Application of Lessons Learned for Less Advanced Waste Management Programmes During the DOPAS Project – Case Study: RWM

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The DOPAS project ("Full-Scale Demonstration Of Plugs And Seals") aims to improve confidence in the industrial feasibility of plugs and seals in geological disposal facilities (GDF). This includes demonstrating different design options at full-scale, under realistic boundary conditions and monitoring the evolution of the plug and seal system. The project is built around a set of full-scale demonstrations, laboratory experiments and performance assessment studies, and is jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations.

A large amount of information has been generated as part of the DOPAS project, which is of benefit to the UK implementer, Radioactive Waste Management Limited (RWM), which should be considered at the early stages of plug and seal design development. One of the main objectives of this paper is to show how such learning can be applied within RWM's programme. A similar approach could be applied by other less advanced waste management programme. The paper includes lessons learned from Safety Functions and Requirements, Conceptual Designs, Design Assumptions and Technologies and also discusses how the DOPAS Project has contributed to the advancement of the RWM generic programme.

The project provided direct input to determining when, and at what level of detail, plugs and seals should be developed as part of the UK programme, providing feedback on how the design data sheets and Disposal System Technical Specification (DSTS) could be updated.

Here the main findings are presented, but RWM internal reports address specific topics in more detail. Thus, for this paper and in the context of the DOPAS project, we focus on those issues which might be relevant for other countries in a similar position to the UK programme.

1 Introduction

RWM has been established, in the UK, as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable geological disposal facility (GDF), for the UK's higher activity wastes. In order to identify potential sites, where a GDF could be located, RWM and the UK Government are developing a voluntarism approach based on working with communities that are willing to participate in the siting process. In order to progress the programme for a GDF, in the absence of a specific site, RWM has developed generic illustrative designs for three different host geologies:

- Higher strength rock (e.g. Crystalline Rocks)
- Lower Strength Sedimentary Rock (e.g. Clay)
- Evaporite (e.g. Salt)

The concepts which make up RWM's illustrative designs [i], are derived from international concepts which are supported by extensive research and development, and have been subject to detailed safety assessment, regulatory scrutiny and international review. The illustrative designs form part of RWM's generic disposal system safety case (DSSC). The generic DSSC is used for initial dialogue with regulators and communities, as well as to support waste packaging advice through disposability assessments for waste producers.

Figure 1 below shows how RWM intend to progress from its current generic phase through to implementation of a GDF.

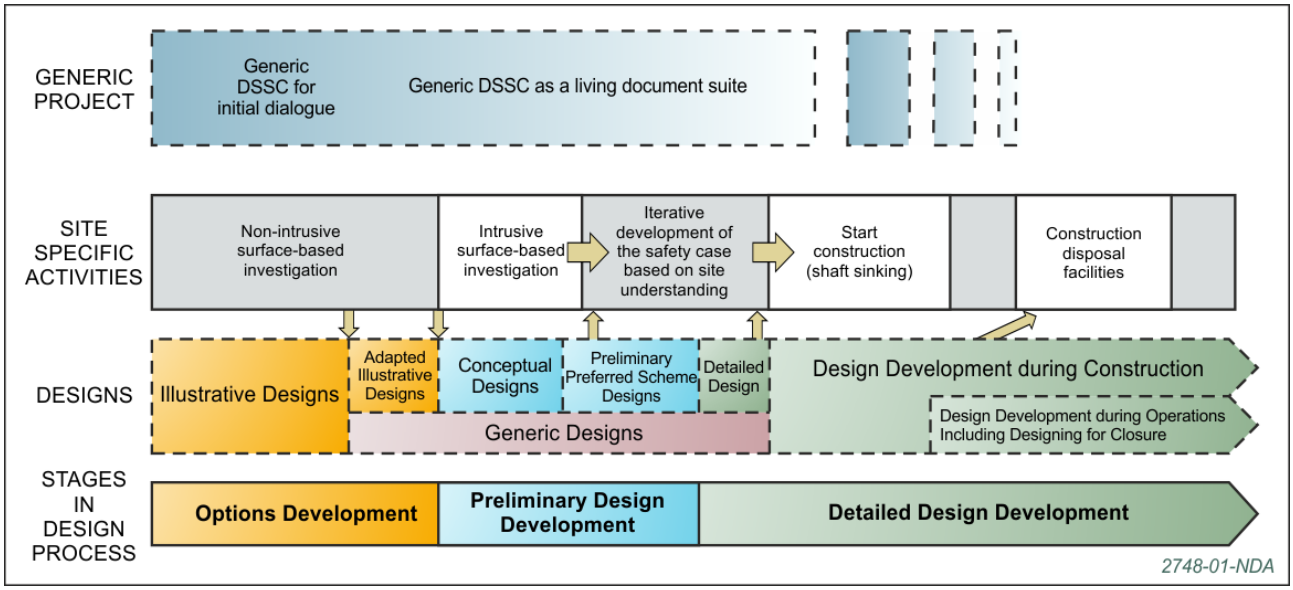

Figure 1: RWM Engineering Design Development Stages

Due to RWM's current generic phase of development, the design of plugs and seals within the illustrative designs does not need to be detailed, in order to meet the needs of the generic DSSC. However, now that tested designs exist, RWM's illustrative designs could be updated to incorporate the learning from the DOPAS project.

1.1 Scope

The DOPAS project ("Full-Scale Demonstration Of Plugs and Seals") aims to improve confidence in the industrial feasibility of plugs and seals in geological disposal facilities (GDF). This includes demonstrating different design options at full-scale, under realistic boundary conditions and monitoring the evolution of the plug and seal system. The project is built around a set of full-scale demonstrations, laboratory experiments and performance assessment studies, and is jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations. Comprehensive background on the DOPAS project can be found in the final reports of the project (and references therein) and the proceedings of this seminar.

The DOPAS project is focused on the development of plugs and seals for disposal tunnels, drifts, disposal vaults and shafts in crystalline rocks (broadly equivalent to RWM's higher strength rock), clay rocks (broadly equivalent to RWM's lower strength sedimentary rock) and salt rocks (broadly equivalent to RWM's evaporite rock). These include:

- *Crystalline Environment*: experiments related to plugs in horizontal disposal tunnels, including the Dome Plug (DOMPLU) experiment being undertaken by SKB at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, the Posiva Plug (POPLU) experiment being

undertaken by Posiva at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland, and the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef URC and underground laboratory in the Czech Republic.

- *Clay Environment*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a surface facility at St Dizier in France, is an experiment on the construction of a drift and ILW disposal vault seal.
- *Salt Environment*: tests related to seals in shafts as part of the development of shaft closure concepts (ELSA) experiment, being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by laboratory testing performed by GRS in Germany.

This paper captures the outcomes of *DOPAS Lessons Learned Project*, summarising the relevant benefits to RWM's programme from the DOPAS project, and more generally, other waste management programmes. The work, undertaken collaboratively by RWM, MCM and Galson Sciences, is based mainly on DOPAS Work Package (WP) 2 (Requirements and Design Basis), WP3 (Design and Technical Construction Feasibility) and WP4 (Appraisal of plug and seal system's function) and the additional experience gained throughout DOPAS project meetings and workshops.

2 Specific aspects of the RWM programme

In the following section, the main aspects of the RWM programme for which specific lessons have been identified are summarised briefly. It should be noted that, although the basis for this work was for the UK programme, currently in a generic phase, similar conclusions could be drawn by other waste management organisations at an equivalent early stage of repository implementation.

2.1 Disposal system specification and design basis

As part of the project, RWM's generic Disposal System Technical Specification (DSTS), which describes the requirements on the disposal system, together with a justification for each requirement, [ii] was reviewed, with regards to plugs and seals. Due to the generic nature of the DSTS, the detail on plugs and seals is at a relatively high level, where the types of plugs and seals and their safety functions, are discussed in a generic manner.

The following types of plugs and seals can be recognised, with some having multiple functions and therefore recognised by location, and some having a specific (singular) function: High-heat Generating Waste (HHGW), Disposal Tunnel Plugs; Low-heat Generating Waste (LHGW), Vault Seals; Mechanical Plugs; Shaft Seals; Borehole Seals; and Human Intrusion Plugs. Suggestions for revising the RWM specific descriptions of plugs and seals, in the DSTS, can be taken forward at an appropriate stage in the future.

Significant work on the development of the design basis for plugs and seals was undertaken in the DOPAS project. It was recognised that this work was relevant to general processes used to develop GDF designs. Key lessons included:

- The design basis incorporates requirements and the conditions under which these must be met.
- The design basis should include a description of how compliance will be demonstrated.
- Requirements are developed in parallel with designs; each level in the requirements hierarchy provides requirements for successively more detailed designs.

Within the DOPAS project, a *Design Basis Workflow* [iii] was created which describes a generic process for the parallel development of a design basis and actual designs for plugs and seals. The design is developed in an iterative manner, with input from regulations; technology transfer; tests

and full-scale demonstrations; and performance and safety assessments. The majority of these activities are undertaken in parallel and therefore close coordination of interfaces is required.
It has to be recognised that the Workflow is applicable to all GDF design work and is a useful tool for planning activities, in particular understanding the level to which designs need to be developed at each stage in implementation of geological disposal. It also addresses the ability to test and confirm the reliability of the construction (e.g. define the tolerance required before safety functions are undermined). At the current stage of the UK Programme, not all design work has to be undertaken to the same level of detail. However, an understanding of the basic designs of plugs and seals may be necessary to undertake cost and programme analyses for illustrative designs, which may require drawing on the more detailed work available through the DOPAS project.

2.2 Conceptual designs of plugs and seals

The DOPAS project provides a sound basis for the first stage of generic design development. However, the plug and seal designs developed in the DOPAS project are clearly related to the status of specific programmes – very detailed designs for advanced programmes such as in Sweden and Finland or more experimental designs such as in the Czech Republic. Common to all is that plugs and seals are composite structures with several components, each with specific functions. The designs are dependent on the host rock, the overall disposal concept, the waste types and also respond to requirements (including stakeholder requirements). The conceptual design options developed during the DOPAS project could be, with modifications, applied in the early stages of the RWM plug and seal design development, recognising that, at an early stage of a programme (e.g. host rock not defined and specific host rock parameters not available), going further than a preliminary conceptual design is not necessary. A stepwise approach "What is needed, When and at What level of detail" will be defined and communicated. Considering the fact that the DOPAS project addresses mainly disposal tunnel plugs and seals based on the well-advanced Nordic concept (DOMPLU and POPLU) and the French FSS (vault sealing and plugging for ILW), it is clear that further input from ongoing work outside DOPAS, should also be analysed for its benefit to the UK programme. Detailed work on plugs and seals, such as gas permeable seals, alternative designs and construction techniques were presented, for example, at the Performance of Engineered Barriers (PEBS) conference in Hannover in 2014 [e.g. iv, v, vi, vii, viii, ix].

The current draft of the Geological Disposal Facility Designs (GDFD) contains a section entitled *Sealing Strategy*, describing the locations and materials used for plugs and seals in higher strength rock, lower strength sedimentary rock and evaporite rock [i]. RWM has produced a database with generic design assumptions to underpin the information in the GDFD. Based on the experience gained within DOPAS, the assumptions made were critically reviewed and proposals for amendments were made, to ensure that the GDFD and the design assumptions are consistent and not in contradiction to the main conclusions drawn by the DOPAS project. The review of the UK illustrative designs identified a need for greater tailoring of design solutions to safety functions. Alternative assumptions were identified for RWM to further consider at a later date. In particular, the specific function for each type of plug and seal needs to be carried through to the next iteration of the design. In addition, DOPAS illustrated the differences between references designs and experimental plug designs. Thus, it is important to specify those elements and functions which are based on the repository conceptual design and those related to the needs of experiments. These different requirements need to be clearly specified and handled in the requirements management system (RMS).

2.3 Geological Disposal Facility (GDF) technology and Engineered Barrier System materials

The DOPAS project demonstrated the feasibility (and practicability) of constructing plugs and seals under almost realistic conditions, providing a *toolbox* of proven and demonstrated technologies for

emplacement & construction of such structures. The solutions provided are, however, specifically tailored to the concepts and specific boundary conditions found or assumed at the repository sites that were focus of these projects e.g. the POPLU experiment.
The design, construction and the selection of suitable materials for plugs and seals is more complex than was originally expected at the start of the project. However, the effectiveness of plugs and seals is governed by a relatively small number of parameters, e.g. pre-existing joints, fractures or other geological connections in the vicinity of a plug; presence and extent of an Excavation Damaged Zone; the rock surface characteristics; or the length of the plug. It should be noted that the relative importance of these parameters and the resulting engineering solutions are dependent on the host rock environment and, even within a specific host rock, the local characteristics at the plug position need to be taken into account. Specifically, for the UK programme, the following aspects should be considered:

- The requirements as formulated in the DSTS are generic, and therefore not site specific. These requirements will be further developed as RWM progresses towards implementation.
- An iterative cycle of design, testing and assessment allows engineering solutions to be developed, based on a realistic design basis, requirements and conditions.
- An integrated view, considering the entire repository system and sub-systems, in addition to operational safety aspects, is required when further developing UK specific plug and sealing systems and / or identifying research needs.
- An integrated approach to capture input from engineering, operational safety and long-term safety teams is also required at an early stage. Detailed assumptions and requirements for all types of plugs and seals have to be systematically included in a RMS.
- Specific materials / components might not be available on an industrial scale in future decades, so it is not sensible to develop detailed designs which are not going to be implemented in the near term, the technology used to construct plugs and seals may also evolve over time.
- The design - construction process should provide flexibility to react to new (or changing) boundary conditions, such as requirements for monitoring.

3 Examples of DOPAS lessons learned linked to RWM functions and associated deliverables

In the following selected examples, DOPAS lessons learned are linked to RWM functions and associated deliverables are presented.

Design	
Functions and deliverables	GDF Design Reports, Engineering Design Manual and supporting procedures, Geological Disposal Facility Design status report
• Design assumptions and design procedures need to be critically reviewed and updated. • Input to the Technical Maturity Analysis, raising the Technical Readiness Level (TRL) of underground designs. • The generic work flow, illustrating the iterative steps from conceptual to detailed design, provides a flexible approach to linking safety functions with design specifications that can be tested via a demonstration programme and Quality Control procedures applied in during disposal operations. • Considering the fact that DOPAS addresses mainly the disposal tunnel plugs and seals based on the well advanced Nordic concept and, with the French FSS, the vault seals and plugs for ILW, it is obvious that further input, from outside of DOPAS, is required for the UK programme.	

- At the current stage of the UK Programme, concentration of effort on conceptual design will guide the R&D programme required for the next years, until a preliminary decision on host rock(s) has been taken.
- While further developing a Generic DSS a holistic view is needed; besides disposal tunnel plugs and seals as tested in the DOPAS, other plug types need to be addressed (e.g. gas permeable plugs).
- The design - construction process should provide flexibility to react to new (or changing) boundary conditions, such as requirements for monitoring (e.g. development of wireless monitoring system for plugs).

Research	
RWM functions and associated deliverables	Science and Technology Plan, Research Status Reports

- Identification of knowledge gaps. Guidance on the level of detail required and iterative steps during GDF implementation.
- The conceptual designs for plugs and seals depend on the host rock environment. The R&D programme and activities related to plugs and seals should reflect the current needs of the implementation programme. Spending resources in developing detailed plugs designs and related materials (concrete formulations) at a generic stage of the programme, without knowing key host rock parameters, is not sensible.

Disposal System Specification	
RWM functions and associated deliverables	Science and Technology Plan, Research Status Reports, Disposal System Technical Specification

- DOPAS provides a sound basis for the first generic design work.
- Consistent use of terms right from the very beginning (and indeed throughout all departments) is extremely important. The development of safety functions and requirements for individual repository elements (e.g. plugs, seals) needs to be integrated within the overall repository system, as specific elements / subsystems influence each other.
- A clear time horizon for the performance and related safety functions (e.g. 100 or 300 year operational / open phase of the repository) is required, even at the stage of first conceptual designs.

Safety Assessment (not a focus of the project)	
RWM functions and associated deliverables	Environmental Safety Case, Operational Safety Case

- Guidance of representation of plugs / seals in post-closure safety assessment.
- Approaches to operational safety in other programmes, including mitigation measures employed.

• DOPAS illustrated specific compliance demonstration strategies, which need to be closely linked to regulatory requirements.

Communications	
RWM functions and associated deliverables	Web-site, Brochures, Information material, Publications
• DOPAS provides comprehensive documentation on the state of the art of plugs and seals. • DOPAS provides a sound basis for the first generic design work and associated communication to the public and other stakeholders. • An active communication via scientific papers, brochures, websites etc. should be initiated, highlighting solutions demonstrated and the active role of RWM in this project. • Use of demonstrations in URLs in defining operational procedures, licensing and commissioning of a GDF.	

4 Conclusions

The DOPAS lessons learned project has demonstrated that plugs and seals are complex structures, which should be recognised in more detail, as the UK programme advances. A wide range of plugs and seals are required, with different operational and post-closure safety functions. RWM's programme could benefit from adopting, through formal change control, a comprehensive set of plugs and seals to cover the design options for the three illustrative GDF designs. This would provide a consistent basis for developing plug and seal designs, leading on from the early generic phase of the programme. The requirements on, and designs of, plugs and seals depend on the geological environment, and different plug and seal types and designs for each type need to be incorporated into the illustrative designs. The R&D programme and activities related to plugs and seals should reflect the current needs of the programme.

The DOPAS project has further developed the design basis and specific designs for a range of plugs and seals relevant to higher strength, lower strength sedimentary and evaporite host rocks. However, the work in the DOPAS project has not considered all types of plugs and seals, for example, there has been no sealing of major water conducting fracture zones. Therefore, RWM will need to undertake further work to develop design solutions for the full range of plugs and seals needed. This should include incorporation of clearly justified conceptual design assumptions with respect to plugs and seals in the illustrative designs; these assumptions could have significant implications for the technical feasibility, safety performance, cost and schedule of a GDF, and should, therefore, be understood within the current generic programme.

Plugs and seals are composite structures, with specific components required to deliver the safety functions. Work in DOPAS has also illustrated a wide range of design options for these components, for example, the bentonite strips applied in POPLU, the filters and delimiters used in DOMPLU, and the mixed pellet/crushed pellet bentonite system employed in FSS.
The DOPAS design basis workflow has been developed from the understanding and experience from the different design approaches used by specific waste management organisations. The workflow is now consistent with the design processes used by all partners, serving as a useful tool in planning GDF design.

An integrated view, considering the entire GDF system and associated sub-systems, is required when further developing UK-specific plug and seal systems and identifying research needs.

Integrated engineering, operational safety, and post-closure safety teams are required to work on such design development.

5 Acknowledgements

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