Feasibility Studies for the Design of Disposal Vaults for Multi-Purpose Containers (MPCs): Construction, Operation, Ventilation and Management of Heat – 15175

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ABSTRACT

The Nuclear Decommissioning Authority (NDA) subsidiary, Radioactive Waste Management Ltd (RWM) is responsible for the safe implementation of a Geological Disposal Facility (GDF) for radioactive waste in the UK. As part of their generic programme to underpin the planned designs for a GDF, work is ongoing to explore a range of possible geological disposal concepts. This work developed GDF concept designs for Multi-Purpose Containers (MPC) disposal in the generic host rock types considered: higher strength (crystalline), lower strength sedimentary (sedimentary / clay formations) and evaporite rocks. This paper is specific to concepts for the disposal of MPC for Pressurised Water Reactor (PWR) spent nuclear fuel (SF). The key outcomes of the feasibility studies to improve the understanding of the MPC disposal concept and the specific challenges to construct, operate, ventilate, manage heat and backfill associated with this concept are summarised in this paper.

The management of the high loading of radiogenic heat (from 12 PWR SF assemblies in MPCs compared to 4 in 'standard' disposal containers) during an extended open phase (delayed backfilling of the disposal area) of up to 300 years was investigated. The concept designs developed demonstrate it is feasible to construct, operate and ventilate disposal vaults to accommodate open 'storage' periods required for transitional thermal decay of high heat generating waste in higher strength and lower strength sedimentary host rock types considered by RWM.

This work focused on developing two contrasting disposal concepts which are applicable to both higher strength and lower strength rock environments; both of which illustrate how vault temperature, stability and groundwater inflows can be controlled to delay backfilling and allow MPC package thermal output to decrease.

MPC disposal in evaporite rock does not require a cooling period due to its high thermal conductivity and favourable performance at higher temperatures; therefore the concept developed for this rock includes immediate backfilling of disposal tunnels.

A clear understanding of the interactions and limitations associated with heat management during the open period was developed by investigation of a "Heating Ventilation and Air-Conditioning System" (HVAC). It was concluded that removal of heat from the disposal tunnels / vaults is feasible, but introduces significant operational complexity.

INTRODUCTION

In support of UK government policy [1], Radioactive Waste Management Limited (RWM) is responsible for planning and delivering geological disposal of UK radioactive wastes. RWM maintains illustrative designs to demonstrate the viability of geological disposal of Intermediate Level Waste (ILW), High Level Waste (HLW) and spent fuel (SF) in the UK. In addition to these, RWM is exploring a range of possible Geological Disposal Facility (GDF) layouts, safety concepts and the materials used to construct the disposal packages containing the wastes and other engineered barriers.

In 2010, a feasibility study exploring options for storage, transport and disposal of SF was commissioned by the Nuclear Industry Association (NIA), [2] which identified a number of viable options for SF management. In particular, the study recommended further work to evaluate the feasibility of a Multi-Purpose Container (MPC) disposal concept that meets requirements for safe containment of radioactive waste during interim storage, transport and disposal.

The current MPC system design is focused on requirements to satisfy disposal of UK PWR spent fuel. This considers 12 PWR spent fuel assembles (heat output 3.6 kW per MPC) contained in a basket arrangement within a stainless steel container (see Figure 1) that can be used with a variety of specific overpacks for storage at Nuclear Power Plants (NPPs), transport to a GDF and disposal at a GDF [3].

The initial variant being developed for disposal considers a carbon steel overpack (see Figure 1). For the management of the relatively high radiogenic thermal loading, an extended open period (delayed backfilling of the disposal vaults/tunnels for hundreds of years) is required to meet the current thermal targets for bentonite-based backfill. The objective of this work (which is described in detail in [4]) is to improve understanding and explore the feasibility of MPC disposal concept designs, considering UK-specific boundary conditions. This specification was used for the development of feasible MPC concept designs in order to:

- Demonstrate overall compatibility with requirements and assumptions within the generic Disposal System Technical Specification (DSTS) [5] and further develop understanding of the technical requirements on the disposal system;
- Support the scoping assessment of the safety, environmental, social and economic impacts of a GDF;
- Support assessment of the disposability of high heat generating waste packages proposed by waste producers.

We have considered a range of factors that would impact feasibility, surveyed the performance targets that could be set on the backfill and considered specifically the heat management aspects of MPC concept designs. The main tasks included:

- Setting parameter values for the MPC system – i.e. the shape, size, weight, thermal load and surface dose rate of the MPC disposal package;
- Timing and scheduling – waste arising, cooling periods for waste underground and timing of backfilling;
- Concept design practicalities for major underground infrastructure – waste emplacement strategies and heat management, ventilation and drainage requirements;
- Backfill materials that could be used in the MPC concept – clays, cements, mixed rock, sand, salt and other combinations or mixtures, including wastes that can be used as void fillers; and
- Target properties for the different backfill materials – their safety functions, performance requirements, and quality levels for assuring target properties.

This work has developed credible concept designs for MPC disposal necessary to inform decisions during RWM's implementation of a GDF siting programme, support assessment of MPC packaging proposals and underpin strategic advice to Nuclear Decommissioning Authority (NDA), UK government and waste producers.

DEFINITIONS

RWM use specific terms and definitions within their concept and design process which are outlined below for clarity within this paper:

The MPC disposal container – a carbon steel disposal overpack (see Figure 1) which houses a stainless steel MPC with the internal MPC basket holding twelve spent fuel assemblies. This is used with the MPC system to meet either transport or disposal requirements (referred to herein as 'the MPC').

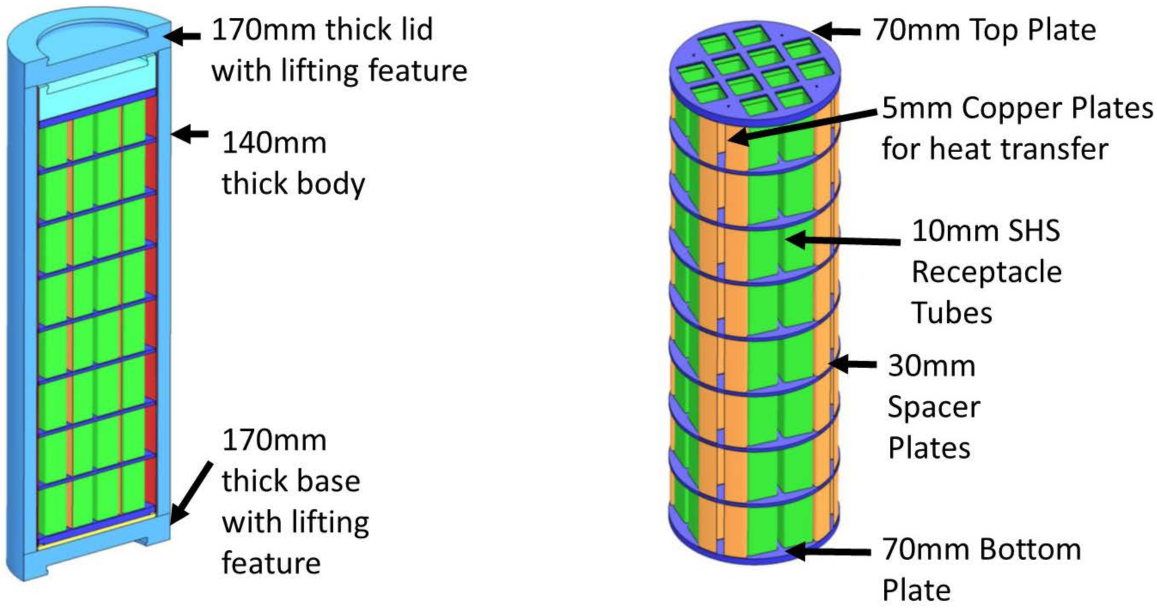
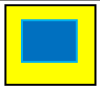
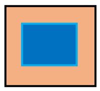
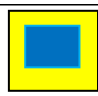
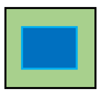
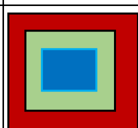
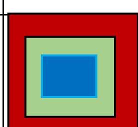
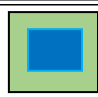


Fig 1: MPC disposal container containing the stainless steel MPC (left) and internal MPC basket design (right) *(Figure courtesy of Arup)*.

MPC system – this includes the waste package and transport system used to transport the waste package from interim storage to the location of a GDF and, thereafter, its emplacement underground at the GDF (i.e. the emplacement system). Table 1 summarises this system (which is described in more detail in [3]).

Table 1: The MPC storage, transport and disposal system (adapted from [3]).

Process step	MPC overpack system	Process step description
Nuclear power plant		Twelve SF assemblies are packaged into MPC and the MPC into transfer overpack to form a transfer Package.
Storage		Transfer Package is transported to storage facility (assumed to be adjacent to NPP). MPC is lowered from transfer overpack into storage overpack.
Transfer		The MPC is transferred from storage overpack to transfer overpack.
Packaging MPC into disposal overpack		The MPC is transferred from a transfer overpack to a disposal overpack.
Transport to a GDF		Disposal container is loaded into transport overpack & into a transport package before transport from packaging plant to a GDF.
Transit underground		The transport package is transferred underground on a GDF wagon.
Disposal at a GDF		The transport overpack is unloaded from the GDF wagon and the disposal container is unloaded from transport overpack. The disposal overpack is then transferred to a disposal area.
Key: MPC, Transfer overpack, Storage overpack, Disposal container, Transport overpack		

Disposal vault and disposal tunnel - Disposal vaults typically have cross-sections of about 200 m^2 to 250 m^2. Disposal tunnels typically have a relatively small cross-section of about 2.5 m^2 to 4.5 m^2 [6].

Backfill –Three types of backfill are defined:

1. Localised backfill is emplaced around waste packages;
2. Peripheral backfill is emplaced between the localised backfill and the host rock;
3. Mass backfill is the bulk material used to backfill the excavated volume outside of the disposal areas e.g. access tunnels.

Both localized and peripheral backfill are often referred to as ‘buffer’ - an engineered barrier that protects the waste package and limits the migration of radionuclides following their release from a waste package. The host rock descriptions used by RWM have been reproduced below for the three generic rock types which occur in the UK [7] and that are considered potentially suitable to host a disposal facility for higher activity wastes, based on studies carried out in the UK and internationally [5]:

Higher Strength Rocks (HSR) - these would typically comprise crystalline igneous, metamorphic or geologically older sedimentary rocks, where fluid movement may occur predominantly through discontinuities in the rock, often referred to as faults or fractures.

For the evaluation of the MPC concept designs, properties of a granitic host rock formation similar to those considered in Sweden and Finland were assumed as a reference.

Lower Strength Sedimentary Rocks (LSSR) - these would typically comprise geologically younger or more tectonised sedimentary rocks, where fluid movement may be predominantly through the rock mass itself or focused in more permeable layers.

For the evaluation of the MPC concept designs, properties of a sedimentary formation similar to those considered in Switzerland, France and Belgium were assumed as a reference.

Evaporite Rocks (ER) - these would typically comprise anhydrite (anhydrous calcium sulphate), halite (rock salt) or other evaporites, which are characterised by an absence of flowing groundwater.

For the evaluation of the MPC concept designs, properties of German salt formations were assumed as a reference.

CONCEPT DESIGN DEVELOPMENT

A MPC concept specification was developed to provide a bounding envelope for feasible concept designs. Figure 2 outlines how this specification was used to select feasible options from which concept designs were developed.

Using the specification process illustrated in Figure 2, concept options were evaluated in a structured, stepwise approach, to prioritise requirements, identify conflicting requirements and elicit MPC performance and geological environment assumptions. The specification included relevant GDF '**user requirements**' which are derived from Nuclear Decommissioning Authority strategy and the Integrated Waste Strategies for UK civil nuclear sites.

Relevant '**system**' and '**sub-system**' requirements were also collated; these are performance requirements for operational and post-closure safety components. For example, these were derived from RWM's Disposal System Technical Specification (or 'DSTS') [5] which provides a clear definition of the requirements of the disposal system and forms an input to the development of cost-effective GDF designs and supporting assessments. The DSTS will be developed into a site specific version when a site is identified [5].

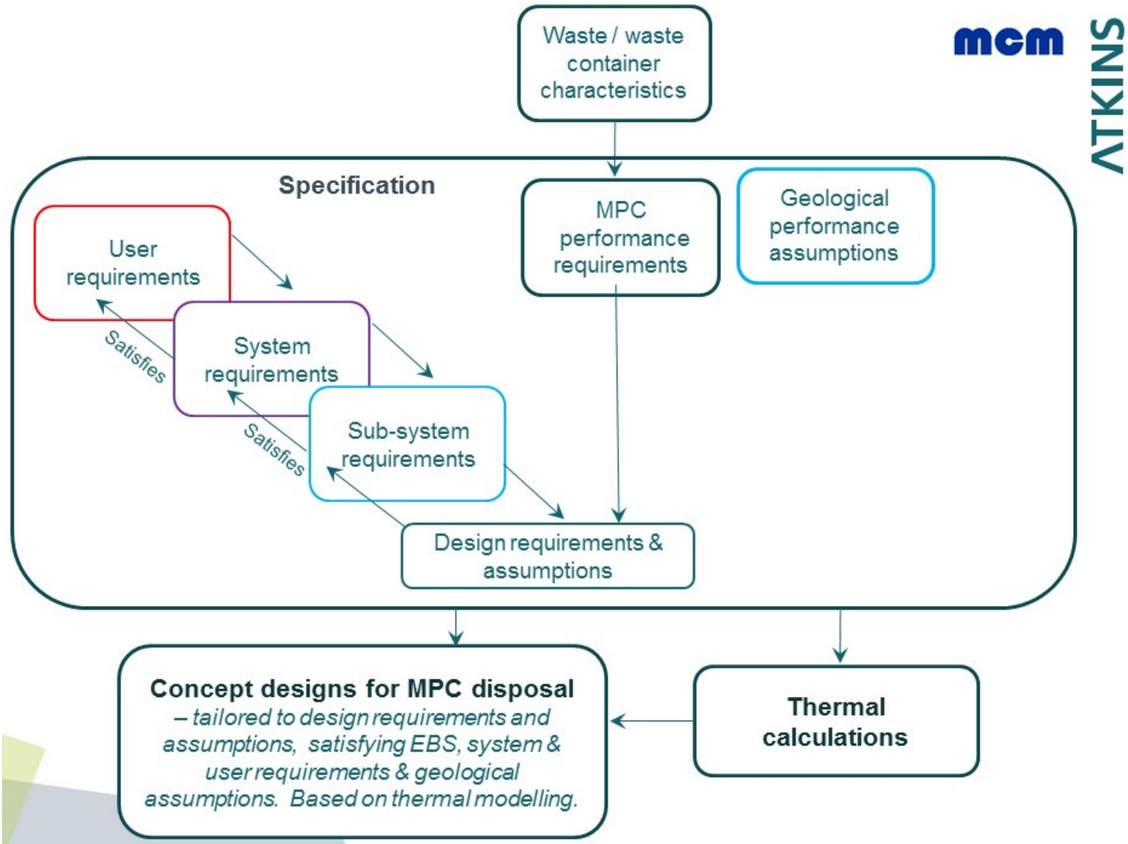


Fig 2: The process used to develop Concept Designs for MPC disposal.

The **Geological performance assumptions** were based on those made by RWM for the current illustrative designs and represent a wider spectrum of possible future disposal environments. It should be noted that the concept designs developed during this work represent examples of what is feasible in these three generic host rock types and are not optimised. In particular, the achievable size and duration of excavated opening are directly influenced by assumptions made and in reality these will be heavily dependent on site-specific conditions. When prospective sites for a UK GDF are identified and site-specific geological information becomes available, the specification developed in this work should be tailored to site characteristics and used to reassess the viability of concept designs developed.

The '**design requirements**' and assumptions identified were specific to MPC disposal performance requirements and used to constrain the concept designs to satisfy the user, system and sub-system requirements.

CONSTRUCTION AND OPERATION CONSIDERATIONS

A range of options (vault-based, silo-based, in-tunnel deposition hole, in-tunnel axial and mined borehole matrix) were considered as potential concept design layouts that could be implemented for MPC disposal in the specified range of generic host rock environments. Silo and borehole layout options were discounted as impracticable for MPC disposal based on existing technology as they would either involve emplacement of large MPC into relatively small excavated spaces or require complex handling movements with specialist lifting and emplacement equipment. Vault layouts were selected for both concept designs applicable to HSR and LSSR, as they provide large cross-sections (16 m high by 16 m wide assumed for HSR and 12 m diameter assumed for LSSR) which facilitate cooling and ventilation and thus support the option to delay backfilling until the MPCs have sufficiently cooled.

Deferred backfilling would require vaults to be inspected and maintained, which would in turn require personnel access resulting in an increase of the number of necessary package movements during an open, 'storage' phase. This would conflict with Design Requirement '*the number of MPC movements should be minimised*'. To examine this issue further, the required open period and the lifetime of vault infrastructure under operational period temperatures would need to be clarified. This requirement to delay backfilling emphasised that the Design Requirement '*a liner monitoring, inspection, maintenance and repair regime for the required duration of 'open' phases should be such that risks to operators shall be ALARP'* would only be satisfied if the concept designs accommodated removal of MPCs from vaults or additional in-situ shielding was provided.

The option to defer backfilling is necessary for active management of heat to satisfy the Design requirement *"….temperature targets of 100°C on the external surface of the disposal container at any time following emplacement"*. Selection of this option in HSR is relatively practicable, with an assumed 300 year period of possible operation. However, in LSSR 120 years was assumed to be the limit of possible operations based on the indicative working life of civil engineering structures [8]. In both geological environments it was assumed that a liner system (see Figure 3) would be implemented during construction to maximize the vault lifetime.

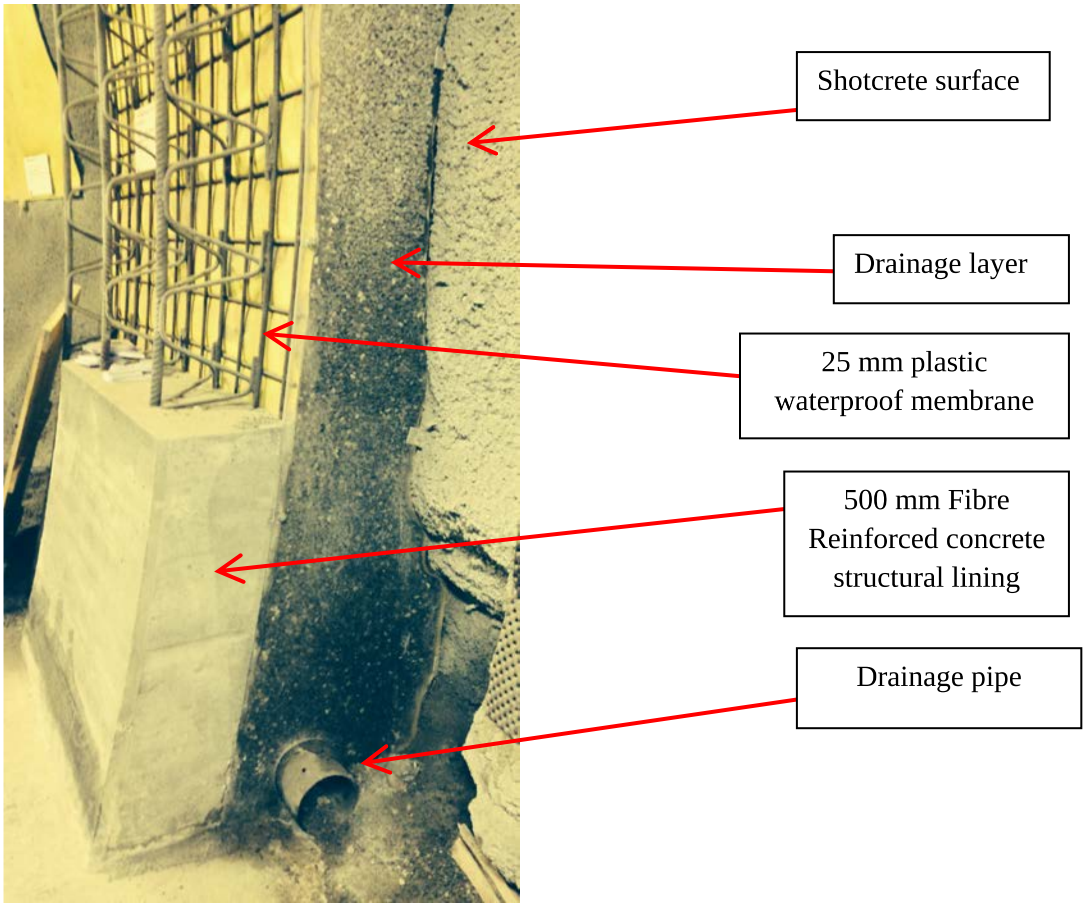


Fig 3: A typical liner system (at the Hagerbach Test Facility, Switzerland) used to manage mechanical strength and groundwater ingress.

THERMAL MANAGEMENT & VENTILATION CONSIDERATIONS

A vault-based concept was chosen in both HSR and LSSR as it enables cooling and ventilation and therefore close spacing of MPCs, which would result in relatively small underground footprint. Vaults could be used for storage, providing option to retrieve, then backfilled once MPCs have sufficiently cooled. This would provide time for consensus with stakeholders on decision to close and the option to reverse the decision on disposal of what may, in future, be considered a resource.

In HSR (the best case), approximately 25% of the heat can be removed by the rock with the vault operated at 50°C; the remainder must be removed by mechanical cooling. No detailed calculations were performed to measure the impact of thermal interference between vaults for the reference case pitch of 50 m, but from temperature profiles developed it can be inferred that a significant thermal interaction will take place between multiple vaults operated at 50°C, reducing the ability of the rock to remove heat. Relying on the rock to absorb even 25% of the heat would therefore necessitate larger inter-vault spacing of high heat generating waste. Figure 4 below summarises results from this study, illustrates the portion cooling supplied by the rock and by the plant with the vault operated at 50°C; with no heat taken into the rock by operation at 28°C the red as well as the blue portion of the graph would have to be supplied by mechanical cooling.

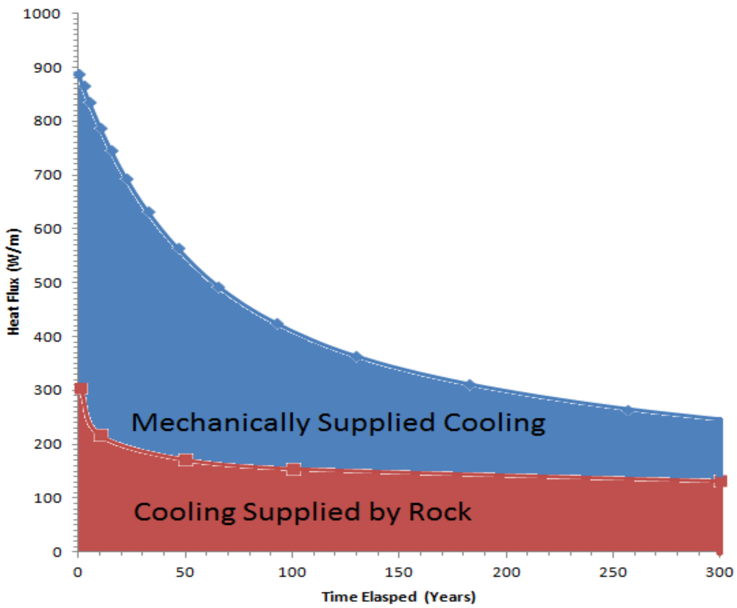


Fig 4: Proportion of cooling from rock vs. mechanical means

A Design Requirement '*During operations in vaults before backfilling, temperature should be actively managed to maintain ambient rock temperature*' was elicited and is based on satisfying the most conservative of Performance Requirements by meeting the initial state temperature conditions assumed in the post-closure safety assessments. Whilst is it possible to remove large quantities of heat by air, heat can be transferred to other physical media via heat exchange processes. This transfer potential allows thermal management by other means, and this work evaluated the options for the thermal management of the vaults, consistent with the current state of the art in underground heat management and geothermal exploitation. Conceptually, the thermal management and cooling system should be considered and manipulated independently of the ventilation system, though in some options they may share some components. The cooling system will be the predominant mechanical service to heat generating waste areas of a GDF in order to satisfy the Design Requirement stated above.
Operations at ambient temperature (assumed to be 28ºC) rather than 50°C (which is the current RWM target necessary to control [1]unshielded ILW package corrosion [5]) would enable personnel entry for extended periods if necessary and would preserve the lifetime of electronic equipment and lining support structures. This would also avoid impacts due to the significant difference in the coefficient of linear thermal expansion of steel and cementitious grout, which would affect the efficiency of the rock-bolts in resisting shearing stresses in the rock mass surrounding the vaults.

The concepts for ventilation during the construction phase of the illustrative designs have been previously considered in [9]. This study did not repeat that work. The previous study also considered ventilation throughout the GDF for LLW and ILW packages during an operation phase, and general conclusions from it can mostly be taken over for use with MPCs.

[1] This target was adopted as a design assumption for the SF disposal area operational temperature as RWM's Disposal System Technical Specification [3] does not currently include a target specific for SF.

BACKFILLING OPTION CONSIDERATIONS

The feasibility and practicability of backfill technology options for application to MPC disposal were reviewed [13]. This was based on review of the current state-of-the-art, with particular emphasis on lessons learned from Underground Research Laboratory (URL) tests. Bentonite-based and cement-based backfilling materials were considered for higher and lower strength rocks. Crushed salt backfilling technologies were considered for evaporite rock.

Although developed for very specific repository designs (and boundary conditions), backfilling technologies such as pre-compacted bentonite blocks, granular buffer emplacement using highly compacted bentonite pellets (e.g. using auger technology), in-situ compaction of horizontal / inclined layers and combinations of methods (blocks and pellets) were considered as viable backfilling methods. However, some technologies are difficult to implement under realistic boundary conditions and need to be tailored to the specific boundary conditions of the MPC concept (geometry, size of the disposal vaults) or the expected geological and hydrogeological conditions (e.g. humidity/localized water inflow).

The following two concept designs are based on the MPC concept design specification and the considerations summarised above.

RETRIEVABLE VAULT CONCEPT DESIGN IN HIGHER STRENGTH ROCK

In HSR, a vault-based concept which enables cooling of MPCs during an open storage period was selected. This concept has similarities to the CAvern REtrievable (CARE) concept [11], which was developed in response to Japanese programme stakeholder requirements for retrievability and a compact underground footprint. To accommodate the currently predicted PWR spent fuel inventory [191 MPC units], four vaults, each 16 m wide by 12 m high, 300 m long would be required. For consistency with the reference design in HSR, these are assumed be constructed at a depth of 650 m, primarily by a drill and blast method. Figure 5 illustrates a potential layout of the four vaults. In a specific site, the location of such vaults may be constrained by structural elements (major faults) or oriented to optimise performance with respect to the local stress field or the hydraulic gradient. In terms of the latter, if there is a strongly preferred flow direction, dead-end vaults may present some post-closure performance benefits. Such tailoring can, however, only be done on the basis of site-specific characteristics.

The vaults would be protected by a concrete liner for operational safety reasons. This liner would also include a drainage system to prevent water from entering the vaults. The MPCs would be periodically moved out to allow personnel to carry out visual inspections and carry out any needed maintenance work on the vaults, which would be kept open for 300 years as assumed in a RWM 2010 retrievability position statement [12]. Remote monitoring of parameters, such as rock stability, would provide data necessary to manage the integrity of the vaults while they remained open.

Upon arrival at a GDF, the MPC transport package would be taken underground on a rail wagon. The MPC disposal container would be taken out of the transport overpack underground. The disposal packages would be individually lifted by an overhead crane and moved into the vault. The MPCs would be vertically placed directly onto the vault liner floor in pre-determined positions.

MPC storage would be in 2 rows of 32, in an 8 m pitch grid spacing and 4 m to the vault walls, providing space for 192 in three vaults (see Figure 5). Three of the vaults would be used for MPC storage and disposal, leaving the fourth space to be used as a temporary holding area while the storage vaults underwent inspection and maintenance. At the time of closure, it would be possible to use the fourth vault as an additional disposal location, either for MPCs to spread the post-closure thermal load (although emplacement logistics would need to be modified) or for other wastes (e.g. resulting from decommissioning of surface structures).

A ‘basic’ ventilation concept is proposed to remove heat and maintain operations at or near 28°C, so that the vault is operated with negligible heat transfer to the rock. Air would be cooled in an air handling unit (AHU) and then supplied to the vault. As it returns along the length of the vault, the air would pick up heat convectively from the MPCs, and also remove heat convectively from the walls of the vault.

After 300 years, the MPCs in one vault would be moved to the spare, fourth vault. The empty vault could then be partially or completely emptied of AHUs, AHU infrastructure and lining infrastructure, depending on post-closure safety requirements. A bentonite base layer would be emplaced by in-situ horizontal compaction [10].

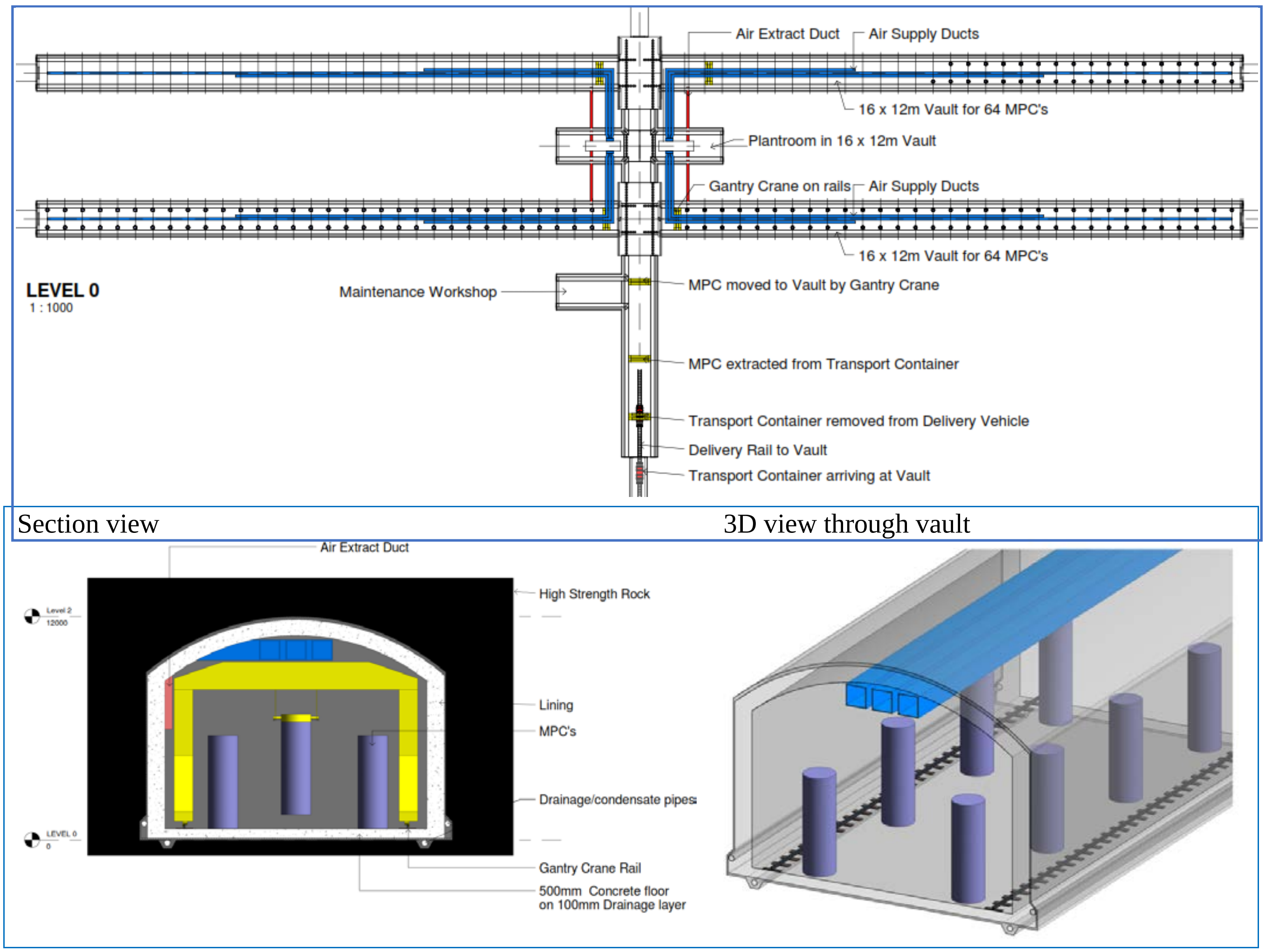


Fig 5: Plan, section and 3D views of the REtrievable VAult (REVA) concept design in Higher Strength Rock (HSR)

The integrity of the MPC disposal container would be inspected prior to backfilling to assure long-term containment requirements. MPCs would then be returned from the buffer storage vault and horizontally emplaced in highly compacted bentonite emplacement units. These could be prefabricated boxes e.g. as in

[13] or, more simply, the mechanical integrity of these units would be preserved by introducing a perforated steel handling shell (super container concept) and mechanical stability of the base would be provided by steel support plates on the vault floor.

Backfilling around the horizontally emplaced MPCs could be conducted remotely or semi-remotely, depending on practicality or operator dose constraints. Standard compaction techniques could be used to establish a high density layer of local backfill (if required) using bentonite pellets. Once the MPCs are covered, bentonite pellets via auger emplacement could be used to fill the remaining void space [10]. Figure 5 is an outline of the REVA layout in HSR and views of sections through vaults.

CONCRETE EMPLACEMENT MODULE CONCEPT DESIGN IN LOWER STRENGTH SEDIMENTARY ROCK

To accommodate the currently predicted PWR spent fuel inventory [191 MPCs] in LSSR, five vaults, 12 m wide by 12 m high by 315 m long would be constructed to accommodate the PWR SF inventory. It is assumed each vault would have a separate plant room used for maintenance. In the reference case, vaults would be kept open for up to 120 years. In LSSR, the lining would be designed to support all expected loads over the duration of the open period. Lining replacement for LSSR would be complicated and hence not recommended, although feasible in principle. Water inflow and vault wall integrity could be managed by the liner system supplemented by rockbolts/cable ground anchors and sprayed shotcrete as required. An outline concept lining system has been assumed with fibre-reinforced concrete structural lining over a membrane and drainage liner over grout and rock bolts. It is expected that the vault infrastructure, monitoring, drainage and liner systems would be inspected regularly. Where no deterioration is found on inspection, then the requirements for maintenance would be evaluated based on monitoring of the structural integrity of the system.

It is assumed that LSSR vault liner may require localised or extensive patching (rather than replacement) through life, in line with structural performance of both the liner and the rock mass. Repair could take the form of intervention depending on the identified causes of the loss of integrity. Potential causes could be excessive pore pressure behind the lining (in which draining effectiveness needs investigation), excessive ground movement (in which case additional support in the form of rock bolts or anchors may be required), etc.

Concrete Emplacement Modules (CEMs) (see Figure 6) are assumed to house MPCs during storage and disposal. The CEMs would provide additional shielding in case of personnel access to the vaults during storage, although remote handling is assumed for all operations. This provides the option of direct monitoring, inspection and repair of the lining system and vault infrastructure. CEMs could be constructed off-site using a MPC shaped mould. Each CEM would have a concrete lid with two steel lifting handles. Potentially, the CEMs could be cast in-situ to avoid having to move them underground. However, pre-cast CEMs would permit better quality control and would also be easier to replace in the event of a failed unit than cast in-situ units.

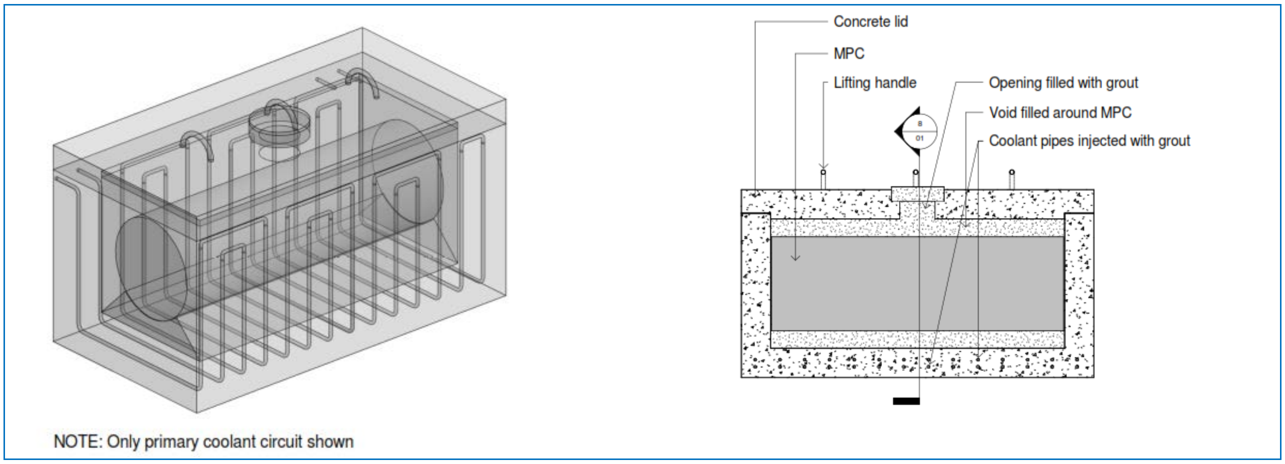


Fig 6: Illustrations of a filled CEM, illustrating the lifting, coolant and grouting features (not to scale).

A 150 tonne Safe Working Load overhead crane would emplace the pre-cast CEM units in one row – there would be room for 38 CEMs in each vault. An overhead crane would carry the MPC horizontally along a vault to a designated CEM and lift the MPC disposal package into place. The overhead crane would then collect a concrete lid and place this over the emplaced MPC to complete the CEM. In order to capture the heat near the source to prevent the rock and vault becoming heated, it is proposed to cool the CEMs directly via coolant pipework, which would be cast in-situ within the CEM walls. These will be maintained at the rock temperature of 28°C so that there is no heat transfer between the CEM and the rock. The MPC within the CEM will transfer heat radiantly and by convection. However, as the surrounding CEM extracts the convective heat from the enclosed air, the air temperature within the CEM will be a little above the CEM temperature. Each CEM will incorporate two separate cooling circuits to provide resilience; each capable of removing the heat required. Duplicate piped circulating cooling water infrastructure will be installed within the vault and the individual CEMs connected to both cooling water systems by pipework. After 120 years, it is assumed that the vault liner infrastructure and water cooling infrastructure would be removed. A steel plug on the CEM lid would be removed and local cementitious backfill would be injected through CEM lid openings to fill any internal void space between the MPC and the internal surface of the CEMs. If required, the internal CEM pipes used for cooling during storage would also be injected with low permeability grout.

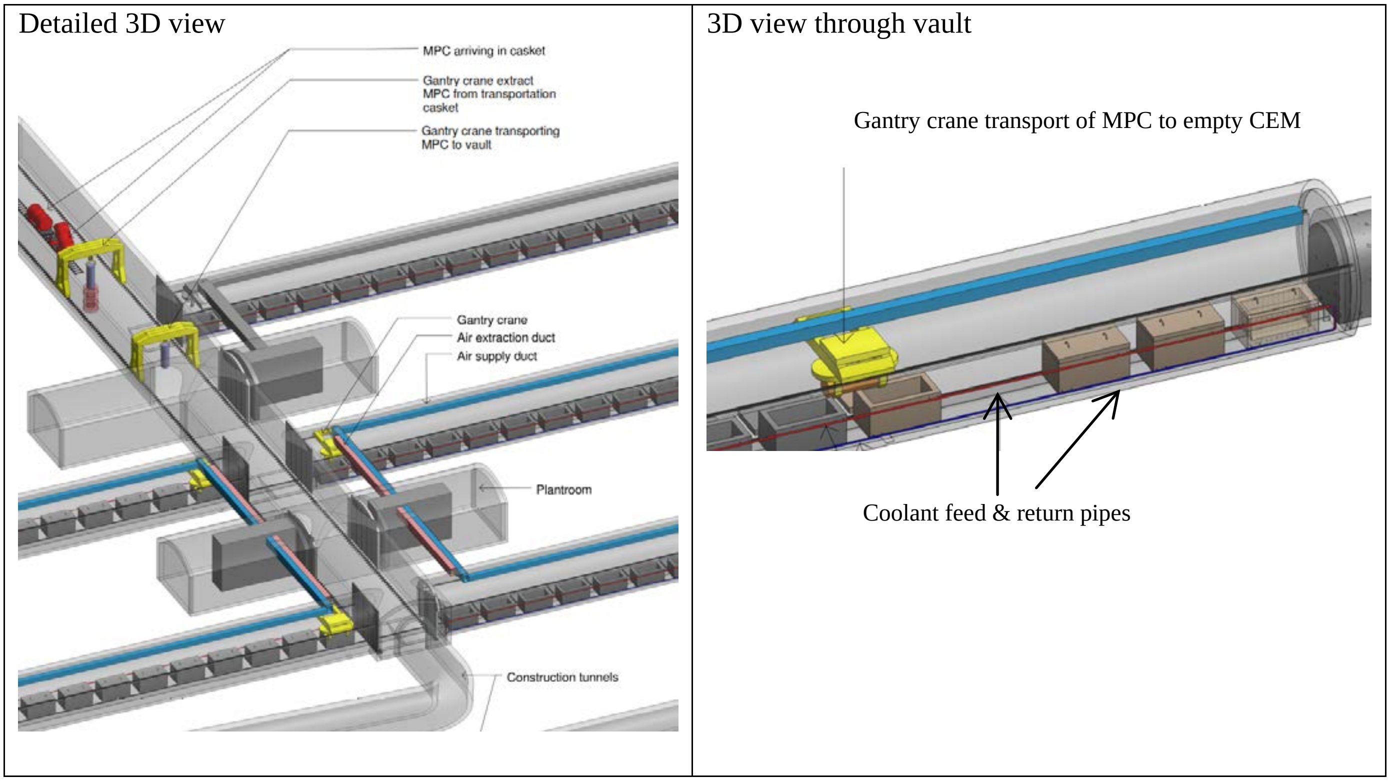


Fig 7: CEM concept in LSSR

EVAPORITE ROCK

Tunnel emplacement was selected for ER, which has high thermal conductivity and favourable performance at higher temperatures and hence a cooling period is not required. For the PWR SF inventory, MPC disposal would considerably reduce the disposal footprint in evaporite rock compared to an illustrative design for PWR SF in conventional disposal containers.

An ‘in-tunnel on floor’ concept was selected, based on a German concept for Pollux Cask SF disposal at Gorleben [14], which is also the basis of the UK evaporite illustrative design for HLW/SF disposal [9]. Before disposal in evaporite rock, a cooling period following discharge from a reactor would be necessary to comply with the assumed thermal limit of 200^{0}C to 300^{0}C. This would be relatively short compared to the cooling duration required prior to emplacement in higher or lower strength rock. In evaporite rock, it is assumed that backfilling of tunnel sections would take place immediately after emplacement and that, during the short time between emplacement and backfilling, MPC radiogenic heat output would not have a detrimental impact on operational safety.

CONCLUSIONS

Packaging of 12 PWR SF assemblies in MPCs offers the potential to reduce a GDF disposal footprint compared to disposal in standard containers (4 assemblies), if the associated trebling in thermal loading can be managed to avoid detrimental impacts on operational and post-closure safety.

Two contrasting concept designs have been developed for HSR and LSSR which demonstrate how mechanical strength, groundwater ingress and temperature can be managed in order to construct and operate vaults for PWR SF in MPCs. This work has not evaluated the disposal configuration necessary to meet post-closure thermal limits; this is investigated in parallel work commissioned by RWM.

This work has proven that it is *feasible* to construct, operate, ventilate and manage heat and backfill in higher strength rock and lower strength sedimentary rock vaults over durations sufficient to accommodate thermal decay of PWR SF in MPCs. Disposal of PWR SF in MPCs becomes *practicable* if the concept designs presented in this paper are combined with (a) the relaxation of the post-closure temperature target to more than the current generic assumption of 100ºC [4] and/or (b) extending above-ground storage of PWR SF beyond 2075. Without (a) or (b), it would be challenging and relatively costly compared to RWM's illustrative concept designs to manage heat and maintain vault integrity for long enough to meet post-closure thermal targets – although it is recognised that the required technology is developing very rapidly at present [15].

However, this work has identified a number of issues. For PWR SF, storage to cool and reject heat until both the current post-closure thermal limits assumed by RWM are achieved and the GDF footprint is used efficiently would be challenging to implement, operate and maintain at depth.

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