describes the emplacement of rows of Multi-Purpose Containers standing vertically in a disposal vault. A cementitious backfill and higher-strength host rock have been assumed.
- **Concept C** (Fig. 2b) – Concept C describes the emplacement of pre-fabricated engineered modules (‘supercontainers’) horizontally along emplacement tunnels. The pre-fabricated engineered modules incorporate a carbon steel disposal container within a cementitious over-pack. Any remaining volume in the emplacement tunnels is backfilled with cement. A lower-strength sedimentary host rock is assumed.

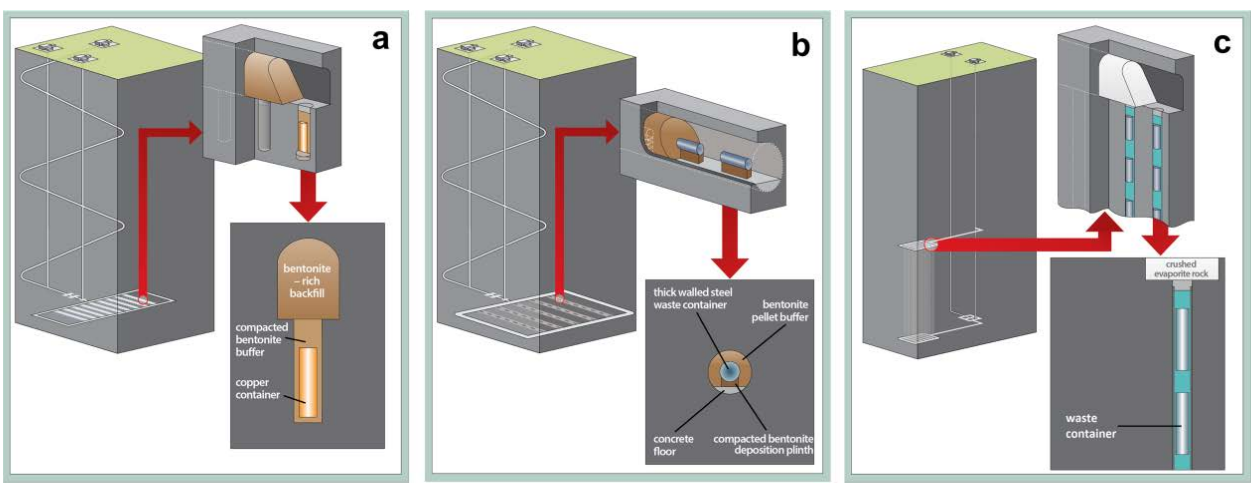

Fig. 1. (a) Concept A1, (b) Concept A2, (c) Concept A3

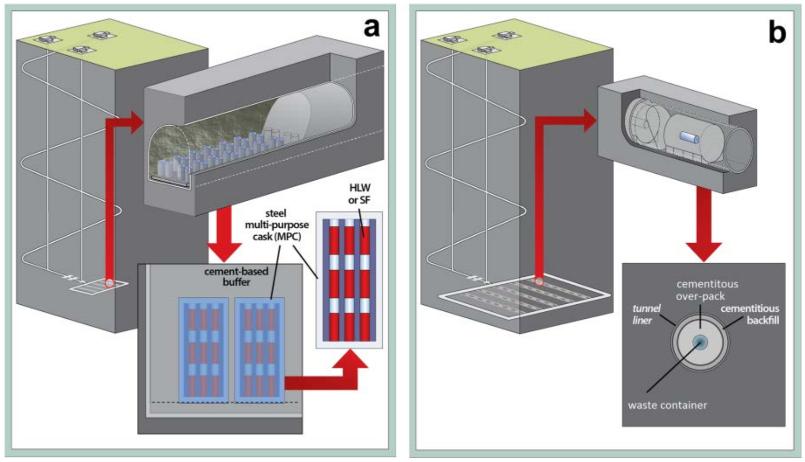

Fig. 2. (a) Concept B, (b) Concept C

The key safety features, or safety functions, of the individual concept options were identified; the potential for each of these to be impacted by higher thermal loadings was then evaluated. In particular, consideration was given to where further work would be required to understand the impact of higher thermal loadings on specific barrier combinations and scenarios. The areas of uncertainty, identified from this exercise, were used to define the scope of work to be undertaken in Phase 2 of the Project and, as defined in the Project Roadmap published in January 2013 [1], can be summarised into the following five broad categories:

- **Compilation of the inventory of UK high-heat-generating wastes**, which will allow definition of a range of irradiation scenarios and waste packaging options;
- **Waste package performance work** to ensure that pre-existing work on potential candidate container materials takes account of the elevated temperatures experienced in the thermal period for higher activity wastes;
- **Development of a better understanding of thermal constraints for different buffer materials**, with a focus on swelling clays (e.g. bentonite);
- **Exploration of the range of disposal parameters using a thermal dimensioning modelling tool**, which will allow optimised disposal scenarios to be identified for the full range of generic geological settings and outline concept designs; and
- **Concept engineering design work** to examine the feasibility of the disposal concepts for high-heat-generating wastes in relation to the engineering design and implementation.

In addition to the core scope of work, the project includes an integration scope, to support the broader aspects related to the disposability of high-heat-generating wastes being carried out by RWM. Such ‘integration’ activities support progress with the core tasks and ensure consistency with respect to source data and assumptions supporting iterative development of the disposal system.

INVENTORY DEVELOPMENT

The potential range of UK high-heat-generating wastes is diverse, encompassing vitrified HLW, spent fuels of many different types and separated plutonium. In order to develop a sound basis for geological disposal, it is important to ensure that the nature and quantities of these materials is well understood. Furthermore, it is necessary to provide a means for retaining and interrogating data pertaining to the inventory of these materials to allow different disposal scenarios to be readily explored.

Despite the development of a comprehensive UK Radioactive Waste Inventory [3], significant uncertainty remains to be associated with the available information for high-heat-generating wastes. Examples of such uncertainty include the irradiation history of wastes and materials that have not yet arisen, and in relation to future operation of existing and potential future facilities e.g. how long reactors will operate. Particular uncertainty relates to a potential new nuclear programme in the UK. Given the potential significance of such uncertainties on heat output, it was identified that the early focus of the Project would be to reduce the uncertainty in the projected inventory potentially received by a GDF.

Of the set of high-heat-generating wastes selected for analysis within the project, inventory data were not previously available for all material types, particularly those relating to future arisings from existing and potential new build power stations. To address this uncertainty, work was therefore undertaken to develop a set of reference inventories using ORIGEN and FISPIN calculations. These reference inventories, along with the existing legacy waste stream inventories, form the basis of the calculations performed within the Inventory Tool, developed for use within the project.

In the Inventory Tool, the user may aggregate various types of heat-generating material; for each material the user may specify a mass and a decay time and, if appropriate, burnup, rating and initial enrichment. This functionality, in combination with the underpinning reference inventories, provides a flexible approach for the examination of a range of inventory scenarios including potential future arisings. The Inventory Tool allows the user to generate:

- The inventory of spent fuel or HLW in a single disposal package
- Total radionuclide inventories for a whole vault or a whole GDF

The outputs are then used in the Thermal Dimensioning Tool (see later section) to calculate the evolution of heat against time and hence the temperatures in a GDF.

Data on actual enrichments, ratings, burnups and cooling times of spent fuel assemblies from some of the UK's existing fleet of reactors has also been examined and the current and future decay power produced has been estimated. Analysis of the distributions of power provides useful information not only for the disposal of these particular materials but may also provide insight into the variation that could be seen among spent fuel assemblies from a future UK New Build programme.

So, in summary, significant progress has been made in both the development and application of tools to underpin the inventories of high-heat-generating wastes and, for specific waste streams, to better understand the variability in the power output of heat-generating waste.

WASTE PACKAGE PERFORMANCE

RWM has considered the likely performance of a range of potential candidate container materials (copper, carbon steel/cast iron, titanium alloys, nickel alloys and stainless steel) for high-heat generating waste packages for a range of disposal scenarios based on illustrative disposal concepts that might be appropriate for the UK. Initial work has focused on the long-term (post-closure) corrosion behaviour of candidate materials in conditions relevant to disposal in a GDF. Subsequent work considered the durability of candidate container materials in conditions relevant to scenarios of interim storage and GDF operations, and evaluated the potential impact of operational factors on the durability of the candidate container materials in any following stage. The high-heat generating waste Project will build upon this work by exploring different container and buffer material combinations and the impacts of elevated temperature on long-term performance.

NRWM has commissioned a series of studies examining the long-term performance of different high-heat generating wasteforms, specifically to understand how wasteforms such as HLW glass and uranium oxide matrices release radionuclides through ageing processes. Further work within the current Project will consider the effects of thermal decay on these ageing processes, for example, in terms of thermal creep of fuel cladding and chemical oxidation of fuel pellets. This is particularly relevant to the UK situation due to the unusual nature of certain spent fuel types generated in the UK, e.g. stainless steel clad AGR fuel, for which understanding is quite limited when compared to Zircaloy-clad LWR spent fuels.

THE INFLUENCE OF HEAT ON BUFFER MATERIALS

The various components of the multiple barrier geological disposal system contribute to fulfilling the high-level safety objectives of containment and isolation in different ways over different timescales. A range of materials, both natural and synthetic, are available for fabrication of an engineered barrier system (EBS). The choice of barrier components and materials to integrate in a disposal system remains open at the current (generic) stage of development. The EBS consists of the wasteform, waste container, buffer and geosphere. The buffer is a material placed immediately around an emplaced waste container and acts as a barrier between the waste container and the geosphere.

International radioactive waste management organisations have developed many potential designs for a GDF. Often these designs use cement, or swelling clay (e.g. bentonite), or both in the near-field of the GDF (as buffer or backfill). As part of Phase 2 of this project, reviews were undertaken to elucidate the current status of work related to (i) the methods for enhancing the thermal properties of bentonite and (ii) the performance of cement at high temperatures.

This work provided a significantly deeper understanding of the viability and constraints on the use of bentonite and cement in a higher temperature environment. Areas for further development were identified and these mainly consisted of further experimental investigations which would help to fill the proposed knowledge gaps. The two studies are summarised in the following sections.

Review of the Current Status of Work on Enhanced Bentonite Buffer Materials

Bentonite is used as a buffer material in GDF designs because:

- It will swell, leading to closure of voids;
- The high swelling pressure will reduce microbial activity;
- It will have a very low permeability and therefore restrict water-borne migration processes;
- It will filter colloids; and
- It will strongly sorb some important radionuclides.

The use of bentonite has important implications for the management of high-heat-generating wastes. This is because bentonite could undergo chemical alteration if its temperature were to increase much above 100 °C for an extended period. Adoption of a thermal limit of 100 °C has been identified as a constraining factor for some of the hottest spent nuclear fuels, for example new build spent fuel, and represents a challenge to waste producers. It would therefore be beneficial if the thermal conductivity of the buffer material could be enhanced such that the temperature of the buffer surrounding a spent fuel canister can be maintained below 100 °C. This limits the power input on the canister which may have major implications on waste loadings and cooling times for many of the spent fuel types.

Bentonite is extracted from a range of different geographical locations and comes in a variety of mineral compositions. Its thermal conductivity depends on the type of bentonite, and is sensitive to its density and water content. It has been suggested that by mixing materials of higher thermal conductivity with bentonite, the resulting mixture can have thermal conductivity higher than bentonite alone. A review on enhanced bentonite buffer materials [4] was carried out to gather information which could be applicable to a range of conceptual designs. The objectives of the review were to:

- Summarise the most recent work on bentonite mixtures;
- Quantify the natural spread in thermal conductivity of the basic bentonite materials as a basis for comparison with mixtures that have been designed to have enhanced thermal conductivity;
- Quantify the effect of adding material to enhance the thermal conductivity of bentonite;
- Understand to what extent the other important buffer properties continue to be in an acceptable range (i.e. preserve the safety functions of the buffer); and
- Quantify the extent to which potential practical enhancement to the thermal conductivity can improve the thermal management of the buffer.

It is noted that, although a high thermal conductivity is desirable, the bentonite would still need to be able to carry out its function as a buffer. The criteria for other functions, and hence for the selection of buffers, have yet to be identified (in a UK context). Aspects of the hydro-mechanical criteria for bentonite buffers proposed in the Swedish KBS-3V concept were therefore used as a reference. In particular, it is likely there will be a requirement that the hydraulic conductivity of the buffer material is sufficiently low, for example less than 1×10^{-12} ms^{-1}, and a requirement that the swelling pressure is sufficiently high, for example, greater than 2 MPa.

Two additives were considered to increase the thermal conductivity of the buffer: sand (quartz) and graphite. The thermal conductivities of the additives are high: for quartz the thermal conductivity can be as high as 10 $Wm^{-1}K^{-1}$ and for graphite it is over 100 $Wm^{-1}K^{-1}$. The thermal conductivity of bentonite is in the range 0.5 - 1.5 $Wm^{-1}K^{-1}$.

Figure 3 illustrates the thermal conductivities of different bentonite materials as a function of density. Ca-bentonite 15 wt% graphite is plotted as an empirical relationship which was determined by Jobmann and Buntebarth from fitted data [5].

In determining thermal conductivity values:

- For bentonite without any additives the range of values identified is between 0.61 and 1.76 $Wm^{-1}K^{-1}$.
- For bentonite mixtures with sand additives the range is between 1.00 and 1.82 $Wm^{-1}K^{-1}$. As demonstrated in Figure 3, this range is almost entirely within the range of bentonite without any additives, showing that sand additives do not have a significant effect on increasing thermal conductivity.
- For bentonite mixtures with graphite additives the range is between 1.50 and 2.91 $Wm^{-1}K^{-1}$. It is possible to achieve a significant increase in thermal conductivity using graphite additives, but further investigation would need to be carried out to show that safety functions are not compromised.

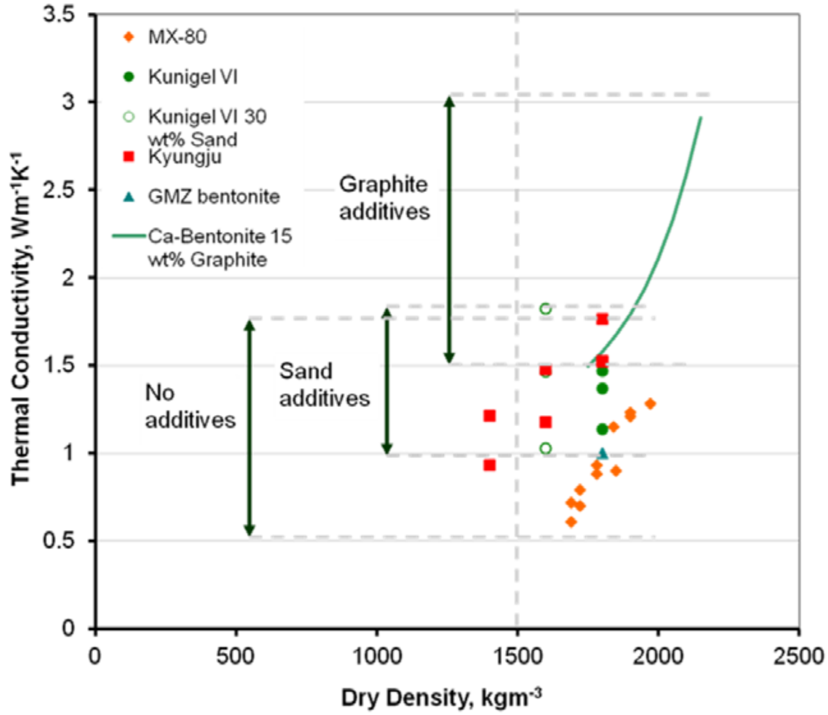

Fig. 3. Thermal conductivities of different bentonite materials as a function of density

Preliminary numerical analysis of an illustrative concept based on the Swedish KBS-3V concept with comparatively modest levels of thermal conductivity enhancement arising from the addition of sand demonstrates there is very little benefit to be gained from sand from a thermal management perspective. However, the enhancements offered by the addition of graphite can provide the opportunity to more substantially influence its thermal performance. In particular, illustrative calculations showed that for a fixed cooling time of 83 years it was possible that the maximum buffer temperature could be 6 degrees lower if the thermal conductivity is 3 $Wm^{-1}K^{-1}$. Alternatively, to achieve the same maximum buffer temperature of 100 °C, emplacement could be made twelve years earlier (i.e. a cooling time of 71 years), when the waste was hotter. The illustrative calculations were made using a scoping tool originally developed by SKB which has been adapted and modified by Radioactive Waste Management Limited [6]. The heat source in the calculations was taken as four PWR assemblies of spent fuel, each with a burnup of 50 GWd/tU.

In summary, it was found that the addition of sand to bentonite does not provide a large enough increase in thermal conductivity to warrant further consideration as a means to enhance the thermal performance of the buffer for a KBS-3V based disposal concept. The addition of graphite appears to show promise although the benefits are relatively modest and there is incomplete information on how all aspects of the buffer safety functions are affected. In the UK, as conceptual designs become clear, it will be necessary to investigate the performance of bentonite materials available to the UK and this may lead to further investigation of the possible use of bentonite/graphite based materials.

Review of Cement Performance at High Temperature

Cementitious materials have been extensively investigated as backfill material for ILW and LLW disposal facilities and are now also being considered for use in disposal concepts for high-heat-generating wastes, for example, in the Belgian supercontainer concept for HLW and spent fuel and in multi-purpose container (MPC) vault concepts.

Cement is used as a buffer/backfill material in GDF designs because:

- It can provide structural support;
- It can be used to backfill areas within the GDF; and
- It can provide alkaline conditions, which would:
  - reduce steel corrosion
  - reduce the solubility of some important radionuclides
  - increase the sorption of some important radionuclides

As with bentonite, the effect of increased temperature on cementitious materials is of interest if cement is to be used as a buffer material in disposal concepts for high-heat-generating wastes. A review was therefore carried out to determine the current status of research into, and understanding of, the performance of cement exposed to high temperatures, with respect to its ability to deliver the required safety functional requirements [7]. This was particularly concerned with operating conditions in which cementitious materials are subject to sustained exposure to temperatures in excess of 100 °C.

A variety of sources were investigated including research relating to fire resistance, applications in nuclear power facilities and refractory concrete for use in furnaces and kilns. The information available on performance under sustained exposure to elevated temperatures above 100 °C is very limited and deals largely with mechanical and thermal properties.

In all of the limited investigations on the effect of sustained exposure to elevated temperature the following behaviour was reported:

- The **compressive strength** is reduced with increasing temperature by about 25%, up to the assumed maximum GDF operating temperature of 300 °C and with significantly greater reductions as the temperature increases above this level. The tendency is for strength degradation to be higher when drying occurs. At the maximum assumed operating temperature of 300 °C, the relative strength (to that prior to heating) is about 75%.
- The **elastic modulus** is reduced to a greater extent than the compressive strength and is much more sensitive to the various influencing factors. The relative modulus tends to reduce linearly from 100 °C to close to zero at 800 °C but is highly variable and at the maximum assumed operating temperature of 300 °C, the relative elastic modulus may range from 40% to 90%. However, degradation of the elastic modulus, although significant at elevated temperature, will not jeopardize the integrity of a GDF. Maintaining a high elastic modulus is only critical if deformation under load is to be limited. In a GDF, the primary loading after exposure to elevated temperature will be the result of restraint to thermal and shrinkage deformation. Under these conditions, achieving a low elastic modulus is beneficial as it reduces the stresses generated by the restraint to deformation and hence reduces the risk of cracking.
- The **coefficient of thermal expansion** of concrete (cement, sand and aggregate) is approximately constant up to the assumed maximum operating temperature of 300 °C, with a value of about 10 $\pm$ $2x10^{-6}$ mm/mm °C. For mortar (cement and sand) or cement paste, deformation at elevated temperature may be dominated by the effect of shrinkage if drying occurs, such that the net deformation is contraction.
- The **thermal diffusivity** of concrete reduces approximately linearly over the range from 20 °C to 300 °C, with the relative thermal diffusivity at the higher temperature being about 0.4.
- The **permeability** of concrete is increased at elevated temperature, based on very limited data on the change in porosity of cement paste at elevated temperature, and using background information relating permeability to porosity, the estimated permeability at the assumed maximum operating temperature of 300 °C may be ten times higher than the value at ambient temperature. This could

lead to higher rates of flow of groundwater through the GDF, although the effect of the change in the cementitious material will be relatively small compared with any cracking that has occurred.

A relatively recent and extensive review was undertaken by Naus [8]. This study deals principally with the mechanical and thermal properties of the concrete and provides a useful chart (Figure 4) which describes the physiochemical processes that occur in concrete as the temperature increases. Of particular interest is the review of the effects of long-term exposure to elevated temperature, however, in the context of a nuclear power plant, the testing has been limited to months or years and rarely to decades or longer.

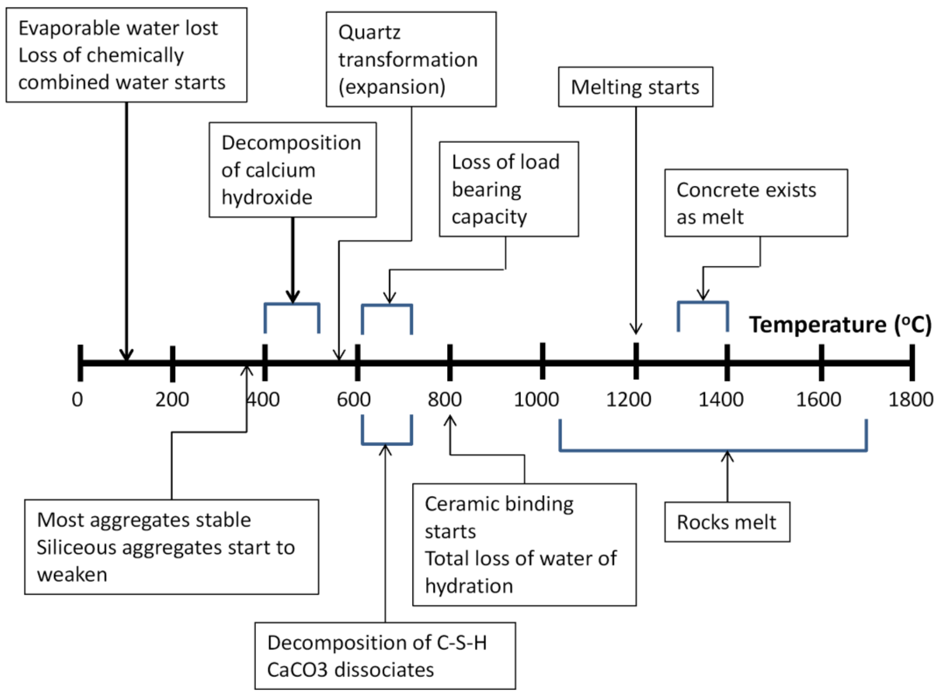

Fig. 4. Physiochemical changes in Portland cement concrete during heating [8]

Research into the impact of elevated temperature which is sustained over long periods is severely limited. Where research has been undertaken it has focused largely on the mechanical and thermal properties of the concrete. Some research has been identified which deals with changes in mineralogy but none has been identified that deals with pore solution chemistry.

In summary, the review provided no evidence to suggest that any of the commonly used cements within the scope of BS EN 197-1 (the British Standard for the UK implementation of the European Standard EN 197-1) or calcium aluminate cements covered by BS EN 14647 1 (the British Standard for the UK implementation of the European Standard EN 14647 1), would be unsuitable for use in GDF applications at temperatures above 100 °C. However, insufficient information was available to enable cements to be ranked in order of performance. Areas requiring further development include investigations into the impact of elevated temperature sustained over longer periods and/or development of an accelerated testing procedure. The research to date has focused largely on the mechanical and thermal properties of the concrete with some research dealing with changes in mineralogy. No research was identified concerning pore solution chemistry so undertaking tests to measure the pore solution chemistry over time and at different temperatures is another area for development.

Thermal Dimensioning Studies

One of the priority areas to be addressed within the high-heat-generating waste Project concerns the effect of heat on the engineered barrier systems. Thermal dimensioning tasks were performed to explore methods and approaches for mitigation of this heat in different disposal concepts. This can be achieved by varying the parameters affecting heat transfer, including waste package loading and spatial configurations of those packages. To accomplish these objectives:

- A robust appraisal was made of the key data used for thermal analysis, uncertainty in that data and the information was incorporated into a project database;
- A thermal dimensioning tool was developed to manage the wide range of concepts and data uncertainty;
- Thermal dimensioning analysis was performed to identify constraints on those disposal concepts;
- Numerical modelling was used to augment (justify and verify) the thermal dimensioning analysis; and
- Parallel studies from international projects, such as DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) and the EBS Task Force, were considered in order to support simplifications and provide technical and scientific underpinning.

The output of this area of work is described in the associated conference paper 15411 [9] so is not described in detail here.

Concept Engineering Design

In order to develop disposal concepts for high-heat-generating wastes, it is necessary to understand the engineering feasibility associated with construction and operability of such concepts. A number of work streams have been carried out to investigate design feasibility issues including.

- Consideration of whether the heat from the spent fuel and HLW disposal areas could affect the temperature constraint of ILW vaults (note that the UK situation currently envisages a co-located facility for disposal of both ILW and high-heat-generating wastes);
- Whether there are any implications for the emplacement of backfill materials around hot packages (e.g. drying of bentonite);
- Operational issues associated with handling and emplacement of larger packages, particularly MPCs, in different geological settings;
- Large vault construction, maintenance and ventilation for an extended operational period and backfilling. Again, this is particularly relevant to the concept being considered for larger MPC type packages where a period of deferred backfilling may be desirable for the management of the higher thermal load that might be associated with these.

Work, including a series of review tasks, has been carried out to elucidate the current understanding of some of these aspects and to identify what future tasks may be required to overcome some of the design challenges posed by the disposal of high-heat-generating wastes.

The output of this area of work is described in the associated conference papers 15466 and 15175 [10,11] so is not described in detail here.

CONCLUSIONS

The work of the IPT has, over a two year programme of work, made significant progress towards developing a technically robust and safe solution for the disposal of high-heat-generating waste. Key project outcomes include:

- Significant progress in both the development and application of tools to underpin the inventories of high-heat-generating wastes and, for specific waste streams, to better understand the variability in the power output of heat-generating-waste.
- A significantly deeper understanding of the viability and constraints on the use of bentonite and cement in a higher temperature environment.
- The development of flexible and easy-to-use tools to support the concept option selection process; these tools are already being used to update the illustrative GDF design and support further concept development work.
- The identification of additional focussed R&D activities to support design developments for high-heat-generating wastes.
- The provision of data and understanding to inform the waste package specification and the application of project tools to support packaging advice and decisions for specific waste streams.
- Inform the disposal system specification requirements for high-heat-generating wastes.
- The implementation of a successful communications strategy: internally using newsletters; externally through conferences, technical papers and collaboration with other international organisations to maximise the benefit of collective knowledge.

The completion of Phase 2 of Project Ankhiale will provide a robust and fully integrated platform for future development of disposal concepts for high-heat-generating radioactive wastes. The outcomes of the project will be described in a final project report due for publication in 2015.

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