Site Restoration Programme

Winfrith End State:

Design Substantiation Report (Concept Stage) – SGHWR and the Dragon Reactor

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COMPLIANCE AND END STATES - WINFRITH END STATE:

DESIGN SUBSTANTIATION REPORT (CONCEPT STAGE) – SGHWR AND THE DRAGON REACTOR

Review/Revision Register

A review/change of this document was carried out as follows:

Date	Author	Amendments / Change
October 2024		Issue 1 following comments

Acronyms

ALARA	As Low As Reasonably Achievable
BAT	Best Available Technique
BoD	Basis of Design
CQAP	Construction Quality Assurance Plan
DC	Dorset Council
DfR	Deposit for Recovery
DSR	Design Substantiation Report
EA	Environment Agency
EAC	Emplacement Acceptance Criteria
EIA	Environmental Impact Assessment
EPR	Environmental Permitting Regulations
FML	Flexible Membrane Liner
FR	Functional Requirement
GCL	Geo-synthetic Clay Liner
GRR	Guidance on Requirements for Release from Radioactive Substances Regulation
RSR	Radioactive Substances Regulation
HDPE	High Density Polyethylene
HGV	Heavy Goods Vehicle
HRA	Hydrogeological Risk Assessment
IEP	Interim End Point
LLDPE	Linear Low-Density Polyethylene
LLW	Low Level Waste
LTP	Lifetime Plan
NDA	Nuclear Decommissioning Authority
NE	Natural England
NRI	Non-Radiological Inventory
ONR	Office for Nuclear Regulation
OoS	Out-of-Scope
PC	Primary Containment (SGHWR or Dragon)
PVC	Polyvinyl Chloride
RC	Reinforced Concrete
RMP	Restoration Management Plan
SGHWR	Steam Generating Heavy Water Reactor
SRS	Site Reference State
SPA	Special Protection Area
SWESC	Site Wide Environmental Safety Case
SWMMP	Site Wide Materials Management Plan
TH	Turbine Hall (SGHWR)
TN	Technical Note

Executive Summary

This Design Substantiation Report (DSR) describes the end state concept designs for the proposed disposals/deposits at the Steam Generating Heavy Water Reactor (SGHWR), Dragon Reactor and the Mortuary Holes adjacent to Dragon.

The DSR also describes how the concept designs have been developed in accordance with current industry codes and standards and relevant best practice. This has involved significant engagement on the developing concepts within Nuclear Restoration Services (NRS) as well as with the Nuclear Decommissioning Authority (NDA), the Environment Agency (EA), the Office of Nuclear Regulation (ONR), Dorset Council (DC), and industry specialists. The concept designs also draw upon the results of extensive structural investigations and analysis, as well as radiological and non-radiological risk assessments. These demonstrate that the concept designs satisfy a pre-determined set of Functional Requirements (FRs) (Ref. 1) and meet the EA's expectations on current and future structural integrity (Ref. 2). Credible concept designs were assessed for near-term and long-term technical performance, with the best performing design selected on the balance of benefits and detriments. The DSR also addresses the EA's requirements on structural verification in the current reactor starting states, end state preparation, demolition and void filling through to future structural evolution. Where the engineering may need to be enhanced to ensure continuing structural integrity (e.g., sealing penetrations, wall propping etc) and avoiding direct discharges, then simple engineering solutions are available to ensure the structures hold their integrity.

The preferred concept designs for the SGHWR and Dragon end states are:

- Above-ground structures demolished to ground level (Dragon) or 1m below (SGHWR);
- Remaining below ground voids backfilled to ground level or 1m below ground level with large 'blocks', demolition arisings and some of the existing rubble stockpiles;
- An engineered cap constructed over the disposals;
- Landscaping, including surface water drainage from the cap, to be consistent with local environs and topography.

In SGHWR, the Primary Containment concrete, where possible, will be cut into 'blocks' using diamond wire cutting or similar techniques. These larger sections of concrete will be carefully placed into the base of the below ground voids using the existing overhead crane. The SGHWR Annexes and Turbine Hall will be demolished using conventional machinery which will produce concrete demolition arisings, which with some of the existing stockpiled rubble, will be used to fill the below ground voids, with an engineered cap then placed over the below ground structures.

In Dragon, the thicker concrete sections which surround the core will be cut using diamond wire cutting or similar techniques and lowered into the basement slab. The concrete rubble produced by conventional demolition of the remaining structure will be placed on top, along with any additional rubble required to complete void filling from the existing rubble stockpiles. Dragon's above ground steel liner and roof steelwork will be disposed off-site and recycled where practicable. The Dragon Mortuary Holes will be grouted to form a below ground monolith and the Dragon reactor cap will be extended to cover the grouted Mortuary Holes.

Engineered cap designs over both SGHWR, the Dragon reactor and the Mortuary Holes adjacent to Dragon have been developed. They will use conventional materials to reduce water infiltration and provide mitigation against animal and plant intrusion and help prevent inadvertent human intrusion, with surface water drainage from the caps achieved using conventional drainage channels. The detailed specification for the surface of the caps will be defined in accordance with the site's Restoration Management Plan (RMP) (Ref. 3).

Based on the work completed, it has been demonstrated that the concept designs will be structurally sound for the period of the disposal permit, assumed to be up to achieving the Site Reference State (SRS). Therefore, the engineering has been sufficiently demonstrated at a conceptual stage to meet the relevant legal requirements (GRR, DfR). The application of the Construction Quality Assurance Plan (CQAP) will ensure delivery of compliant disposals (Ref. 4).

Contents

1 Introduction 7
2 Background 8
2.1 The Site 8
2.2 Current state of SGHWR 8
2.3 Current state of the Dragon Reactor and the Dragon Mortuary Holes 10
2.4 Optimised End State 11
2.5 Radiological Performance and Hydrogeological Risk Assessments 12
2.6 Hydrogeology 13
2.7 Emplacement Acceptance Criteria, EAC 14
2.8 Construction Quality Assurance Plan, CQAP 14
2.9 Documents Supporting Concept Design and GRR Permit Variation and Planning Applications 15
3 Concept design functional requirements, constraints, assumptions, exclusions, uncertainties 15
3.1 Functional Requirements 16
3.2 Constraints 17
3.3 Assumptions 18
3.4 Exclusions 18
3.5 Uncertainties 19
4 Design Process 19
4.1 Design Phases 19
4.2 Concept Design Development 21
5 SGHWR End State Description 27
6 Dragon reactor and Mortuary Holes End State description 31
7 Meeting the design requirements and the EA's performance expectations 32
7.1 How the Functional Requirements have been met 32
7.2 How the EA's expectations on structural integrity have been met 35
8 Conclusions 43
9 References 44

1 INTRODUCTION

The current End State strategy for the Winfrith Site is to prepare the site for its next planned land use which is 'heathland with public access' as determined through community consultation in 2006 (Ref. 5). This strategy includes proposals for the on-site disposal of the concrete structures associated with the SGHWR and the Dragon Reactor and the Dragon Mortuary Holes. These disposals form a key part of the end state for the site (Ref. 6).

In order to achieve the Interim End Point (IEP) where the site is suitable for its next land use, concept design proposals for the SGHWR and Dragon Reactor on-site disposals were developed. These designs have been utilised in the Conceptual Site Model (CSM) (Ref. 7) for the proposed site end state, the Site Wide Environmental Safety Case (SWESC) (Ref. 8), Deposit for Recovery (DfR) (Ref. 9) and planning (Ref. 10) applications for the proposed Winfrith end state.

The concept designs are guided by a set of Functional Requirements (FRs), and constraints and assumptions which were established to ensure that the disposals complied with the regulatory requirements set out in the 'Guidance on Requirements for Release from Radioactive Substances Regulation (GRR) (Ref. 11) and are implementable. The concept designs were developed through a series of engineering design assessments and workshops employing specialist contractors, along with engaging with stakeholders, regulators and local authority planners to understand their expectations.

In addition, the Environment Agency (EA) has stated (Ref. 2) that they expect structural verification at different stages of the end state preparatory work, backfill emplacement and disposal closure:

- *Verification of the structure in its basic starting state;*
- *Verification of structure post preparation/pre-emplacement (e.g. following sealing of wall penetrations etc., if applicable);*
- *Verification during implementation and if applicable, during grouting;*
- *implementation;*
- *Post closure.*

The engineering proposals presented in the permit applications has been driven by legal requirements and the radiological and non-radiological risk assessments. This Design Substantiation Report (DSR) has captured information on structural integrity, underpinned by 'lines of evidence' which presents an understanding of the below ground structures, how their characteristics evolve with time, and the role they play in controlling pollutant releases.

The concept design proposals are based on the strategy of demolishing above ground structures and using the concrete arisings and stockpiled rubble to backfill the below ground voids. This will be followed by the construction of caps over the disposal to provide environmental and safety protection. The concept designs have been underpinned by structural assessments which demonstrate that the below ground concrete structures, that will form the boundary structures, are robust and will remain robust during demolition, backfilling operations through to achieving the Site Reference State (SRS). This will prevent development of rapid leak paths to the environment through the boundary structures i.e., direct discharges of pollutants to the surrounding groundwater will not occur for the lifetime of the permit applications.

The purpose of the DSR is to provide a justification that the SGHWR and Dragon end state concept designs have been optimised and will meet all regulatory requirements and expectations. The report objectives have been to:

- Set out FRs, design constraints and design assumptions;
- Explain the concept design process that has been followed;
- Describe the concept designs that have emerged from the design process;

- Explain how the FRs have been satisfied and that the EA's expectations for engineering verification will be met.

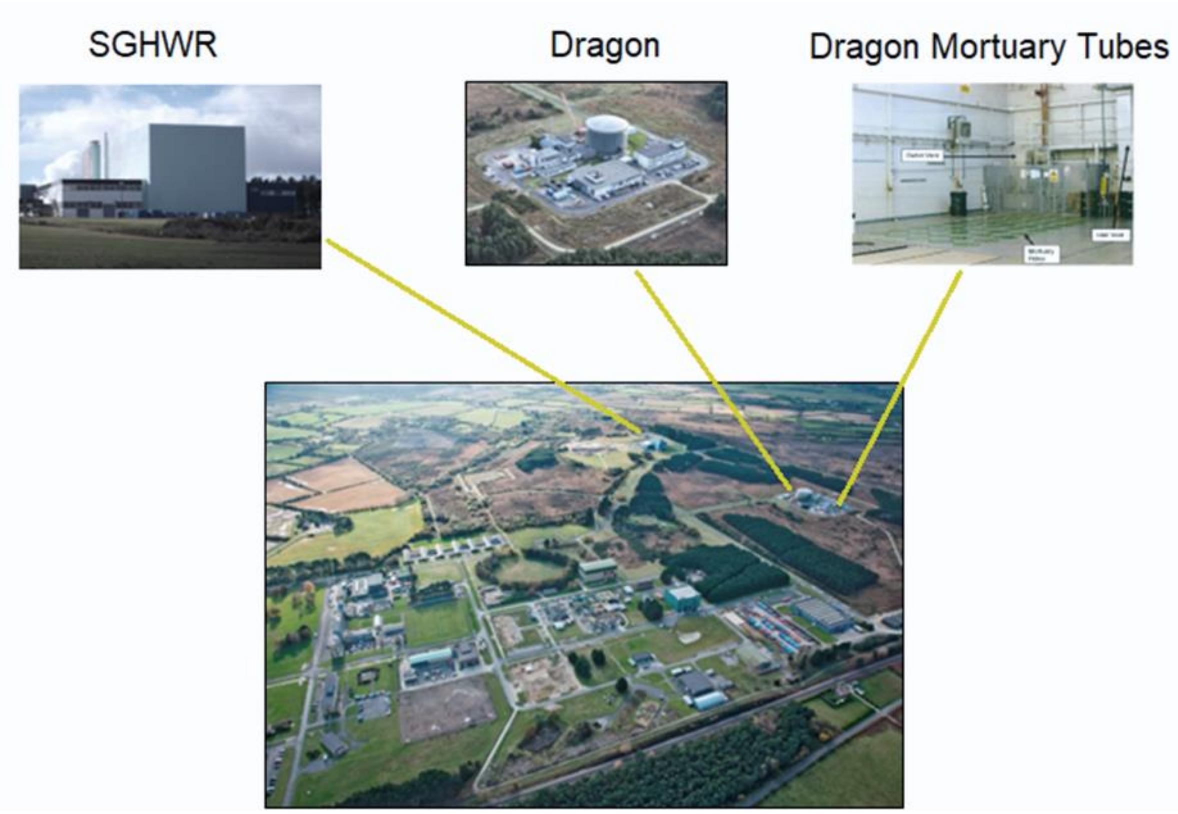
2 BACKGROUND

2.1 The Site

The Winfrith nuclear site, located in Dorset, is a former nuclear power research and development site, which housed research and prototype reactors as well as laboratories. The site included nine experimental reactors in total, each with a unique design, with construction commencing in 1957 and the last operational reactor shut down in 1995. The site, owned by the Nuclear Decommissioning Authority (NDA) and operated by Nuclear Restoration Services Limited (NRS), is currently being decommissioned.

Figure 1 shows an aerial view of the site showing the locations of SGHWR and Dragon Reactors.

Figure 1 Aerial view of Winfrith Site



2.2 Current state of SGHWR

SGHWR consists of a large and robust concrete structure, partly below ground level, with steelwork and cladding forming the superstructure and weather envelope. At the heart of the structure is the Primary Containment which formally housed the operating reactor core, steam drums and fuel storage pond. To the north and south of the reactor building are adjoining annexe structures that are partly above and below ground level and consist of a complex system of rooms. Figure 2 shows a plan view of SGHWR, and Figure 3 shows a cross section through the Primary Containment and North and South Annexe structures.

Figure 2: Plan view of SGHWR at ground level (NB the Primary Containment is approx. 50m in length)

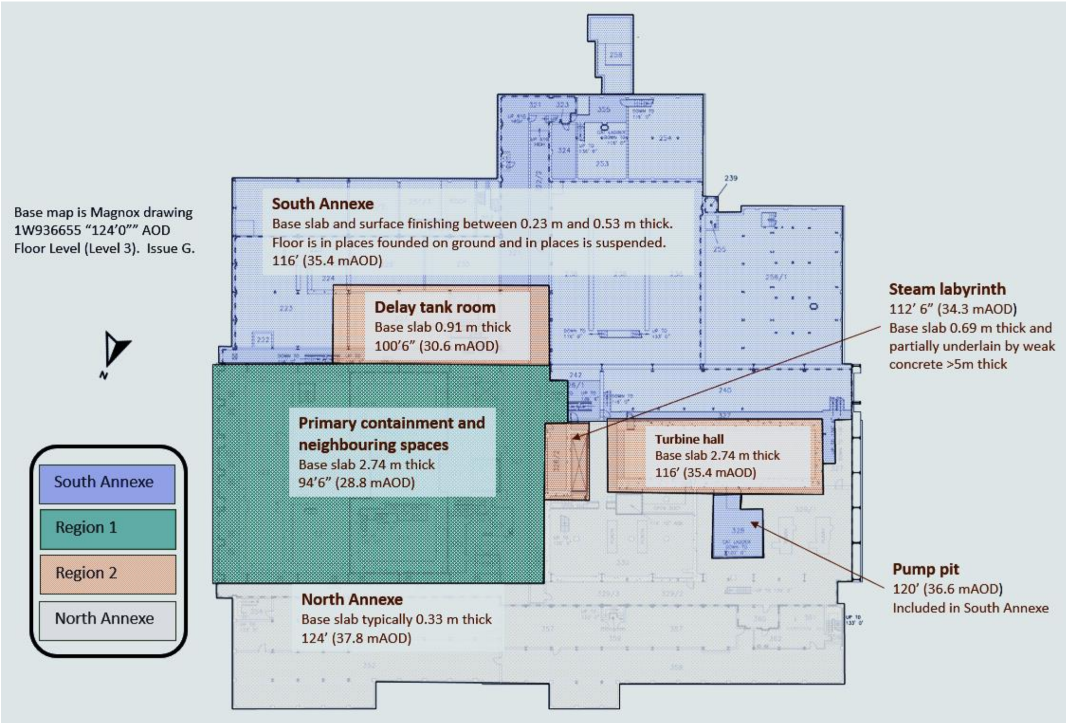
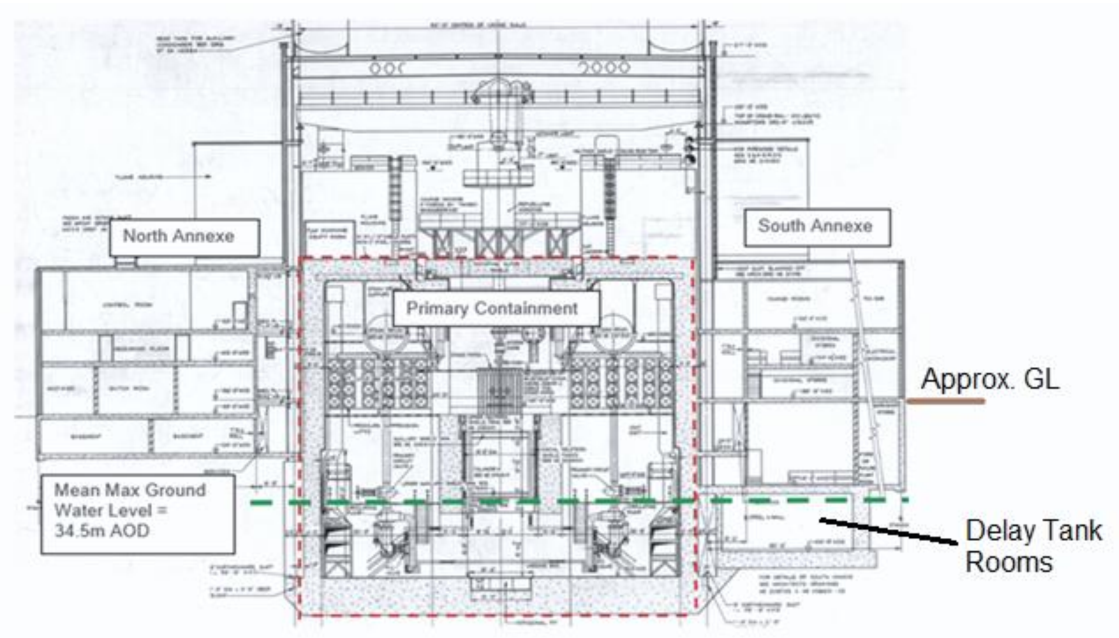


Figure 3: North-South section through SGHWR showing the Primary Containment and Annexe structures, relative to groundwater level



The Primary Containment was designed to prevent water ingress and egress, contain pond water and to remain as 'leak-tight' as possible. The structure is made up of 1.2m thick reinforced concrete walls and a 3m thick reinforced concrete raft foundation that transfers the weight of the structure to the underlying strata. The construction specification is not available, so no technical definition of 'leak tight' or 'watertight' has been found. However, it is clear that the parts of SGHWR which are exposed to groundwater were specifically designed to resist water egress and ingress as far as was reasonably practicable with polyvinyl chloride (PVC) water bars. An admixture was also added to the concrete mix to make it less porous. Above the

Primary Containment, a conventional steel-framed and clad structure was built to form the weather envelope.

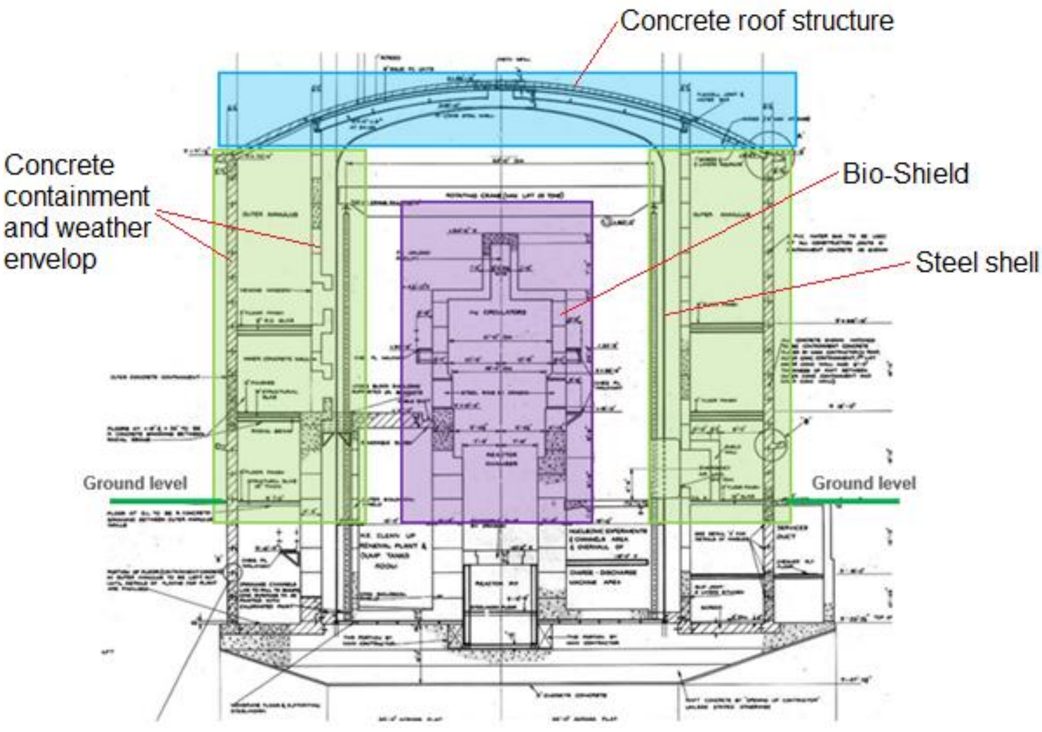
Elsewhere in SGHWR, the structure is more conventional. The Turbine Hall consists of large robust concrete turbine plinths supported on a thick concrete raft. Again, the weather envelope is formed using a conventional steel framed and clad structure.

The North and South Annexe structures are formed of reinforced concrete floor slabs supported off a mixture of steel or concrete columns and reinforced concrete walls. Expansion/contraction joints are provided in the floor slabs as well as the external walls. At the interface between the annexe basement slabs and the Primary Containment, there is a 25mm wide expansion / contraction joint filled with 'Flexcell' compressible joint filler. There are also likely to be construction joints in the basement floor slabs, though these are not shown on any of the available drawings and are in any case not visible due to the presence of floor screeds.

2.3 Current state of the Dragon Reactor and the Dragon Mortuary Holes

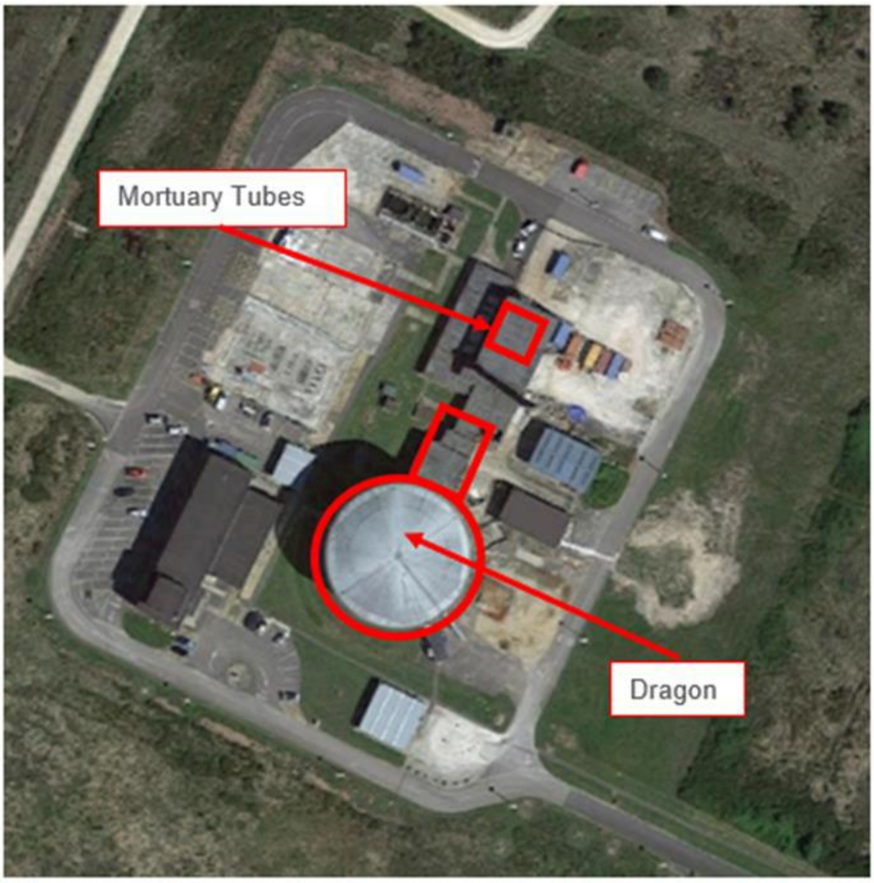
The reactor is cylindrical in shape, 26 m high and 35.5 m in diameter with a basement extending to 7.6 m below ground level, with a 3.7 m steel-reinforced concrete base slab beneath. The structure includes an inner concrete bioshield, a metal internal structure and a concrete shell and roof. Figure 4 shows a general section.

Figure 4: Cross section of the Dragon Reactor



The Dragon Mortuary Holes that are to be disposed of in-situ consist of ~4 m long galvanised mild steel tubes in a concrete lined pit, buried below ground a short distance (22m) from the Dragon Reactor. The tubes were originally used for the storage of spent fuel elements and waste materials and have a narrow bore. It would not be possible to backfill the tubes with demolition concrete. Therefore, each mortuary tube will be grouted to reduce the possibility of surface water infiltration. Figure 5 shows the location of the Mortuary Holes close to Dragon.

Figure 5: Aerial view of the Dragon reactor and the Mortuary Holes.



2.4 Optimised End State

In order to develop the optimised end state for the site, in 2016/17 credible end state options for the key potential SGHWR end state components were systematically identified, characterised and assessed using a structured approach (Ref. 12). The unconstrained optimised SGHWR end state was determined in a series of workshops between NRS, specialist contractors, the NDA, regulators, the planning authority and representatives of the public (Ref. 13). Dragon followed and the optimised end states were then assessed together to determine the optimal end state option for the site.

In 2018, the NDA approved the business case for a preferred optimised end state of the Winfrith site, where there will be a combination of in-situ disposal of the below-ground structures at SGHWR and Dragon and the emplacement of waste into their below ground voids (Ref. 6).

The radiological and non-radiological risk assessments that underpin the SWESC, have modelled the disposal concept design and include (Ref. 14, Ref. 15):

- The source term (i.e. the radioactive and non-radioactive disposals and their associated inventory);
- The closure features and how each feature will function;
- The disposal concepts and how they are implemented;
- How the disposal performance complies with the requirements of the radiological and non-radiological regulations in the short and long-term to ensure the protection of the environment and people.

The risk models that underpin the risk assessments have informed the concept designs by ensuring:

- The models employed when assessing risk are realistic, account for uncertainties and applicable parameter ranges and are implementable;

- The engineering designs reflect the broad performance standard that must be achieved to comply with the GRR and non-radiological regulations;
- The output of the risk assessments and design will inform the permit conditions given to the site that the design must achieve.

The engineering concept derived through this process, and set out in this document, will be the basis of the detailed design stage as set out in the NRS design management process, MAN 0004 (Ref. 16). Assuming the on-site disposals are permitted, the following list sets out the main steps to meet the SRS, when the site can be removed from regulation:

- SGHWR and Dragon will continue decommissioning, with the removal and packaging of Intermediate Level Waste (ILW) and bulk Low-Level Waste (LLW) from the Primary Containment of SGHWR and Dragon as the main tasks;
- After bulk ILW and LLW removal from SGHWR and Dragon, enabling works for dismantling will be completed, including soft strip, ahead of end state implementation. Waste generation will be minimised, and materials recycled where practicable;
- Clean-up of residual contamination in the SGHWR basement structures to remove any remaining contamination that exceeds the Emplacement Acceptance Criteria, EAC, other LLW materials and any remaining bulk hazardous material e.g., asbestos where required. This will ensure that the material remaining within the basement areas will meet the EAC. These issues are less significant for Dragon, as its contamination levels are relatively minor;
- Complete the detailed design for the disposals in accordance with the concept design and MAN-004 (Ref. 16). Any amendments made during consultation and any conditions placed by the EA or Dorset Council (DC) in the environmental permit and planning permission for on-site disposal will be incorporated at the stage;
- Undertake any inspection and physical works that are required to ensure the below ground boundary structures (external walls and ground slabs in contact with groundwater) maintain their structural integrity to prevent direct discharges through to the SRS. This may include identification and sealing of penetrations, checks for water ingress and cracking with associated remedial works, condition surveys, etc. End State construction quality will be assured by implementation of an agreed Construction Quality Assurance Plan (CQAP);
- Undertake demolition and backfilling in accordance with the detailed design. This will involve demolishing what remains of the above ground structures to ground level, or 1 m below, with any compliant material being used to backfill the below ground voids. Where there is a shortfall of material for this purpose, rubble from the existing stockpiles will be used to complete the backfilling. Only backfill that is consistent with the supporting technical assessments (detailed engineering design, hydrogeological risk assessment and radiological risk assessment) as detailed in the EAC will be used to fill the below ground voids at SGHWR and Dragon;
- The backfilled voids will then be capped and landscaped in accordance with the detailed design;
- Shortly thereafter the site will meet its targeted end state at the IEP when all physical works and waste management activities across the site are complete;
- The site will then be passively managed as part of the site end state Stewardship Plan (Ref. 17), for a period of time (to be determined but likely to be several decades) to confirm that the disposals perform as described in the SWESC and the site landscape evolves as proposed in the site's Restoration Management Plan (Ref. 3);
- Finally, after demonstrating to the EA that the SRS has been met, the site can be removed from environmental regulation.

2.5 Radiological Performance and Hydrogeological Risk Assessments

Conservative radiological (Ref. 18) and non-radiological (Ref. 19) inventory estimates have been prepared for the proposed SGHWR and Dragon end states, including backfill materials. The inventories have been developed using data collected to date and reasonable assumptions associated with ongoing decommissioning. The inventories inform the DSR in terms of defining how much waste may be managed on-site and its likely location in the disposals to best minimise impacts on workers and the environment. With decommissioning on-going, there has been limited access to some areas of both SGHWR and Dragon. Further characterisation is anticipated as decommissioning continues and until such a time as the final disposals have been made (Ref. 20).

The inventory of non-radiological components (concrete, brick etc) and contaminants (inorganic and organic hazardous) defines the end state materials. The non-radiological inventory, NRI was determined for (Ref. 19):

- Newly generated rubble from the demolition of SGHWR and Dragon;
- SGHWR and Dragon demolition blocks;
- SGHWR and Dragon below ground in-situ structures;
- Metals remaining as integral parts of below ground structures (i.e. re-bar and structural beams providing structural integrity) (Ref. 47);
- Other contaminated non-inert materials where a Best Available Technique (BAT) assessment shows disposal is optimal e.g. residual levels of asbestos and oil contamination, glass fibre pond liners, structural steelwork;
- Void-filling and sealant grout deemed necessary to stabilise the end state structures and seal penetrations where direct discharges could occur;
- Existing stockpiled rubble.

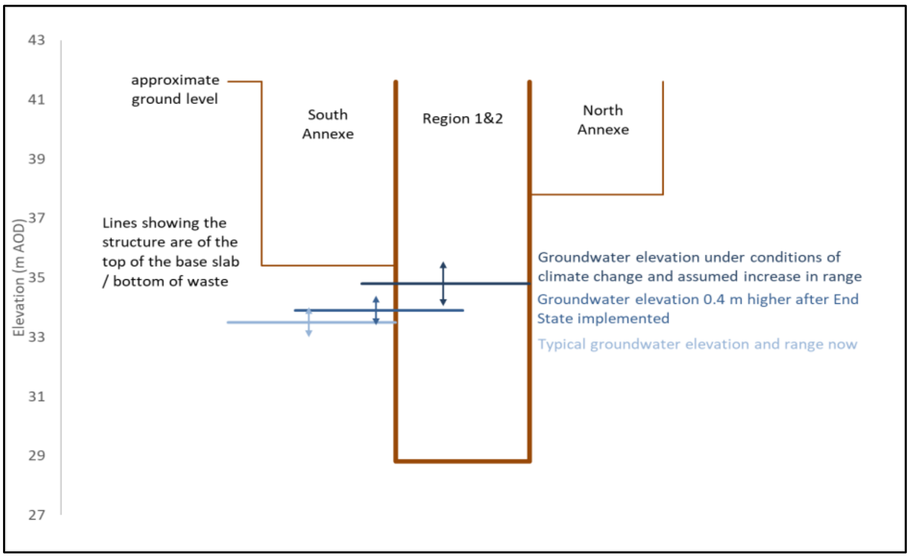
Further characterisation of the reactor structures and backfill is anticipated as decommissioning progresses (Ref. 20).

A wide range of uncertainties have been identified at the concept stage which will need to be managed through to end state implementation and, where appropriate, beyond. NRS is applying its uncertainty management process (UMP) to manage the uncertainties, identify mitigations and approve outcomes (Ref. 21).

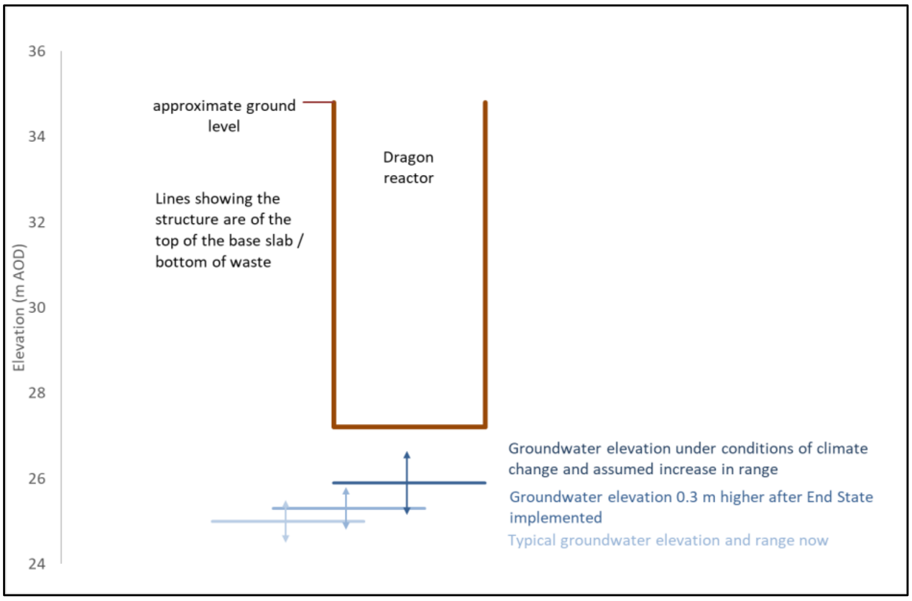
2.6 Hydrogeology

Groundwater can interact with the SGHWR and Dragon end states, leading to the release of contaminants which may subsequently have an environmental impact. Therefore, understanding groundwater behaviour through current and future climate scenarios has been a key consideration in the development of the reactor end state concept designs. The concept designs have had to consider current and future groundwater levels and the potential behaviour of contamination during these scenarios as modelled in the radiological Performance Assessment (PA) and the Hydrogeological Risk Assessment (HRA) (Ref. 22). Figure 6 shows groundwater levels increasing from present day conditions (actual data), and as anticipated after changes to the site's drainage system at the IEP (as modelled) and during one of a number of future climate change scenarios when groundwater levels are expected to increase further (based on modelling). The PA and HRA have considered expected groundwater levels, a variant case in which groundwater levels are higher due to future climate change, seasonal variation of the latter, and an extreme what-if scenario where groundwater annually inundates the South Annexe (Ref. 14, Ref. 15).

Figure 6: Illustration of current and future (to 2100) groundwater elevations and range at SGHWR and the Dragon reactor



SGHWR Disposal



Dragon Disposal

2.7 Emplacement Acceptance Criteria, EAC

A set of EAC have been developed to ensure that the risks to human health and the environment from retaining below ground material in-situ and using materials as infill are as low as reasonably achievable (ALARA) (Ref. 23). Material proposed to be left in situ within the reactor below ground structures or used as infill into the below ground voids will need to conform with the EAC before being considered as part of the end state. If a material does not meet the EAC, then further optimisation would be undertaken to determine whether any risk associated with the material is acceptable. Further engagement with the EA will be required to ensure that regulatory expectations were understood.

2.8 Construction Quality Assurance Plan, CQAP

The CQAP will ensure that the detailed design will be implemented. An application CQAP has been issued for the concept design and this will be developed further to reflect the configuration of the reactors after core retrieval and processing, as well as the final detailed design (Ref. 4).

The purpose of the application CQAP is to explain how NRS will ensure construction of the SGHWR and Dragon Reactor end states is consistent with the claims of the SWESC. The application CQAP is therefore intended to support the environmental permit application. The

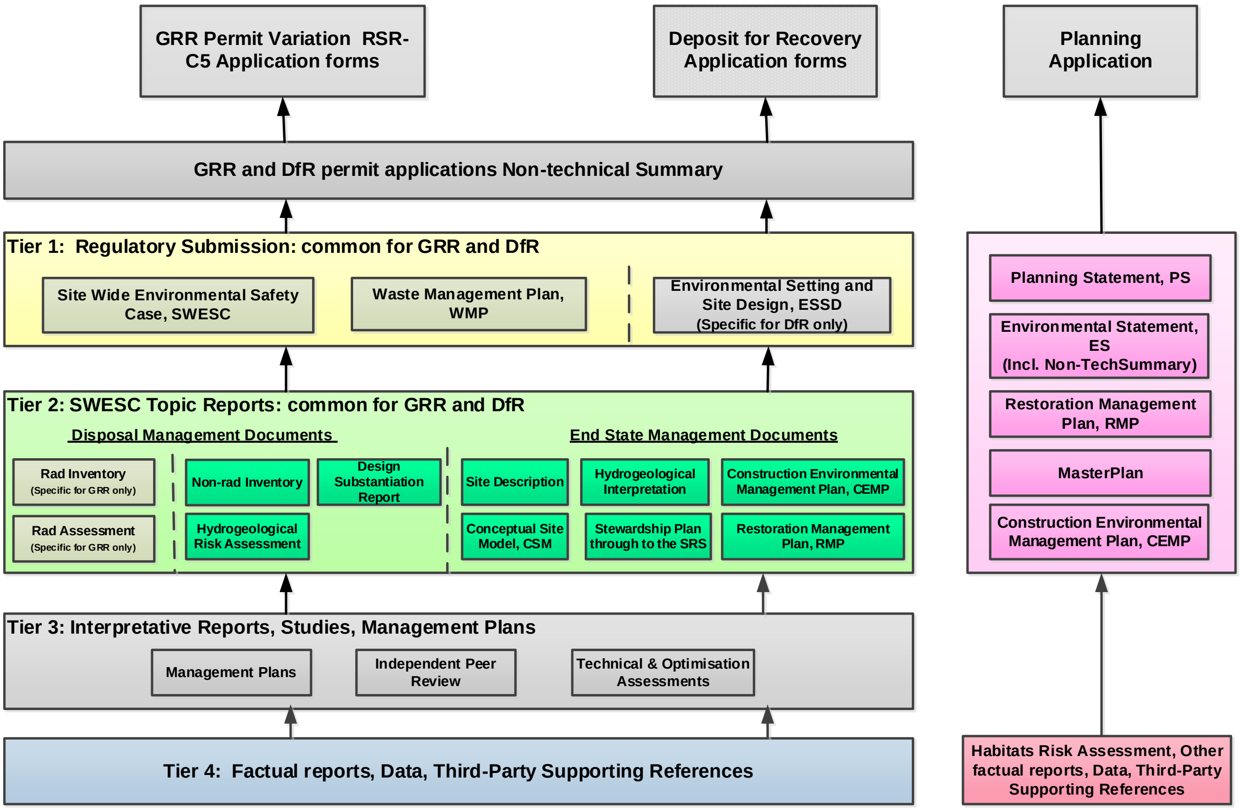
Final CQAP, which may be presented in a series of documents each addressing specific aspects of the works, will only be produced once the permit and planning conditions are known and a demolition contractor has been engaged. The scope of the application CQAP includes how:

- The decommissioned below ground structures are assessed before demolition and backfilling to remove materials that do not meet the EAC i.e. removal of materials unacceptable in the disposals;
- The demolition material rubble backfill and any other introduced material emplaced in the below ground voids will comply with the criteria for on-site disposal (both radiological and non-radiological characteristics);
- The end state engineering design and construction will comply with the end state specification, which will be finalised in the detailed design stage;
- The disposal caps will be constructed to meet the detailed design specification.

2.9 Documents Supporting Concept Design and GRR Permit Variation and Planning Applications

The GRR and DfR permit, and planning applications are supported by a series of documents which are grouped in a tiered hierarchy as shown in Figure 7. This DSR is one of several Tier 2 documents that will be submitted in support of the case for disposals. Tier 3 documents, that support and underpin the concept design, will be discussed in the DSR to demonstrate that the FRs and EA expectations have been addressed.

Figure 7: Documentation hierarchy for the permit and planning applications



3 CONCEPT DESIGN FUNCTIONAL REQUIREMENTS, CONSTRAINTS, ASSUMPTIONS, EXCLUSIONS, UNCERTAINTIES

The concept design proposals for the SGHWR and Dragon end states set out how the existing building structures will be disposed of in-situ. The proposals cover all aspects of the below-ground and above-ground structures together with methods for capping the disposals.

The scope of work for the concept design proposals was bounded by, and based on, sets of functional requirements, constraints, assumptions and exclusions developed during the early stages of the site end state (Ref. 1). The period for retaining these functions will need to be confirmed at the detailed design stage, however there will be an intent to avoid direct discharges of pollutants to groundwater for the period of the permits.

3.1 Functional Requirements

The following functional requirements, as set out in Table 1, chosen by a group suitably qualified and experienced project members, set out the engineering requirements to be met by the SGHWR and Dragon end state concept designs.

Table 1: Winfrith End State Concept Design Functional Requirements

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR2	Minimise the demolition of the below ground structures at SGHWR and Dragon in order to reduce the production of waste, reduce the amount of work and the resultant increased risks to worker health and safety and protection of the environment.	
FR3	Throughout all stages of demolition and construction of the disposals, maintain the structural integrity of ground bearing slabs and external walls which will form the disposal boundary structures such that direct discharges are prevented by:	
	FR 3.1	Avoid construction activities that may damage boundary structures, noting the relative performance of boundary structures is defined in the structural integrity assessment.
	FR 3.2	Ensure that demolition is controlled to avoid detrimental point loading of walls and slabs and also to restrict impact loading from falling demolition rubble to acceptable levels.
FR4	Make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter ground water levels (current or assumed climate change scenarios). Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.	
FR5	Consider the condition of the structure and identify any degradation mechanisms, current or future, that could give rise to direct discharges. Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.	
FR6	Maximise the use of concrete arisings from demolishing above ground section of SGHWR and Dragon reactors in order to fill below ground voids.	
FR7	Maximise the use of the existing demolition rubble mounds to fill any remaining below ground voids after FR6 has been met.	

FR8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).	
FR9	Provide engineered caps above the disposals at SGHWR and Dragon to:	
	FR 9.1	Ensure structural integrity, including resistance to degradation, slumping and applied loading.
	FR 9.2	Provide a deterrent to inadvertent human intrusion, plants with deep roots and deep animal burrowing.
	FR 9.3	Prevent ponding on and around the caps by ensuring the caps are laid to appropriate falls and are connected to passive drainage systems.
	FR 9.4	Inhibit water ingress through the caps.
	FR 9.5	Disposals need to have points of overflow into the unsaturated zone
	FR 9.6	Support colonisation of grasses and native plant species above the cap.
FR10	Provide a landscaped surface above the capped disposals that is consistent with the site's Restoration Management Plan, RMP and is suitable for use (both radiologically and non-radiologically) to a sufficient depth to be safe for public access.	
FR11	Determine a demolition and construction strategy that allows for the implementation of the SGHWR and Dragon disposal facilities as soon as reasonably practicable after the site receives approval for the disposals, so as to allow the site to achieve its IEP on the timescales set out in the sites decommissioning programme.	
FR12	The SGHWR and Dragon structures should be demolished down to a cutline not greater than 1 m below ground floor slab level.	

3.2 Constraints

The following constraints, as set out in Table 2, apply to the concept designs of the SGHWR and Dragon end states.

Table 2: Winfrith End State Concept Design Constraints

C1	The SGHWR and Dragon end states delivered should always be safe (the risk will need to be broadly acceptable and below the level of regulatory control) for people and the environment in the short and long-term.
C2	The physical condition in the site's end state is to be heathland which will allow re-use of the site for public access for recreation purposes and more natural habitats. The selected end state designs must therefore deliver appropriate levels of safety to allow public access and to ensure that any radioactivity remaining on the site meets the GRR requirements R9 (dose constraint), R10 (risk guidance level or any future use of the site), R11 (human intrusion), R12 (natural disruptive events), R14 (environment / non-human biota) and R15 (non-radiological hazards).
C3	Credible SGHWR and Dragon end state engineering designs must be consistent with any decisions which have already been made on the Winfrith site that may be precursor activities e.g. current SGHWR and Dragon decommissioning works.
C4	Wastes and materials arising from achieving the SGHWR and Dragon end states that do not meet the EAC must be planned for, with on-site segregation and storage locations available, as well as approved off-site disposal routes.

3.3 Assumptions

The following assumptions, as set out in Table 3, apply to the SGHWR and Dragon concept designs.

Table 3: Winfrith End State Concept Design Assumptions

A1.	The next land use agreed with the NDA is heathland with public access.
A2.	There are no requirements to return the site to pre-development levels, and landscaping requirements are set out in the Restoration Management Plan, RMP.
A3.	The EA does not alter its current interpretation of the GRR and how it will be applied, and **that there are** no changes to relevant radiological and non-radiological substances legislation.
A4.	The planned legislation changes, arising from the DESNZ-sponsored regulation of nuclear sites in the final stages of decommissioning and clean-up, will lead to regulations and guidance that supports the currently envisaged application of the GRR and its implementation at Winfrith.
A5.	The case for in-situ and disposal for a purpose of radioactive wastes and recovery of non-radioactive wastes and material at SGHWR and Dragon is accepted as compliant by the regulators.
A6.	The in-situ and disposal for a purpose of radioactive wastes and recovery of non-radioactive wastes and material at SGHWR and Dragon does not require a non-RSR EPR landfill permit for disposal and the associated engineering requirements imposed (note a DfR Permit is required).
A7.	The planned disposal at Winfrith do not require a separate groundwater activity permit.
A8.	The long-term risk assessments (radiological and non-radiological) will support the development of the SGHWR and Dragon end state designs.
A9.	Concrete arisings from the demolition of the SGHWR and Dragon above ground structures that meet the EAC will be suitable for use in backfilling below ground structures Such radioactive arisings will be radioactive waste subject to Disposal for a Purpose, while non-radioactive demolition rubble will be subject to a recovery operation.
A10.	Where reasonably practicable, arisings from demolition of reinforced concrete structures, identified for below ground void infilling, will have the reinforcing steel removed for off-site recycling or disposal.
A11.	Environmental monitoring, which will include groundwater monitoring, will be maintained for about ~3 decades (period length to be confirmed) after the site's IEP to provide data to the regulators and local stakeholders to show the disposals at SGHWR and Dragon perform as modelled in the SWESC that underpinned the disposal permit variation.
A12.	The requirements for engineering substantiation and verification are agreed with the EA in advance of detailed design development, through submission of applications for on-site disposal / recovery.

3.4 Exclusions

The scope of work for the concept designs excludes the following:

- Requirements concerning the management of safety and protection of the environment during demolition, backfilling, capping, and landscaping;

- Materials removed during decommissioning and soft strip which are non-compliant with the EAC as these materials will be managed off-site according to separate waste management routes and will not be part of the end state (Ref. 23).

3.5 Uncertainties

The engineering and design uncertainties are managed through the NRS UMP (Ref. 21). Those uncertainties identified through the concept design stage are listed in Appendix B, along with the uncertainty descriptions, how the uncertainties are treated along with any underlying assumptions, their significance and recommended actions. Appendix B lists 16 uncertainties: 13 identified by contractors and a further 3 identified by NRS following completion of the contractor report.

4 DESIGN PROCESS

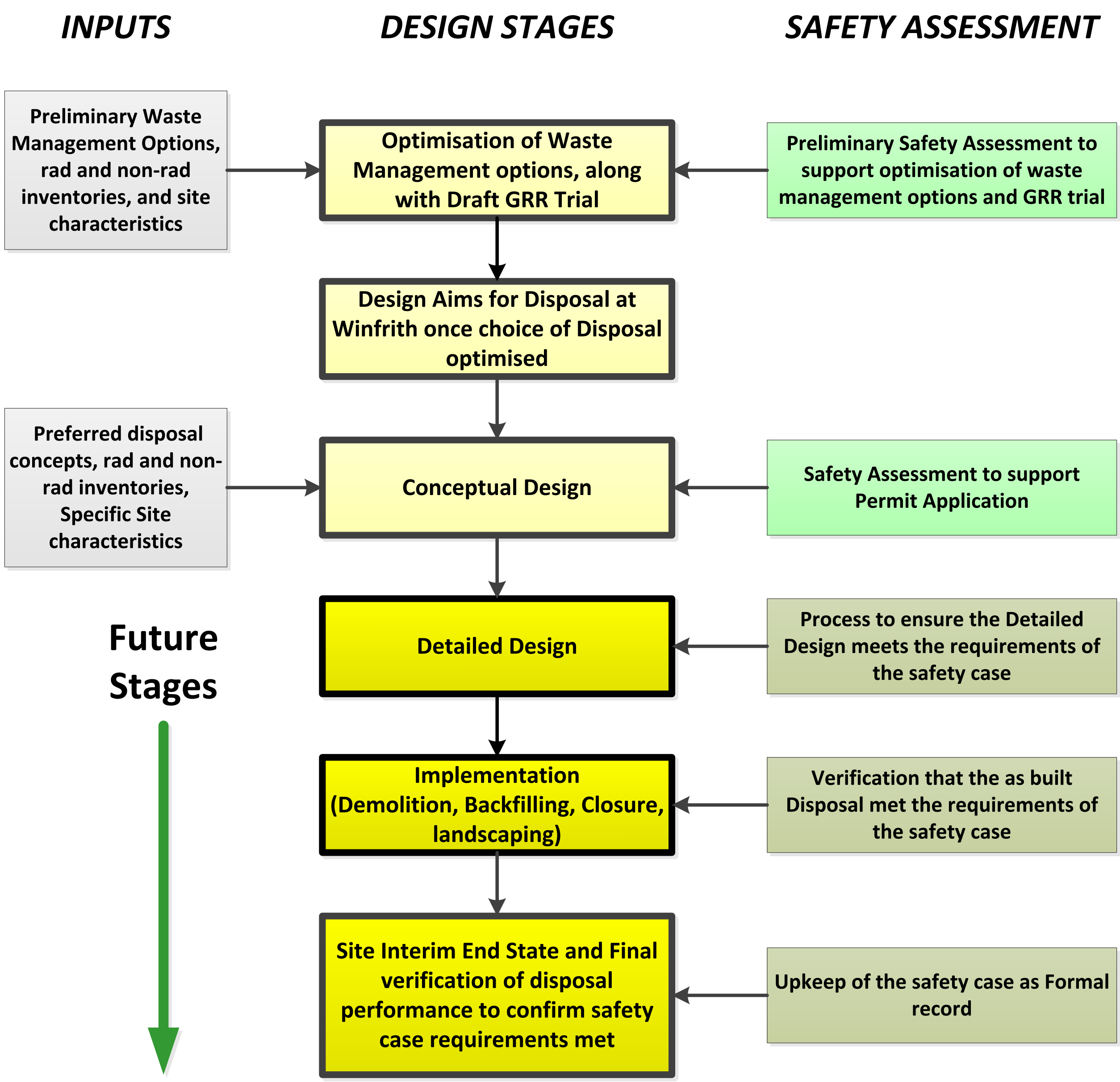
4.1 Design Phases

The design process for the types of disposals being proposed at Winfrith has been multi-staged and iterative, involving safety assessments and information on disposal components, types of wastes and materials and site characteristics. It has allowed the engineers to modify the disposal design concepts to achieve the desired safety requirements consistent with good engineering practice and operational and decommissioning needs. It is important to recognise the iterative nature of developing and optimising the disposal designs. The design process has been developed in conjunction with the radiological and non-radiological risk assessments and not in isolation. The interrelationship of the various disposal components is shown in Figure 8.

The major design activities, required as part of the overarching design process MAN-0004 (16), are:

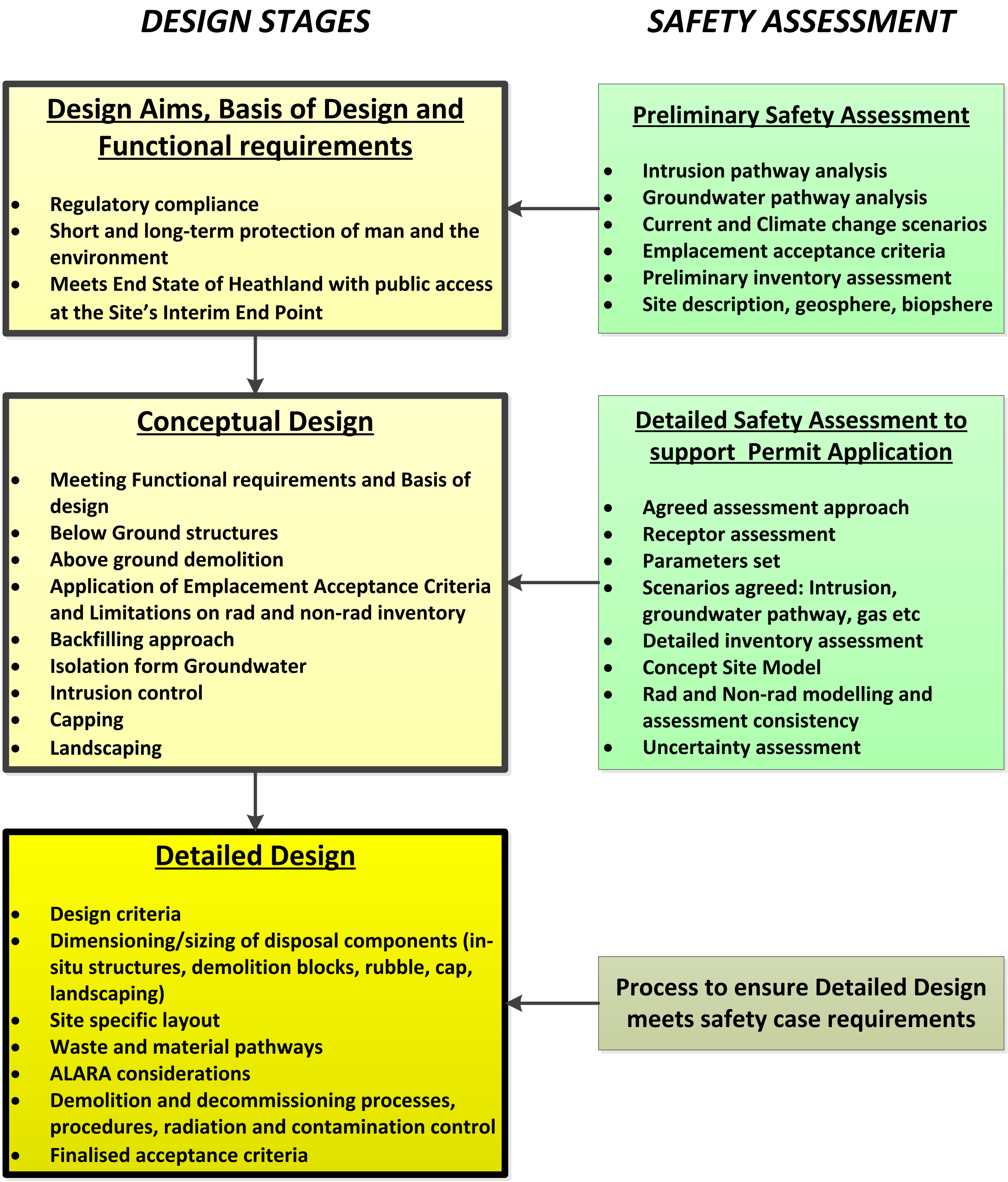
- **Concept Design**: The concept design phase which supports decision-making on the end state of the Winfrith site. This phase is now complete, and it has resulted in ‘frozen’ SGHWR and Dragon concept designs;
- **Detailed Design:** The detailed engineering design phase, where all input data (site, disposal concepts, environment, etc.) has been fixed, taking account of new information and data arising as decommissioning continues and the impact of any conditions on the site as part of the permit and planning approvals. The detailed design stage will define the exact demolition and emplacement sequence, taking account of building loadings and safety parameters.

Figure 8: The Design Process showing the relationship between the design phases and the design aims, safety assessments, information input and implementation



The concept and detailed design stages are described further Figure 9.

Figure 9: Application of the Design process to the Winfrith Disposals



How the detailed design phase is structured will be decided by the design teams at that stage.

4.2 Concept Design Development

The concept design appraisal consisted of technical, economic and safety evaluations of various disposal design options taking account of factors such as: safety (e.g. compliance with the established safety principles and regulatory requirements); environmental impact (e.g. compatibility with the characteristics of the Winfrith site); technical performance (e.g. how the disposals might be constructed); social and economic factors and programme and cost. The design options evaluation included the descriptions and functions of the disposal components, and the intended performance, safety and environmental functions assigned to each of the components that comprise the disposal system.

The concept design has evolved through:

- A set of FRs which describe design requirements for the proposed on-site disposals (Ref. 1);
- A Basis of Design (BoD), which set out the design criteria to form a framework for the design process (Ref. 24);
- Radiological (Ref. 18) and non-radiological (Ref. 19) inventories and general characteristics as well as the associated PA (Ref. 14) and HRA (Ref. 15);
- Site characteristics (generic or specific) (Ref. 25), and data (geology, hydrology, hydrogeology, geochemistry, climate) (Ref. 7, Ref. 22);
- Safety and regulatory criteria (operational/decommissioning, demolition, and long term).

The principal engineering assessments and studies are summarised below, with further descriptions set out in Appendix A:

- SGHWR structural assessment and demolition study (Ref. 26);
- Engineering appraisal and concept design (Ref. 27);
- Consideration of concrete hydraulic conductivity (Ref. 28);
- Evidence for in-leakage of groundwater (Ref. 29, Ref. 45);
- Review of construction joints and water bars (Ref. 30);
- Review of penetrations in the structures (Ref. 31);
- SGHWR and Dragon reactor structural integrity assessment (Ref. 32).

4.2.1 SGHWR Structural Assessment and Demolition Study (Ref. 26)

Atkins were commissioned in 2018 to carry out a preliminary structural assessment and demolition study for SGHWR. This work was undertaken in collaboration with NRS and a specialist demolition contractor, KDC. The ‘high level’ objectives of this work were to:

- Develop credible demolition and backfilling sequence(s) that align with the end state configuration options, taking account of identified structural engineering limitations and constraints;
- Undertake a ‘high-level’ preliminary structural assessment to consider the availability of reserve strength in key primary structural members to accommodate selective and progressive removal of other members and allow below ground structure backfilling.

The key findings were:

- The Primary Containment and Turbine Hall can be demolished in a safe and compliant manner without reducing wall and base structural integrity;
- The South and North Annexes can be safely demolished, however floor and possibly wall damage may occur due to falling rubble;
- Arisings from the demolition process can be used as backfill for the basement areas, although some additional fill material from site stockpiles will be required to make up a fill deficiency;
- No formal compaction of the rubble backfill is required to meet settlement requirements;
- For the Primary Containment and Turbine Hall, heavy concrete above ground structures should be cut into large concrete blocks, with these blocks being placed into the below ground basement areas using the existing 60t crane. This method of demolition is preferred on safety and cost/times grounds;
- Demolition can be carried out using conventional techniques, i.e., long reach excavators (fitted with breakers or cutting jaws) and diamond wire sawing;
- Due to the vulnerability of some structural elements, exclusion areas around some buildings will be required to prevent heavy plant imposing surcharge loading to the below ground retaining walls leading to overloading and possible collapse;
- Temporary propping of some of the retaining walls may be required as demolition and backfilling proceeds.

The output from this work informed subsequent options development.

4.2.2 Engineering Appraisal and Concept Design (Ref. 27)

Atkins carried out an engineering appraisal of credible options for the construction of the SGHWR and Dragon disposals. To ensure that the options proposed were consistent with NRS expectations and the ongoing risks assessments, the engineering appraisal evolved through several stages:

- Site visits and walkdowns of the SGHWR and Dragon Reactors;
- Basis of Design workshop;
- Option development workshop;
- Option evaluation workshop;
- Presentations of concept design options to NRS and regulators.

Feedback at each of these stages was used to inform the development of the concept designs.

Structural assessments and demolition: Several credible options were considered, and cost and programme implications identified. It was recommended that demolition should be top-down using long reach machines. Furthermore, heavy concrete structures within the demolition zones should be cut into blocks and placed directly into the below ground voids. The remaining sections of concrete should then be reduced to rubble and placed on top of the blocks without the need for additional processing or mechanical compaction.

Concrete degradation and hydraulic conductivity: The need to control groundwater movement into and out of the disposals was recognised, particularly the movement through disposal boundary walls and ground slabs. Whilst contaminant rate of loss through concrete is governed by degradation and hydraulic conductivity, it was concluded there were no physical or chemical degradation mechanisms that would significantly affect the quality of the concrete over the lifetime of the permit application (i.e., conservatively assumed to be up to 100 years).

Cap options: The appraisal considered various cap options; with the purpose of the cap being to:

- Restrict infiltration and encourage runoff;
- Isolate and protect the waste and control the waste condition through reducing the infiltration of water and minimise the potential for contaminant release (solid, liquid or gas);
- Resist damage due to movement and settlement;
- Resist erosion damage due to wind or rain or intrusion by plants, animals, and humans;
- Perform passively without maintenance or deliberate intervention.

Note that the material placed into the below ground voids will be inert reactor demolition concrete blocks and rubble, topped up with stockpiled concrete and brick from previous demolitions on site. It is therefore considered unlikely that gas will be generated. However, a gas regulating layer will be considered at the detailed design stage, in line with engineering best practice.

The appraisal considered four options for the disposal caps:

- Option 1: A mineral cap using material such as a 1m thick clay layer to reduce permeability. Additional layers providing drainage and protection against intrusion;
- Option 2: A geomembrane and mineral composite cap similar to Option 1 with the exception that the mineral layer is replaced by a geomembrane and a mineral layer with an overall thinner thickness, therefore reduced volumes and vehicle movements are needed;
- Option 3: A geomembrane and geosynthetic composite cap utilising a 2mm thick HDPE layer with a permeability of $1x10^{-14}$. This cap design has the advantage of containing several low-permeability layers. Consequently, it is the most durable, and the most robust against damage and degradation;
- Option 4: A minimal engineered cap comprising a drainage layer, anti-intrusion layer with a soil cover, with no low permeability barriers. This option has the advantage of requiring the

minimum volumes of material to be imported and would offer the minimum construction cost. This option could be viable if, for example, the backfill were to be grouted in-situ, meaning that a more permeable cap could be utilised.

It was determined that a high-performance low permeability cap (specification in Section 5) was preferable for the SGHWR and Dragon disposals. Though most expensive, the cost is insignificant when compared to the cost of disposal construction. Furthermore, the option would provide the most durable, and the most robust cap against damage and degradation. Whilst the option has been chosen for the concept designs and its characteristics used in the risk assessments, it is recognised that further cap design optimisation will be required at the detailed design stage.

Cap settlement: Excessive settlement of the backfill could affect the finished ground profile and performance of the cap. However, concept level calculations showed that the expected settlement of the backfill will not affect the performance of the cap or the final landscaped End State (Ref. 26). The calculations concluded that the total combined settlement was anticipated to be less than 270mm for SGHWR, and less than 120mm for Dragon. This can also be expressed as a distortion factor (D/L) over the width of the cap solution, where D is the vertical settlement distance and L is the horizontal distance over which the settlement occurs (assumed to be half the width of each disposal). Distortion factors for SGHWR and Dragon were calculated as 0.007 (0.27/40) and 0.006 (0.12/20) respectively which compared well with maximum allowable distortions of 0.05 - 0.1.

A further assessment noted that the approach taken was appropriate for the uniform natural soils but would not be appropriate for non-uniform backfill materials (Ref. 33). The fill material, placement methodology and environmental conditions (specifically saturation by water) may also make the fill susceptible to settlement by other mechanisms. Therefore, settlement will be reassessed using the proposed backfill placement methodology and that due consideration is taken of water saturation of the fill. This will be undertaken at the detailed design stage and assured by meeting construction quality assurance conditions.

Backfill Options: The issues associated with the void backfill included:

- The way the material can be placed;
- Whether compaction is needed;
- Whether processing before placement is beneficial;
- If any backfill grouting is needed;
- Whether settlement is an issue and whether it needs to be reduced.

The appraisal concluded that:

- Demolition arisings (blocks and rubble) from SGHWR will not completely fill the available below ground voids. Therefore, some material from the site rubble stockpiles is needed to complete void filling;
- Cap settlement will take two forms: (a) material self-weight settlement (without additional mechanical compaction) and (b) natural ground settlement below the disposals. As calculated settlements of up to 270mm for SGHWR disposal and 120mm for the Dragon disposal are possible, then this will need to be considered at the detailed design stage;
- Grouting the backfill to produce a monolithic backfill is not required to control settlement or to provide stability;
- As larger forms of concrete will produce lower levels of alkali leachate than smaller forms, large blocks of concrete and larger particles of rubble are the preferred backfill in the below ground voids that are below current and future groundwater levels;
- On this basis, the largest concrete sections, i.e., concrete blocks, should be placed below the water table to reduce the potential for leachate;
- Minimising the chance that large pieces of demolition concrete lead to voids in the backfill;
- Segregation of the demolition arisings is of little benefit and would add significantly to the overall cost and duration of the demolition/backfilling process. However, the production of

smaller particles and fines should be minimised, and they should preferentially be placed above the water table, where practicable.

Drainage and Water Management: Shallow stone drains within the cap surface will provide drainage routes and help prevent ponding. By removing water from the cap, the drains would provide an additional layer of defence against rainwater ingress into the disposals. The removed water will then be routed to ditches at the cap toe and flow into the wider Winfrith site.

Landscape: The cap surface is key in determining the potential landscape and visual effects generated by the disposals. The Restoration Management Plan (RMP) sets out the site's habitat and landscape aims (3). This includes the surfaces of the two disposals and how they are likely to develop and what maintenance actions are planned to enable this.

4.2.3 Concrete Hydraulic Conductivity (Ref. 28)

A recent independent peer review of the site's end state Conceptual Site Model (CSM) determined that earlier work on concrete degradation and hydraulic conductivity had not been sufficiently underpinned (Ref. 34). A revised description (Ref. 35) of the evolution of effective hydraulic conductivity has placed less emphasis on the earlier work and instead referred to assessments of near-surface disposal facilities to benchmark assumed parameter values. The time assumed for the concrete in the disposals to hydraulically degrade used in the radiological and non-radiological risk assessments of the SGHWR and Dragon disposals has used the hydraulic degradation rates assumed for concrete barriers in safety assessments for near-surface disposal facilities as set out in Table 4.

Table 4: Assumed hydraulic degradation rates for concrete barriers in safety assessments for near-surface disposal facilities

Assessment	Material	Hydraulic Degradation Rate
Centre de l'Aube (France) (Ref. 36)	Concrete	Instantaneous change: Assumed failure and not modelled after 300 years.
LLWR (UK) (Ref. 37, Ref. 38, Ref. 39)	Concrete base	Linear change: Initial reduction in hydraulic performance after 1,000 years followed by gradual degradation to geosphere values over 10,000 years.
	Concrete walls	
	Grouted LLW	
	Concrete base/walls (future vaults)	Linear change: Initial reduction in hydraulic performance after 100 years followed by a further reduction after 5,000 years.
D3100 (UK) (Ref. 40)	Concrete barriers	Linear change: Reductions in hydraulic performance over 200 and 500 years, complete degradation after 1,000 years.
	Grouted LLW	Linear change: Reductions in hydraulic performance over 300 years and 1,000 years, with complete degradation by 10,000 years.
	Cementitious backfill	
	Unencapsulated (demolition) LLW	Linear change: High initial conductivity decreases by an order of magnitude over 600 years due to clogging and settlement. At 1,600 years conductivity increases as the concrete completely degrades.
El Cabril (Spain) (Ref. 36)	Concrete	Instantaneous change: Degradation to a porous sand after 300 years.
Savannah River (US) (Ref. 36)	Concrete floor	Degradation after 1,050 years.
SFR (Sweden)	Concrete, waste	Intact for 10,000 years or degraded after 1,000 years.

Assessment	Material	Hydraulic Degradation Rate
(Ref. 41, Ref. 42, Ref. 43)	Concrete barriers	Intact concrete hydraulic conductivity is ≤$1x10^{-9}$ m/s. Depending on its use, concrete degrades to a hydraulic conductivity of: $1x10^{-7}$ m/s in 2,000-3,000 years $1x10^{-5}$ m/s in 2,000-22,000 years $1x10^{-3}$ m/s in 12,000-52,000 years.
Dessel (Belgium) (Ref. 44)	Walls, Base, Roof, Grouted waste monolith	Degradation implemented using an "S-shaped" function – fully degraded after 816 years.

4.2.4 Evidence for in-leakage of groundwater (Ref. 29, Ref. 45)

The structural integrity of the below ground structures at SGHWR and Dragon Reactor is generally very good. There has been some historic water ingress at low levels in SGHWR due to roof leaks (now repaired), cutting operations and leaking showers. As a result, nominal low level water egress from the SGHWR end state has been assumed in the radiological and non-radiological risk assessments for the End State configuration. The environmental impact of the nominal volumes of water egress has been shown to be insignificant.

However, more recently (winter/spring 2024) there has been an increased rate of water ingress, which has coincided with very high rainfall and external groundwater levels. The reasons for this increased water ingress and the routes that the water ingress took is under investigation. Whilst this might be a sporadic event, if the water ingress is due to increased groundwater levels, then understanding the mechanisms by which water can enter and therefore potentially leave SGHWR's below ground structure will be important as increased groundwater levels are anticipated with climate change.

The investigation has shown the bulk of the water ingress occurred through the open duct below room 224. The open duct provides the most likely route for the water to flow into the delay tank room, either by the cavity wall separating the two sides of the delay tank room i.e. 125 and 126 or via the pipe-penetration into room 126. Structural repairs to seal these in-leakage routes at the open duct and in the delay tank room cavity wall are planned, and these will reduce water ingress back to nominal levels.

NRS will continue to monitor water ingress at SGHWR as decommissioning work is carried out and then when a more definitive understanding of the situation becomes available, NRS will make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter groundwater levels (current or assumed climate change scenarios). The design of any remedial measures for any identified or potential direct discharge pathways to groundwater will then be optimised.

Likewise at Dragon, some historical water ingress has taken place through the above ground structure and simple repair work has been undertaken to prevent this reoccurring. Some water has also entered the basement of building B72, an adjacent building connected to the Dragon reactor via a cable tunnel. The water ingress into B72 occurred during heavy rain and local flooding. Simple engineering repairs are likely required before reactor demolition to prevent water ingress into the Dragon basement areas from this water source. The exact means of doing this will be determined in the detailed design stage.

Groundwater and boundary structure behaviour will continue to be monitored, and the results reviewed at the detailed design stage to determine if further repairs or mitigations are required.

4.2.5 Review of Construction Joints and Water Bars (Ref. 30)

The integrity of construction joints in the below ground SGHWR and Dragon Reactor has been considered. The concrete joints within the boundary structures are construction joints, mostly fitted with water bars, formed by casting fresh concrete against already placed concrete.

4.2.6 Review of Penetrations in the Structures (Ref. 31)

There are penetrations in the below ground structures of the Primary Containment and Turbine Hall. These penetrations, such as the large openings for the vent stack exhaust pipes and the redundant cooling water mains, will be filled and sealed prior to demolition and backfilling. The number and type of penetrations that will need sealing will only be fully known once the main decommissioning work has been completed and full access across the reactor is available.

4.2.7 SGHWR and Dragon Reactor Structural Integrity Assessment (Ref. 32)

A structural integrity assessment of both the below ground SGHWR and Dragon Reactor buildings was carried out to determine wall and base robustness. Whilst some penetrations, joints and cracks may need attention, it was concluded that the thick-walled below ground structures of the SGHWR Primary Containment and Turbine Hall and the Dragon Reactor will retain their structural integrity during demolition and in their end states.

The structural integrity calculations were undertaken in accordance with Eurocode 2 (EC2) to assess disposal boundary structures in potential demolition and End State configurations. This included assessments for non-uniform loading and dropped loads onto slabs. The calculations showed that there were no underlying concerns with the boundary structures provided that previously identified demolition methodologies and backfilling practices are adopted. For example, there will be a requirement to limit the size of demolition arisings to avoid point loads on the boundary walls and slabs. Furthermore, there may be a need to provide temporary propping to some external boundary walls during some demolition phases. It was concluded that structural integrity of boundary structures could be maintained during demolition and backfilling operations. Where appropriate, remedial measures will address the penetrations, joints and cracks in the boundary structures, where there is evidence of water ingress or structural weakness. Simple engineering solutions are available for these repair tasks. The CQAP programme, agreed with the regulators, will ensure all structural weaknesses have been repaired and verified before demolition works are undertaken.

Buoyancy: The structural integrity assessment considered the impact of buoyancy on the boundary structures in groundwater when the above ground structures were removed. However, the factors of safety against floatation were shown to be considerable, even with the above ground structures removed and the below ground voids left empty, a worst-case scenario that will not occur in practice.

Surface cracking: The structural analysis showed that any changes in stress regimes during demolition will not be detrimental in terms of wall cracking. This is because there will be a tendency to reduce compressive stresses and increase bending stresses as demolition proceeds. Enhanced bending stresses in thick, reinforced concrete retaining walls will mean that the compressive face of the wall will experience additional compressive forces, and this will further reduce the possibility of “through” wall crack formation. Indeed, there are no situations where the retaining walls experience purely tensile forces, a scenario that could give rise to through cracking and the formation of a direct discharge.

Other mechanisms for loss of integrity: No other mechanisms, such as concrete degradation and failed joints, have been found that could give rise to direct discharges to groundwater. This finding will be confirmed by surveys at the detailed design stage. If issues are identified, simple repair solutions are available.

5 SGHWR END STATE DESCRIPTION

The outputs from Section 4 guided the development of the concept design for SGHWR. The concept design is described in the following sections, with reference to:

- The layout and nature of the current SGHWR buildings;
- The work needed to prepare these buildings for demolition;
- The demolition and backfilling process;
- The End State configuration, including capping, drainage and landscaping.

To prepare SGHWR for demolition and backfilling, all internal soft finishes and equipment that do not meet the EAC will be removed. This will include partition walls and ceilings, fixtures and fittings and mechanical and electrical plant and services. The removed materials will be managed through existing waste management routes leading to disposal elsewhere.

In addition, there are several void spaces beneath the suspended basement slabs in the Turbine Hall that will need to be backfilled. Failure to do this could result in unacceptable settlement of the backfill if a suspended slab were to fail in the end state condition (24). The material to fill these voids has not yet been chosen, and material choice and optimisation can be left to the detailed design stage.

After bulk ILW and LLW removal from SGHWR and Dragon, enabling works for reactor structure dismantling will be complete. A final inspection will then be carried out, including completion of penetration sealing to ensure the boundary structures (external walls and ground slabs in contact with groundwater) maintain their ability to avoid direct discharges. How this will be achieved will be confirmed at detailed design stage. This may include checks for water ingress with associated remedial works, condition surveys, etc (Ref. 4).

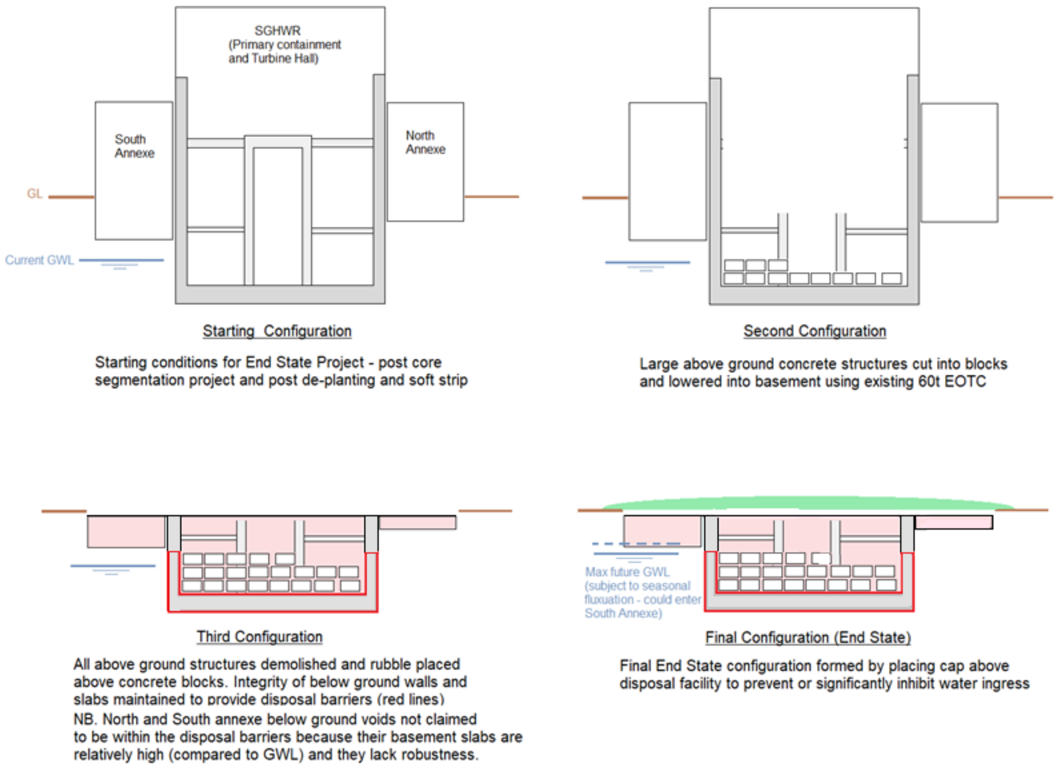
The demolition sequence concept is:

- Large concrete blocks will be cut from the above ground parts of the Primary Containment and Turbine Hall and placed into the deepest part of the below ground voids. The demolition method is to use diamond wire cutting, though the chosen method will be optimised at the detailed design stage. The existing overhead crane will be used to lift the blocks and lower them into accessible locations in the below ground voids. They will be moved into more remote areas of the basement structures, if required and where it is practical to do so;
- Block cutting and placement will be undertaken, as much as possible, with the external weather envelope and roof in place, thereby restricting rainwater ingress into the disposal site at this stage, and to limit the spread of dust;
- When block cutting and placement is complete, the cladding and steelwork, which forms the weather envelope above the Primary Containment and Turbine Hall will be progressively cut back to permit removal of the overhead crane and demolition of any remaining concrete structures using long reach machines;
- Demolition of the remaining above ground structures will be by conventional demolition techniques, e.g. jaws and breakers on long reach machines. This will involve demolishing what remains of the above ground structures to ground level, or just below, with any compliant material being used to backfill the below ground voids;
- Accessible non-structural metal elements will be removed from the above ground structure for management elsewhere;
- The concrete rubble produced will be allowed to fall onto the already placed concrete blocks in the deeper sections of the reactor structure (regions 1 and 2 and other specified rooms in Figure 2), thereby filling the below ground voids. No mechanical compaction will be applied to the rubble fill, although some compaction will inevitably take place as the rubble falls and the density of the placed material increases. Any shortfall in fill material will be augmented by suitable material from the site rubble stockpiles. The need or otherwise for backfill compaction will be revisited at the detailed design stage;
- The rubble will be used to fill around and on top of the already placed concrete blocks, whilst only rubble will used to fill the North and South Annexes. When the roof and cladding are removed, some local tenting could be used to limit water ingress to the working area. There may be a need to pump out rainwater via a series of sumps formed in the backfill with the water then routed down appropriate management routes. The details for this will be worked up in the detailed design phase;

- Where there is a shortfall of compliant material for backfilling, rubble from the existing stockpiles close to SGHWR will be used to complete the below ground void filling. Noting that only fill material that is consistent with the supporting technical assessments (detailed engineering design, hydrogeological risk assessment and radiological performance assessment) as detailed in the EAC will be used;
- The backfilled voids will then be capped and landscaped in accordance with the RMP and the end state detailed design.

The demolition and fill sequences are shown schematically in Figure 10. The below ground structures in groundwater will form boundary structures, as denoted by the red lines, between the backfilled concrete blocks and rubble and the external ground and groundwater.

Figure 10: Schematic representation of SGHWR demolition and filling sequence



The volumes of material that can fill the below ground void at SGHWR are recorded within the NRI (Ref. 19) that supports the HRA (Ref. 15). The figures continue to evolve following continued decommissioning, with assumed underpinned values employed in the HRA and PA (Ref. 14). The disposals/deposits at the SGHWR, Dragon reactor and the Mortuary Holes adjacent to Dragon will be covered by an engineered cap, designed to hinder intrusion into the disposals/deposits and to limit rainwater infiltration. The chosen cap concept for both disposals is set out in Table 5.

Table 5: SGHWR and Dragon Reactor and Mortuary Holes Cap Concept

Cap Component	Description
Cap Top	
Topsoil and subsoil	A layer of at least 0.40 m of subsoil and 0.40 m of topsoil
Geotextile	A dense geotextile should be applied atop the anti-intrusion barrier to minimise particle migration into the underlying anti-intrusion and drainage layers

Cap Component	Description
Anti-intrusion barrier	The layer should be constructed of compacted cobbles in the range 0.10-0.15 m with a thickness of 0.30-0.60 m
Drainage layer	A minimum 0.30-0.45 m thick drainage layer, typically of a coarse (grain size between 16 mm and 32 mm) non-calcareous gravel
Geotextile	A dense geotextile (typically less than 5 mm thick) to minimise the potential for damage to the flexible membrane liner (FML) during emplacement of overlying drainage and restoration materials
Geomembrane	High Density Polyethylene (HDPE) or Linear Low-Density Polyethylene (LLDPE) flexible membrane liner
Geosynthetic Clay Liner	A thin (approximately 5 mm) layer of bentonite embedded between two needle punched layers of geotextile
Mineral Liner	For the purpose of concept design this is assumed to comprise a clay mineral liner of at least 0.50 m thickness, which will be formed by reworking and compaction in defined layers of imported clays or mudstone
Regulating layer	A regulating layer consisting of a coarse gravel (grain size between 16 mm and 32 mm) between 0.30 and 0.60 m thick will be placed directly on top of the geotextile
Geotextile	A dense geotextile (typically less than 5 mm thick) should be laid over the emplaced material prior to capping to provide separation and prevent loss of capping materials during installation
Waste	

Figure 11 shows the current view of SGHWR and once the end state has been achieved.

Figure 11: Current view of SGHWR and after end state implementation and landscape development

6 DRAGON REACTOR AND MORTUARY HOLES END STATE DESCRIPTION

The outputs from Section 4 guided the development of the concept design for the Dragon reactor and Mortuary Holes end state. The engineering concept design for the SGHWR and Dragon disposals, including the Dragon Mortuary Holes, are similar. Therefore, at concept design stage, the technical underpinning of the SGHWR disposal is equally applicable to Dragon. It is expected that as the detailed design for each disposal matures, differences in approach and the solutions adopted will start to develop. For example, the cutline of the Dragon disposal has recently been reset to ground level as result of the variable land surface in the Dragon area. The SGHWR cutline remains at 1 m below ground level (Ref. 46).

The Dragon disposal concept design is described in the following sections, with reference to:

- The layout and nature of the current Dragon reactor and Mortuary Holes;
- The work needed to prepare these buildings for demolition;
- The demolition and backfilling process;
- The End State configuration, including capping, drainage and landscaping.

As with SGHWR, preparations will include soft strip to remove materials within the existing structure that do not meet the EAC. Unlike SGHWR, there are no significant below basement inaccessible voids within the Dragon below ground structure, making preparatory works and concept design much simpler. In addition, the only known potential direct discharge leak path into groundwater might occur at the Dragon service duct. It is therefore anticipated that the penetration leading from the Dragon Reactor service duct to building B72 adjacent to the Dragon Reactor will need to be sealed. Penetration sealing will be required prior to demolition and backfilling.

The demolition sequence of the Dragon reactor is similar to that of SGHWR, noting the design differences below:

- The Dragon Reactor building will be demolished to ground level;
- The above ground Dragon Primary Containment bio-shield concrete will be diamond wire cut into blocks and placed into the below ground void;
- The demolition methodology for the Dragon roof will use conventional machinery and techniques with the roof pre-cast concrete slabs being pulverised and used to backfill the below ground voids, along with wall rubble;
- Once the steel shell top is exposed, sections will be removed and disposed off-site;
- Once sufficient steel shell has been removed, the internal crane can be removed;
- The concrete reactor walls and weather envelope will be diamond wire cut into blocks and relocated in the below ground voids where possible. Otherwise, the remaining walls will be demolished using a high reach machine with a pulveriser or breaker attachment until they are reduced to ground level. All rubble generated will be used to complete the backfilling of below ground voids to ground level. The backfill will be from demolishing Dragon with additional rubble from the existing rubble stockpiles should it be needed;
- An engineered cap will be constructed above the on-site disposal, with the cap footprint extended to cover the Mortuary Holes.

Figure 12 shows the current view of Dragon and the view once the end state has been achieved.

Figure 12: Current view of the Dragon Reactor and its adjacent buildings and after regrowth on top of the disposal cap in its end state

7 MEETING THE DESIGN REQUIREMENTS AND THE EA'S PERFORMANCE EXPECTATIONS

The SGHWR and Dragon Reactor end state concept designs are driven by the need to meet the functional requirements and satisfy the EA's expectations on structural integrity. This led to the concept designs that were then modelled in the radiological and non-radiological risk assessments (Ref. 14, Ref. 15). The results of the risk assessments have subsequently driven concept design optimisation.

The following sections show how the current concept designs meet the functional requirements, Section 7.1 and meet the EA's expectations on structural integrity after disposal construction and as the disposal develop into the future, Section 7.2.

7.1 How the Functional Requirements have been met

Table 6 sets out the FRs, as listed in Section 3.1, and how these have been satisfied by the concept design. Additional information on how the FRs have been satisfied is provided in Appendix A. Table 6: How the Concept design meets the Functional Requirements

FR	Description	How the requirement is satisfied by the concept design
FR 1	The engineering concepts for disposals at SGHWR and Dragon will need to: **FR 1.1** Apply sound management and application of engineering best practice.	The engineering studies and assessments, leading to the concept designs, were carried out by Atkins and KDC, with NRS subject matter expert and intelligent customer assistance and oversight. All assessments, calculations and reports have been appropriately checked and reviewed by a suitable qualified and experienced person. The work has been supported by radiological and non-radiological assessments and concept site modelling based on carefully prepared inventories. In addition, significant regulatory engagement has been undertaken to fully understand the regulator's expectations. Regular updates have been provided to the regulators.
	FR 1.2 Ensure optimal approaches are used, thus confirming proportionality.	Optimisation and proportionality have been key requirements throughout the project.

FR	Description	How the requirement is satisfied by the concept design
	FR 1.3 Maintain flexibility to allow change at subsequent decision-making hold points.	There are sufficient hold points throughout the project to allow change. Detailed design and then reactor demolition will only take place after thorough consideration of how the work is to be done and the performance of the resulting disposals is shown to be compliant. Continued engagement with the EA will ensure the outcomes remain sound and regulatory expectations are met.
	FR 1.4 Adopt simple and established approaches as far as is practicable, which are considered to minimise health and safety risks, costs, and durations.	Only simple well-developed approaches and processes have been considered. The use of respected contractors who have been involved in similar decommissioning and demolition works has ensured established outcomes minimise health and safety risks by using remote working technologies and costs are understood by adopting simple well understood processes.
	FR 1.5 Entail passive rather than active controls after the IEP is achieved.	The Winfrith End State Stewardship Plan (Ref. 40) sets out the controls after the IEP. Active arrangements are minimised.
	FR 1.6 Consistently utilise relevant codes and standards.	All work was based on relevant codes, sound engineering and assessment principles and all persons involved were suitable qualified and experienced persons and specialists in their field.
FR 2	Minimise the demolition of the below ground structures at SGHWR and Dragon in order to reduce the production of waste requiring off-site disposal, reduce the amount of work and the resultant increased risks to worker health and safety and protection of the environment.	The demolition and engineering studies assume that the demolition of below ground structures would be minimised to reduce worker risk. Such demolitions will only be carried out where structures need to be removed to gain access to inaccessible rooms so that blocks and rubble can be correctly emplaced.
FR 3	Throughout all stages of demolition and construction of the disposals, maintain the structural integrity of ground bearing slabs and external walls which will form the boundary structures such that direct discharges are prevented by: **FR 3.1** Avoid construction activities that may damage boundary structures, noting the relative performance of boundary structures is defined in the structural integrity assessment. **FR 3.2** Ensure that demolition is controlled to avoid detrimental point loading of walls and slabs and also to restrict impact loading from falling demolition rubble to acceptable levels.	Demolition strategies and methodologies have been developed to avoid damage to the below ground boundary structure walls and slabs during the formation of the disposals. This has been confirmed by several structural assessments and engineering studies. Demolition work will be specified and controlled to avoid unacceptable stresses developing. Rubble particle size constraints, should they be needed, will be determined at the detailed design stage. Assessments have confirmed that falling rubble will not cause damage to the boundary structure slabs in the SGHWR Primary Containment and Dragon reactor. No claims are made on the integrity of below ground slabs in the SGHWR South and North Annexes, which remain above the water table for all or most of the time.

FR	Description	How the requirement is satisfied by the concept design
FR4	Make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter ground water levels (current or assumed climate change scenarios). Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.	Studies have been undertaken into the presence of penetrations and recommendations have been made for sealing those in the boundary structures. NRS will continue to monitor water ingress at SGHWR as decommissioning work is carried out and then when a more definitive understanding of the situation becomes available, NRS will make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter ground water levels (current or assumed climate change scenarios). The design of any remedial measures for any identified or potential direct discharge pathways to groundwater will then be optimised. The CQAP programme, agreed with the regulators, will ensure all structural weaknesses have been managed appropriately.
FR 5	Consider the condition of the structure and identify any degradation mechanisms, current or future, that could give rise to direct discharges. Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.	The condition of the boundary structures has been considered and degradation mechanisms have been identified that could result in structural failure and the formation of direct discharges. More detailed consideration of the structure will be carried out as part of the CQAP at the detailed design stage.
FR 6	Maximise the use of concrete arisings from demolishing above ground sections of SGHWR and Dragon reactors to fill below ground voids.	All concrete demolition arisings from the above ground structures that are compliant with the EAC will be placed into below ground voids, either as concrete blocks or as rubble.
FR 7	Maximise the use of the existing demolition arisings mounds to fill any remaining below ground voids after FR6 has been met.	The below ground void volumes are greater than the quantity of reactor demolition arisings (blocks and rubble) and therefore some material from the existing rubble stockpiles will be needed to complete backfilling. The concrete available on site (structures to be demolished and rubble stockpiles) will need to meet the engineering requirements for backfill.
FR 8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).	Material placed in below ground voids will comply with the EAC. This will generally be concrete blocks and concrete and brick rubble from the demolition process. Other materials that do not comply with the EAC, such as steel columns and beams not required for structural integrity purposes, and timber will be segregated for removal from site via well-established off-site disposal routes.

FR	Description	How the requirement is satisfied by the concept design
FR 9	Provide engineered caps above the disposals at SGHWR and Dragon to: **FR 9.1** Ensure structural integrity, including resistance to degradation, slumping and applied loading. **FR 9.2** Provide a deterrent to inadvertent human intrusion, plants with deep roots and deep animal burrowing. **FR 9.3** Prevent ponding on and around the caps by ensuring the caps are laid to appropriate falls and are connected to passive drainage systems. **FR 9.4** Inhibit water ingress through the caps. **FR 9.5** Disposals need to have points of overflow into the unsaturated zone. **FR 9.6** Support colonisation of grasses and native plant species above the cap.	Work has been done to demonstrate these FRs could be met using conventional landfill capping techniques and the design will be optimised as part of detailed design. At the concept stage a highly engineered cap has been adopted that meets all functional requirements.
FR 10	Provide a landscaped surface above the capped disposals that is consistent with the site's Restoration Management Plan, RMP and is suitable for use (both radiologically and non-radiologically) to a sufficient depth to be safe for public access.	Consideration has been given at concept stage to the need to provide a landscaped surface above the caps that is in keeping with the surrounding areas and supports native species of flora. This is consistent with the site RMP. The Application CQAP addresses this FR (Ref. 14). The materials used in cap construction will be selected and tested with post-construction checks carried out as necessary.
FR 11	Determine a demolition and construction strategy that allows for the implementation of the SGHWR and Dragon disposal facilities as soon as reasonably practicable after the site receives approval for the disposals, so as to allow the site to achieve its IEP on the timescales set out in the sites decommissioning programme.	Demolition and backfilling strategies have been determined to reduce construction timeframes as far as is reasonably practicable whilst meeting engineering and performance requirements. For example, conventional demolition, using long reach machines with breaker attachments, has been put forward as the appropriate demolition methodology. This has considerable programme advantages over the alternative methods such as dismantling the structures in small pieces.
FR 12	The SGHWR and Dragon structures should be demolished down to a cutline not greater than 1 m below ground floor slab level.	The intention at concept stage is to demolish SGHWR structures to 1m below ground level and Dragon Reactor to ground level.

7.2 How the EA's expectations on structural integrity have been met

This section sets out the factors that show the integrity of the below ground structures are adequately understood now and into the future for assessments to confidently demonstrate compliance with regulatory requirements including radiological performance assessment and non-radiological hydrogeological risk assessment. The purpose is therefore to set out the actions that can be undertaken and the degree to which verification is possible, to meet the EA's stated expectations on engineering verification (Ref. 2).

NRS will ensure construction of the SGHWR and Dragon reactor end states will be carried out in a manner that is consistent with the claims of the SWESC through the application of the CQAP. As noted in section 2.7, the application CQAP describes:

- Appropriate controls before structures are demolished and demolition arisings are placed in the reactor basements. This includes construction quality assurance controls on enhancing the environmental protection function of the below cutline structures (including the boundary structures), pre-demolition radiological and non-radiological characterisation and verification, and controls on pre-demolition planning;
- Construction quality assurance of in-process demolition characterisation and backfilling, and in process engineering verification;
- Construction quality assurance of the engineered cap, drainage and cover soils;
- Post-construction quality assurance.

The application CQAP deals with pre-demolition characterisation and verification and in-process demolition characterisation, engineering verification and quality assurance. Following the completion of this work, the disposals/deposits will continue to be monitored to demonstrate that no significant pollution occurs and that the disposals, backfill and cap remain stable i.e. to demonstrate that the works have been successful, and that the SRS will be reached. The monitoring is documented within the Winfrith End State Stewardship Plan (Ref. 17), which covers groundwater monitoring and cap surveys through to the SRS. The results from this work will be reported to the regulators, communicated to site stakeholders along with results interpretation and any SWESC updates.

How the EA's structural integrity expectations are met during disposal evolution is shown in the following tables:

- Table 7: Verification of the structure in its basic starting state;
- Table 8: Verification of the structure post preparation/pre-emplacement;
- Table 9: Verification during waste emplacement;
- Table 10: Post waste emplacement;
- Table 11: Post closure, assumed to last 3 decades beyond the site's IEP through to SRS.

Table 7: Verification of the structure in its basic starting state

There is significant knowledge about the current SGHWR and Dragon below ground structures. The key factors are:

Claims	Programme to monitor performance
Knowledge and drawings	• There is a library of detailed drawings of the foundations, basements, and superstructure. Drawings show the layout and reinforcement of the structures. NRS had/has a drawing office that has maintained the drawing records throughout the life of the buildings so there is a comprehensive description of how the structures were built and how they have evolved to their current state; • Design drawings show PVC water bars were to be provided in construction joints; • Routine site license condition surveys, backed up by the current facility safety case and local groundwater monitoring show that the below ground structures at SGHWR and Dragon are structurally sound, noting that the early 2024 water ingress into SGHWR is being investigated; • SGHWR Regions 1 and 2 and Dragon below ground boundary walls and bases consist of reinforced thick concrete with the water proofing agent, 'Prolapin', added to the mix designed to inhibit water ingress.
Understanding of the near-field chemistry and low/negligible risk posed.	• NRS has a detailed understanding of the hydrogeological near-field that could impact the SGHWR and Dragon end states. The potential risks to the boundary structures that could arise in the basic starting state include sulphate attack, carbonation, corrosion, alkali-silica interactions, abrasion, freeze-thaw cycles, exfoliation, and natural hazards. Whilst some superficial carbonation is likely, other mechanisms are unlikely. The below ground voids are routinely dry; • Whilst some groundwater entered the below ground voids in 2024, associated with a high rainfall leading to a high water table, investigations are ongoing to correctly identify the pathway into the below ground voids. Simple engineering solutions are available to repair any loss of integrity.
Understanding boundary structure integrity.	• There is no evidence for any loss of structural integrity in the current state. Structural integrity calculations listed below show the current structure is stable: • Stress distribution and associated cracking; • Wall bending and shear forces; • Uniform/non-uniform backfill loadings on walls and base slabs; • Impact loading from demolition material on base slabs; • Soil pressure and structural buoyancy.

Table 8: Verification of structure post-preparation/pre-emplacement

Claims	Programme to monitor performance
Knowledge and drawings.	• Drawing updates of below ground structures will be modified as decommissioning continues, plant and equipment is removed, and internal structures are modified ahead of backfilling; • The CQAP visual surveys and environmental monitoring will continue to ensure that information and data is available to make judgements about the integrity of the below ground structures at SGHWR and Dragon;
Detailed design work	• Construction design will include ensuring structural integrity is not impacted where it is essential (e.g. the Primary Containment in SGHWR); • Detailed end state design will need a full understanding of the current state of the below ground structures at the post preparation/pre-emplacement stage in order to underpin subsequent demolition decisions. This will include updating the information on structural integrity gained at the concept design stage. It will include engineering surveys, where appropriate, before backfilling and updating structural integrity calculations to support the safety case.
Sealing penetrations	• The below ground structures contain a number of wall and base slab penetrations. The penetrations in the boundary structures will need to be sealed (i) to ensure any leachate in the below ground voids below the water table could not be directly discharged, and (ii) to manage any weakness in the structures should the penetrations be left untreated; • Simple verifiable engineering solutions are available to seal penetrations; • The sealing standard will be verified ahead of the backfilling.

Claims	Programme to monitor performance

Managing structure modifications ahead of backfilling	Structural change will occur at both reactors as decommissioning continues and the below ground structures are prepared for their end states. The CQAP will be the mechanism for ensuring changes are fully understood, recorded and that disposal construction is carried out in a manner that is consistent with the claims of the SWESC. This will include the following controls:
	• Pre-emplacement enabling activities:
	  • Condition survey and enhancement of existing boundary structures, where necessary;
	  • Advanced pre-demolition void filling to either enhance the robustness of the structures during demolition or fill void spaces inaccessible during or after the demolition works;
	  • Confirmation of the environmental performance of the reactor structures using the existing groundwater monitoring network to collect baseline data against which the containment function of the boundary structures can be assessed during and after the works.
	• Pre-demolition characterisation and verification:
	  • Radiological classification of all parts of the structures;
	  • Identification of pollutant materials and their locations;
	  • Identification of all structural systems and load paths;
	  • Identification of demolition hazards and risks;
	  • Identification of materials not meeting the EAC;
	• Pre-demolition planning:
	  • Generation of detailed demolition plans to provide cradle-to-grave traceability for all material arisings;
	  • The existing structural assessments of boundary structures are updated to ensure no unexpected loss of structural integrity could occur during the demolition works;
	  • Detailed backfilling plans and specifications to meet the assumptions in the strain assessment calculations;
	  • Detailed communication and management plans;
	  • Submission of demolition plans obtaining approvals to proceed, including hold points, demolition records, backfill material specifications and placement requirements and a Demolition and Backfill Validation report;
	  • Ensuring materials providing structural integrity (e.g. materials used to seal penetrations) meet the EAC.

On the basis of the above, structural integrity will be fully underpinned and verified at the end of the post-preparation and pre-emplacement stage prior to the construction of the SGHWR and Dragon end states.

Table 9: Verification during waste emplacement

Claims	Programme to monitor performance
Structural integrity understanding: Structural integrity can to a degree be directly verified during waste emplacement. Evidence for how the boundary structures react to waste emplacement as it occurs may be a useful indicator of how the structures will perform thereafter. However, once below ground voids are filled, direct verification of the status of boundary structures will be impossible*.*	The controls at the waste emplacement stage that ensure the structural integrity claimed in the disposal case are: • Hold points, where and when possible, for inspections and verification of work elements; • Inspection and recording of the emplacement processes; • Recording the demolition and backfill material and which below ground void it fills; • Carrying out groundwater monitoring as described in the Winfrith End State Stewardship Plan, to collect data against which the containment function of the boundary structures can be indirectly assessed during the waste emplacement works; • Confirming the preparation for backfilling, demolition works, and backfilling have been undertaken as set out in the management arrangements and the CQAP; • Updating the Demolition and Backfill Validation report. The Stewardship Plan sets out stages when the SWESC is updated. New data and information arising from implementing the design can then be compared with the SWESC claims and how the structures perform. Updates to the risk assessments and revision of the SWESC after waste emplacement may be considered.
	SGHWR Regions 1 and 2 and Dragon: For the boundary structures extending below the water table, it is judged that their design, thickness and hydraulic conductivity of the disposal walls and bases will prevent direct discharges after waste emplacement. The evidence underpinning the claims stems from structural appraisals supported by engineering calculations, utilising a CQAP, supported by a comparison with nuclear waste disposal facilities.
No claim is made on the Dragon Mortuary Holes structural integrity	**Dragon Mortuary Holes**: There are no expected environmental impacts with the Dragon Mortuary Holes during grouting. The tubes remain above the water table and if any discharges did take place then they would be into the unsaturated zone.
No claim is made on the structural integrity of the walls and bases in the SGHWR South and North Annexes	**North and South Annexes:** As the bases of the North and South Annexes will be above the water table during waste emplacement, and any contaminated water entering the environment at this time will be into the unsaturated zone; there could not be any direct discharges. The risk assessments (HRA, PA) demonstrate environmental risks are minimal and within regulatory guidance levels. Therefore, the structural integrity of the North and South Annexes during waste emplacement is not important for the performance of the disposal.

Table 10: Post waste emplacement

Claims	Programme to monitor performance
Understanding where chemical and physical degradation processes might impact integrity.	The SWESC, CSM and hydrogeological interpretation provide a detailed understanding of the structures and their interaction with the environment through to the SRS and beyond; No chemical and physical degradation processes are foreseen that will result in a loss of structural integrity over the period of the permit; The boundary structures are constructed in thick steel reinforced concrete. Whilst localised spalling of concrete faces caused by corrosion of reinforcement may occur during the expected life of the permit, no processes have been identified that could lead to a conduit or fracture developing through a concrete wall or base in the boundary structures during this time.
Structural integrity cannot be directly verified after the waste has been emplaced into the below ground voids. Therefore, evidence for continued structural integrity will be indirect.	The claim that structural integrity of the boundary structures at the post-waste emplacement stage will be supported by data gathered from groundwater monitoring and visual inspections of the disposal caps described in the Stewardship Plan; The Stewardship Plan will set out the stages for updating the SWESC. New data and information arising from the implementing the design can then be compared with SWESC claims and how the structures perform. Updates to the risk assessments and revision of the SWESC after waste emplacement may be considered; The Demolition and Backfill Validation report will be updated following interpretation of new information and data during waste emplacement, An update of the SWESC may be needed if results require it.
	SGHWR Regions 1 and 2 and Dragon: For the boundary structures extending below the water table, it is judged that their design, thickness and hydraulic conductivity of the disposal walls and bases will prevent direct discharges after waste emplacement. The evidence underpinning the claims stems from structural appraisals supported by engineering calculations, utilising a CQAP, supported by a comparison with nuclear waste disposal facilities.
No claim is made on the structural integrity of the Dragon Mortuary Holes	**Dragon Mortuary Holes**: Since the end state of the Mortuary Holes is to fill the tubes with grout forming a monolith, then there are no expected impacts that could degrade their structural integrity. The disposal will also be above the current groundwater table and therefore any discharges will be indirect.
No claim is made on the structural integrity of the walls and bases in the SGHWR North and South Annexes***.***	**North and South Annexes:** As the bases of the North and South Annexes will be above the water table after waste emplacement, and any contaminated water entering the environment immediately after waste emplacement will be into the unsaturated zone; there could not be any direct discharges. The risk assessments (HRA, PA) demonstrate environmental risks are minimal and within regulatory guidance levels. Therefore, the structural integrity of the North and South Annexes is not important for the performance of the disposal.

Table 11: Post closure – assumed to last 3 decades beyond the site's IEP through to the SRS

Claims	Programme to monitor performance
Understanding where chemical and physical degradation processes might impact integrity.	The SWESC, CSM and hydrogeological interpretation provides a detailed understanding of the structures and their interaction with the environment through to the SRS and beyond; No processes are foreseen that will result in a loss of structural integrity over the period of the permit; The boundary structures are constructed in reinforced concrete. Whilst localised spalling of concrete faces caused by corrosion of reinforcement may occur during the expected life of the permit, no processes have been identified that could lead to a conduit or fracture developing through a concrete wall or base during this time.
Structural integrity cannot be directly verified after construction. Evidence for integrity will be indirect.	Use of the groundwater monitoring network and visual inspection of the disposals to collect data which can be used to measure the performance of the disposals; An update of the SWESC may be needed if results require it.
	SGHWR Regions 1 and 2 and Dragon: For the boundary structures extending below the water table, it is judged that their design, thickness and hydraulic conductivity of the disposal walls and bases will prevent direct discharges after waste emplacement. The evidence underpinning the claims stems from structural appraisals supported by engineering calculations, utilising a CQAP, supported by a comparison with nuclear waste disposal facilities.
No claim is made on the structural integrity of the Dragon Mortuary Holes	**Dragon Mortuary Holes**: Since the end state of the Mortuary Holes is to fill the tubes with grout forming a monolith and they will always remain above the water table, then there are no expected impacts that could degrade their structural integrity.
No claim is made on the structural integrity of the walls and bases in the SGHWR North and South Annexe end states**.**	**North Annexe:** As the North Annexe base will always be above the water table, even during conditions following climate change, any lack of structural integrity in the North Annexe will not undermine the performance of the disposal. The risk assessments (HRA, PA) demonstrate environmental risks are minimal and within regulatory guidance levels in all scenarios.
	South Annexe: The base of the South Annexe will only be below the water table for short and infrequent periods of time during reasonably worst-case climate change conditions. Therefore, any lack of South Annexe structural integrity is not a determining factor in the performance of the disposal. The risk assessments (HRA, PA) demonstrate environmental risks are minimal and within regulatory guidance levels in all scenarios.

8 CONCLUSIONS

The purpose of the DSR has been to provide a justification that the SGHWR and Dragon engineering concept designs have been optimised and will meet regulatory requirements and expectations. The report objectives have been met:

- A rigorous design process has been followed to take the existing structures through to their end state configuration;
- The developed concept designs satisfy the functional requirements set at the start of the project;
- The DSR describes the concept designs, and how the designs are underpinned. It will form a core part of the GRR permit variation application for on-site disposals and application for a Deposit for Recovery by providing a justification that the decommissioning, demolition, backfilling and capping can be delivered safely and meet regulatory expectations for ongoing structural integrity.

The evidence showing that the SGHWR and Dragon below ground structures have the required level of structural integrity now and into the future is demonstrated through this report and underpinning assessments (Ref. 32):

- The base and walls of the most active regions in the reactor end states are made of thick reinforced concrete;
- The Primary Containment and Turbine Hall in SGHWR and the below ground structure at Dragon were designed to inhibit groundwater into and out of the disposals;
- Whilst repair work has been carried out to eliminate water ingress through the roof and through better decommissioning cutting spray controls, more recently (winter/spring 2024) there has been water ingress which has coincided with very high rainfall and high groundwater levels. The reasons for this water ingress and the routes that the ingress takes are currently being investigated. Whilst this might be a sporadic event, understanding the mechanisms by which water can enter (and therefore potentially leave) the boundary structures requires attention. This is especially the case as increased water levels are anticipated in future with climate change. It has been assumed that the findings in the structural integrity report remain unchanged, i.e., the below ground structures are robust and will not give rise to direct discharges of leachate to groundwater. This assumption will be verified when the results of the investigations are known and as part of pre-demolition checking, a key activity set out in the CQAP (Ref. 4);
- Engineering calculations show the key below ground structures will be stable during decommissioning, demolition and backfilling and capping, with engineering solutions, such as wall propping, available should safety requirements and/or potential loss of integrity need to be protected and/or enhanced;
- The proposed SGHWR and Dragon caps are designed to not impact the integrity of below ground structures and allow for a degree of acceptable settlement;
- Where minor improvements to the structures may be necessary before void backfilling, (e.g., sealing penetrations) then simple engineering solutions are available to ensure the structures hold their integrity for the lifetime of the disposal permit up to the SRS.

On this basis it is demonstrated the SGHWR and Dragon boundary structures are and will continue to be robust for the period of the permit up to the SRS. The location of less robust structures above the water table ensures their lack of structural integrity will not undermine the case for the SGHWR and Dragon disposals.

The underpinning data supporting these conclusions will be revisited through the detailed design phase and after further decommissioning works. The application of the CQAP will underpin the necessary claims.

Following permit and planning approvals, the DSR and the underpinning assessments, e.g., the structural integrity assessment, will be used as the basis for detailed design development.

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Appendix 1:

Assessments that contributed to the development of the SGHWR and DRAGON Reactor end state concept designs

The concept designs for SGHWR and the Dragon Reactor have been developed through a series of technical assessments, studies and stakeholder engagement exercises spanning several years. This work has been captured in a number of reports and other documents.

The purpose of this section of the DSR is to consider this work to reconcile it against the FRs listed in Section 5.1. By doing this it will be shown that the concept design has considered and addressed all necessary FRs and therefore the concept design is fit for its intended purpose.

Whilst a high-level description of concept design reports and technical documents will be given in the following sections, the reader is encouraged to obtain copies of these reference documents if a more detailed understanding of the work undertaken, and the outcomes is required.

The reports considered below are:

A1 SGHWR structural assessment and demolition (Ref. 26);

A2 Engineering appraisal and concept design (Ref. 27);

A3 Concrete hydraulic conductivity (Ref. 28);

A4 Concrete degradation (Ref. 35);

A5 Water ingress into SGHWR (Ref. 29);

A6 Construction joints and water bars (Ref. 30);

A7 Penetrations (Ref. 31);

A8 SGHWR and Dragon reactor basement structural integrity assessment (Ref. 32).

Where FRs have been addressed and closed out, they have been identified. The overall assessment of the FRs was collated in Table 4 in Section 7 of the main report.

A1 SGHWR structural assessment and demolition study (Ref. 26)

Atkins were commissioned in 2018 to carry out a preliminary structural assessment and demolition study for SGHWR. This work was undertaken in collaboration with a specialist demolition contractor, KDC. The objectives of this work package were to:

- Develop credible demolition and backfilling sequence(s) for the SGHWR that align with the end state configuration options. This work was to account for any identified structural engineering limitations or constraints;
- Undertake a 'high-level' structural assessment of SGHWR to consider the availability of reserve strength in key primary members to accommodate selective and progressive removal of other members, to allow backfilling of the below ground structure.

This work was undertaken on the basis the outcome would inform a subsequent phase of work involving the development of disposal concept options and the identification of a preferred option via a more detailed engineering appraisal. The study was carried out by the respective contractors as summarised in the following sections.

Demolition and backfilling techniques

KDC undertook a high level but comprehensive assessment of the demolition requirements and options available considering the nature of the SGHWR structure. The assessment was based on "un-constrained" demolition techniques, with no consideration given to dealing with radioactive contamination. The demolition processes were therefore based on the assumption that the buildings being demolished would be "clean", of a type that would be found on most demolition sites. It was assumed prior decommissioning would target contamination hot spots before demolition commenced, thereby ensuring most of the demolition arisings will be “out of scope” (OoS). However, should low level contamination remain, these areas will be identified and addressed at the detailed design stage. Mitigation measures, following risk assessment, might include localised tenting to prevent the spread of dust and the use of respiratory protective equipment.

KDC looked at a range of demolition techniques including soft strip, wire-sawing, flame cutting, on-site processing, bulk demolition, pulverising and backfilling methods. Based on these considerations a preferred demolition sequence was developed for the SGHWR Primary Containment, Turbine Hall and the North and South Annexe structures. KDC concluded that the preferred method for removing the heavy above ground concrete structures within the Primary Containment and Turbine Hall was to wire saw them into blocks and to use the existing 60t crane to place the blocks into the below ground voids. Initially this would be carried out with the external cladding and roof structures in place, but these elements would be gradually removed to allow long reach machines to cut and pulverise any remaining concrete structures that were not suitable for wire sawing. The concrete rubble that was produced by this process would be allowed to fall and self-compact onto and around the concrete blocks that had already been placed in the below ground voids. Meanwhile, the cladding and other structural steel components from the above ground walls and roof structure would be separated and passed through the appropriate waste disposal routes and removed from site.

The North and South Annexe structures are less robust than the Primary Containment and Turbine Hall structures and KDC concluded that these structures should be demolished using long reach machines fitted with cutting and pulverising jaws. The demolition arisings produced by this method would fall onto the basement slabs and self-compact. Large steel components such as beams and columns would be separated from the rubble and passed through the appropriate waste disposal routes and removed from site.

Apart from the concrete blocks cut from the thicker structures, demolition and backfill rubble would be produced within the range of 0 to 150mm. Any shortfall of backfill material would be augmented by rubble from the existing stockpiles.

Structural assessment

Structural assessments were then undertaken to confirm that the principal structural elements would remain stable during both demolition and backfilling activities. Where such assurances could not be determined, mitigation measures were agreed. In particular, the assessment considered:

- Stability of external below ground retaining walls;
- Loss of lateral support during demolition;
- Pressure from demolition machinery on perimeter basement walls;
- Backfilling and support provided by partially compacted backfill material;
- Potential for wall cracking and water ingress;
- Internal wall stability;
- Stability of boundary slabs;
- Grouting of suspended floor slabs at basement level;
- Geotechnical issues including groundwater flow, permeability of concrete walls and settlement of backfill;
- Mitigation measures, including machinery exclusion zones and temporary propping;
- Health and safety – conventional safety risks.

The above issues were considered and assessed against current Eurocodes and in accordance with good engineering practice. The assessment concluded that a credible demolition and backfilling sequence for SGHWR had been developed from a structural perspective. However, whilst the review and related assessments confirmed the feasibility of the proposed demolition and backfilling sequence, it did identify some potentially vulnerable areas of the structure during interim configurations of the demolition. As a result, mitigation measures were recommended. Overall, the key findings were:

- From a structural perspective, a feasible demolition sequence, including proposals for demolition techniques and equipment, had been developed;
- Due to the vulnerability of some structural elements, exclusion areas around the SGHWR buildings will be required to prevent heavy plant imposing surcharge loading to the below ground retaining walls leading to overloading and possible collapse;
- Temporary propping of some of the retaining walls will also be required prior to backfilling;
- Arisings from the demolition will be used as backfill in the basements of the buildings (cut blocks and rubble). Additional backfill material, which is assumed to be available on site, will be required to make up the backfill deficiency. No formal compaction of the backfill was envisaged.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR 2	Minimise the demolition of the below ground structures at SGHWR and Dragon in order to reduce the production of waste requiring off-site disposal, reduce the amount of work and the resultant increased risks to worker health and safety and protection of the environment.	
FR 3	Throughout all stages of demolition and construction of the disposals, maintain the structural integrity of ground bearing slabs and external walls which will form the disposal boundary structures such that direct discharges are prevented by:	
	FR 3.1	Avoid construction activities that may damage boundary structures, noting the relative performance of boundary structures is defined in the structural integrity assessment.
	FR 3.2	Ensure that demolition is controlled to avoid detrimental point loading of walls and slabs and also to restrict impact loading from falling demolition rubble to acceptable levels.
FR 6	Maximise the use of concrete arisings from demolishing above ground section of SGHWR and Dragon reactors in order to fill below ground voids.	
FR 7	Maximise the use of the existing demolition rubble mounds to fill any remaining below ground voids after FR6 has been met.	
FR 8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).	
FR11	Determine a demolition and construction strategy that allows for the implementation of the SGHWR and Dragon disposal facilities as soon as reasonably practicable after the site receives approval for the disposals, so as to allow the site to achieve its IEP on the timescales set out in the sites decommissioning programme.	

FR12	The SGHWR and Dragon structures should be demolished down to a cutline not greater than 1 m below ground floor slab level.

A2 Engineering appraisal and concept design (Ref. 27)

Atkins were further commissioned to carry out an engineering appraisal. This work was to build on the August 2018 study, to consider all credible options for the formation of the on-site disposals. Atkins established a team of experts and specialist engineers who were experienced in the various disciplines required, i.e.,

- Structural engineering and assessments (incl. concrete degradation);
- Geotechnical engineering;
- Demolition;
- Hydrogeology;
- Land fill cap design;
- Ecology;
- Drainage and water management;
- Waste management;
- Environmental specialists;
- Landscaping.

The appraisal considered how the engineered requirements of the Dragon and SGHWR End States can best be achieved. It provided advice to NRS on the advantages and disadvantages associated with various engineering options that were considered. The work included quantitative information such as cost and programme estimates as well as simple engineering calculations, where appropriate. Where definitive quantitative information could not be provided, qualitative judgements and arguments were used to discuss the advantages and disadvantages associated with particular engineering features.

The work undertaken was progressed in collaboration with NRS and Wood (now WSP) and Galson Sciences who were carrying out the HRA and radiological PA respectively. The engineering appraisal evolved through several stages:

- Site visits and walkdowns of SGHWR and Dragon Reactors;
- Basis of Design workshop;
- Option development workshop;
- Option evaluation workshop;
- Presentations of concept design options to NRS and regulators.

Feedback at each of these stages was used to inform the following topics.

Uncertainties, assumptions and gaps

Throughout the course of the engineering appraisal, a register of uncertainties, assumptions and gaps had been prepared and updated as necessary. For each uncertainty, mitigations were proposed. The register has been updated through the project, following the formal NRS UCM process, see Appendix B.

Demolition approaches

The appraisal initially considered demolition of the Dragon Reactor as this had not formed part of the initial study. For Dragon several demolition methodologies were considered:

- Conventional top-down demolition using high reach machines with multiprocessor attachments;
- Dismantling the structures in sections for material processing at ground level;
- Deconstructing the structures on a piecemeal basis, which is effectively reversing the way in which they were built.

The appraisal provided detailed descriptions of the above processes together with costs, programmes and a list of advantages and disadvantages for the reactor buildings. The above exercise clearly showed that the conventional top-down demolition using high reach machines with multi-processor attachments was the preferred method of demolition. The appraisal also concluded that there were clear health and safety advantages to be gained using the top-down approach, although the demolition methodology would need to take account of the need to avoid damage to below ground basement structures.

The structural stability of the Dragon Reactor was also considered as demolition proceeds. Stability checks were carried out for the existing condition and the demolished configuration with particular emphasis on the stability of below ground walls. No specific structural concerns were identified although some areas of the structure will need to be carefully addressed in the demolition plan, such are the domed roof structure and the service corridor which partly surrounds the main reactor buildings just below ground level.

Demolition sequences were presented for all three Dragon demolition options. All three were based on the need to cut the bio-shield concrete into blocks ahead of the main demolition. These blocks will then be placed in the basement areas with demolition arisings or size reduced demolition arisings placed on top to compete the backfilling. This in essence is very similar to the demolition methodology proposed for SGHWR.

The demolition of SGHWR, including the North and South Annexes, was further developed including consideration of demolition methodologies not previously assessed. In addition to conventional demolition using top-down methods and high reach machines, the appraisal developed proposals for reactor building dismantling in a more careful manner, with for example, all above ground concrete elements size reduced by wire sawing and removed for external processing to form backfill material. Large concrete blocks were still formed from the robust concrete elements within SGHWR, but the cutting process would be extended to include all concrete, with little being pulverised as previously envisaged. Steel components would be removed as complete elements rather than being cut down using shears on long reach machines.

Although there is very little cost and programme difference between the two demolition methodologies the appraisal concluded that there are significant health and safety disadvantages to the dismantling approach described above, principally because of the need to place operatives in close proximity to the workface. This meant that there will be significant working at height issues together with excessive handling of components as they are removed from the structures, processed and returned to the basement areas as backfill material. On this basis, the appraisal concluded that the alternative dismantling method should not be considered any further, and that conventional demolition using top-down methods and high reach machines should be adopted for the demolition of SGHWR. The main findings were:

- Heavy concrete structures, such as the Primary Containment and Turbine Hall plinths, should be cut into large concrete blocks using diamond wire sawing and placed into the basement areas;
- Long reach machines with shears and pulverisers should be used to remove the remaining above ground structures;
- Steel and concrete materials should be segregated, with steel elements being removed off site whilst concrete rubble will be allowed to fall into basement areas as backfill;
- No additional compaction will be applied to the rubble backfill, although some compaction will take place as the rubble falls from height and impacts previously placed rubble;
- Any shortfall of demolition arisings with be augmented by crushed material from the site stockpiles to complete backfilling to ground level.
- Some propping of basement walls may be needed within Primary Containment as demolition proceeds, otherwise below ground structures remain stable;
- Exclusion zones may be needed around basement walls to prevent overloading as demolition proceeds. This is particularly true for the North and South Annexe structures.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR 2	Minimise the demolition of the below ground structures at SGHWR and Dragon in order to reduce the production of waste requiring off-site disposal, reduce the amount of work and the resultant increased risks to worker health and safety and protection of the environment.	
FR 3	Throughout all stages of demolition and construction of the disposals, maintain the structural integrity of ground bearing slabs and external walls which will form the disposal boundary structures such that direct discharges are prevented by:	
	FR 3.1	Avoid construction activities that may damage boundary structures, noting the relative performance of boundary structures is defined in the structural integrity assessment.
	FR 3.2	Ensure that demolition is controlled to avoid detrimental point loading of walls and slabs and also to restrict impact loading from falling demolition rubble to acceptable levels.
FR 6	Maximise the use of concrete arisings from demolishing above ground section of SGHWR and Dragon reactors in order to fill below ground voids.	
FR 7	Maximise the use of the existing demolition rubble mounds to fill any remaining below ground voids after FR6 has been met.	
FR 8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).	
FR11	Determine a demolition and construction strategy that allows for the implementation of the SGHWR and Dragon disposal facilities as soon as reasonably practicable after the site receives approval for the disposals, so as to allow the site to achieve its IEP on the timescales set out in the sites decommissioning programme.	
FR12	The SGHWR and Dragon structures should be demolished down to a cutline not greater than 1 m below ground floor slab level.	

Structural Degradation and Permeability

Key to understanding disposal performance is the permeability and durability of the SGHWR and Dragon reinforced concrete structures. The appraisal set out qualitative and quantitative arguments to provide guidance on both issues. Furthermore, guidance was given on concrete degradation over time, and how this would affect the long-term permeability of the structures. Firstly, potential degradation mechanisms were considered that could affect the remaining below ground concrete structures that will form the on-site disposals. The mechanisms considered were:

Physical: Abrasion/erosion, cavitation, frost, exfoliation, fire, damage during demolition.

Chemical: Sulphate attack, acid attack, carbonation.

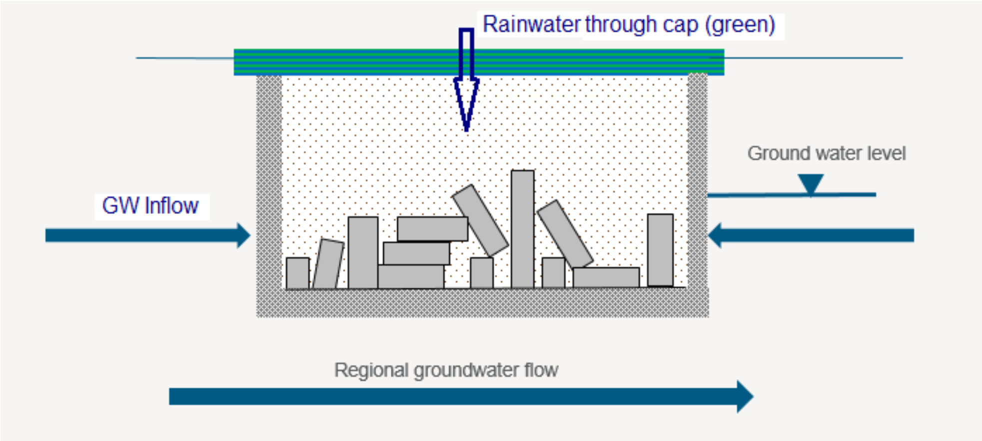
The appraisal concluded that no physical degradation mechanisms could significantly affect the below-ground external walls of SGHWR and Dragon. Additionally, the chemical degradation mechanisms were not judged to be significant. However, there was evidence that some concrete cracking and surface spalling inside SGHWR has occurred. This was likely to be due to carbonation, but further investigation may be required to confirm this. In terms of the long-term permeability of the structure, the effects of carbonation are not judged to be significant since they will not affect the concrete beyond the surface (typically up to 50mm). For an external wall thickness of 1.2m, this is a negligible loss of overall thickness.

The appraisal then considered various publications about concrete permeability, and it concluded that the current permeability is likely to be in the range $1x10^{-10}$ to $1x10^{-12}$. However, it noted that this range is for "typical" concrete and the actual permeability for SGHWR and Dragon Reactors is likely to be lower given that they were built to nuclear standards and designed to be effectively "water-tight". The appraisal then set out how permeability might be expected to change with time in line with engineering judgements made previously for structural concrete at LLWR:

- Current permeability in 2019: Say $1x10^{-10}$ m/s;
- After 100 years: $1x10^{-9}$ m/s;
- After 1000 years: $1x10^{-8}$ m/s;
- After 5000 years: $1x10^{-6}$ m/s.

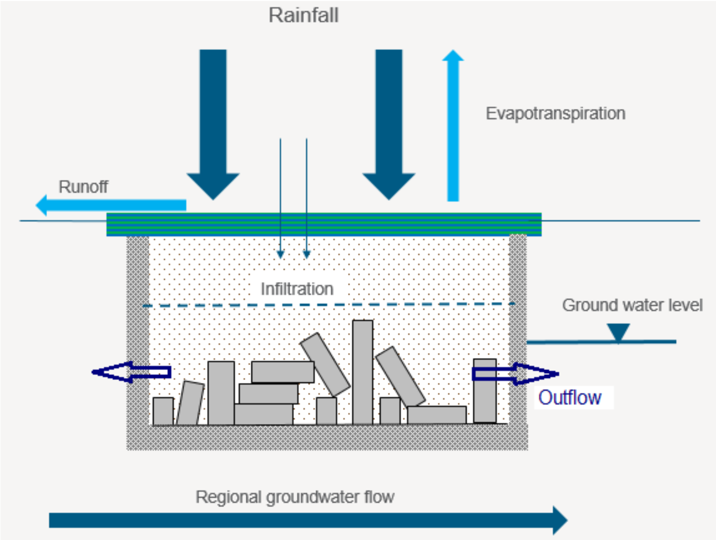
The appraisal then considered how groundwater infiltration could develop. Initially, the disposals will be empty of water and groundwater is then expected to enter through the boundary structure walls and ground slabs. Water will also enter through any cap, although the permeability of the cap is taken to be less than the concrete walls and slabs (a highly engineered cap permeability can be assumed to be $1x10^{-14}$). For this scenario, the groundwater regime is shown in Figure A1, with water entering the disposal primarily through the walls and ground slab, with marginal cap infiltration.

Figure A1: Schematic diagram showing starting scenario at completion of on-site disposal. The capped on-site disposal contains concrete blocks and rubble but no water.



Over time, the water level within the disposal will become equal to the external groundwater level, in which case there will be no inward or outward flow of water. This is the most likely scenario because the permeability of the walls and ground slab is expected to be greater than that of the cap. However, with continued cap degradation, it is possible that the disposals will develop an internal pressure head, and this could create a flow of infiltrated water out of the disposals and into groundwater, although this scenario will take a considerable time to develop, Figure A2.

Figure A2: Water flowing out of disposal due to infiltration.



The appraisal also considered the possibility of the disposals filling with water, a process that could lead to 'bath-tubbing' and surface water breakout. However, it was concluded that this is unlikely to occur because wall and slab permeability will be several orders of magnitude greater than cap permeability, meaning that most water entering the disposal will drain away through the walls and there will be no significant build-up of internal water. In any case such water would drain into unsaturated ground and would not be a direct discharge.

Cap design

The appraisal then considered various concept cap design options. Each option needed to:

- Restrict infiltration and encourage runoff;
- Isolate and protect the waste and control the waste condition by reducing water infiltration and minimising the potential for contaminant release (solid, liquid, gas).
- Resist damage due to movement and settlement;
- Resist damage due to wind or rain-borne erosion or intrusion by plants, animals and inadvertent intrusion by humans;
- Perform passively without maintenance or deliberate intervention;
- Mitigate the generation of gas. (Note that the material placed into the disposal will be inert concrete rubble and stockpiled concrete/ brick work. It is therefore considered unlikely that gas will be generated. However, a gas regulating layer will be included in the design, in line with engineering best practice).

The appraisal then considered cap layers, considering these in the context of the Landfill Directive, where typical capping requirements are:

Cap Detail	**Non-Hazardous Sites**	**Hazardous Sites**
Landscape (soil cover)	>1m required	>1m required
Drainage Layer	>0.5m required	>0.5m required
Mineral Layer	Required	Required
Geomembrane	Not required	Required
Gas Collection Layer/ Drainage Layer	Required	Not required

Four cap options were:

- Option 1 - Mineral layer. A mineral liner utilises material such as a 1m thick clay layer to reduce permeability. Additional layers providing drainage and protection against intrusion can be provided above this. Properties for a clay liner were set out, together with volumes of the materials needed and costs;

- Option 2 - Geomembrane and mineral composite (FML). Similar to Option 1 with the exception that the mineral layer is replaced by a geomembrane and a mineral layer with an overall thinner thickness, therefore reduced volumes and vehicle movements are needed. Properties for the composite layer were estimated along with estimates of material volumes and costs;
- Option 3 - Geomembrane and geosynthetic composite (FML/GCL). Similar to previous options but utilising a 2mm thick HDPE layer with a permeability of $1x10^{-14}$. This cap design has the advantage of several low-permeability layers. Consequently, it was the most durable, and the most robust against damage and degradation. Volumes of material needed, and costs were estimated;
- Option 4 – Minimal engineering. This cap would comprise a drainage layer, anti-intrusion layer then soil. There would be no low permeability barriers. This option has the advantage of requiring the minimum volumes of material to be imported and would offer the minimum construction cost. Volumes of material needed, and costs were estimated for this option. This option could be viable if, for example, the backfill were to be grouted in-situ, meaning that water ingress through the cap was less significant.

The Engineering Appraisal set out the advantages and disadvantages of the above options as:

Cap Option	**Advantages**	**Disadvantages**
1: Mineral Liner	• Construction is straight forwards	• Significant volumes of material to be imported (~625 HGV loads for SGHWR, ~109 HGV loads for Dragon) • Not as durable as other options • More permeable than other options
2: FML	• Reduced volume of material to be imported compared to option 1 • Less vulnerable to damage due to settlement than option 1	• Construction is more complex and requires higher QA/QC than option 1
3: FML/GCL composite	• Best performance in terms of permeability • Best performance in terms of anti-intrusion • Reduced volume of material to be imported compared to option 1 • Most robust option, least vulnerable to damage	• Most complex construction (but still within ‘normal engineering practice’. Requires highest levels of QA/QC
4: Minimal Engineering	• Lowest cost • Lowest volume of material to be imported • Lowest conventional H&S risk associated with construction • Easiest option to construct	• Requires full grouting of backfill for alkali leachate risk to be acceptable • Offers lowest protection against intrusion

The effect of backfill settlement was considered on cap performance. Settlement will take two forms:

- Material self-weight settlement (without any additional mechanical compaction);
- Natural ground settlement below the disposal facilities.

The calculated combined cap settlements were up to 270mm for SGHWR and 120mm for the Dragon disposal. Such settlements were acceptable and not impact the performance of any of the cap options.

After completion of the appraisal, it was determined that a cap design based on Option 3, geomembrane and geosynthetic composite (FML/GCL), would be utilised for the SGHWR and Dragon on-site disposals. This option is the most expensive, but the cost of the cap is small when compared to the cost of forming the End State disposals. Furthermore, this option will provide the most durable, and the most robust cap against damage and degradation. Option 3 is set out below in Figure A3 and Table A2.3.2.

Figure A3: Cap make-up, Option 3

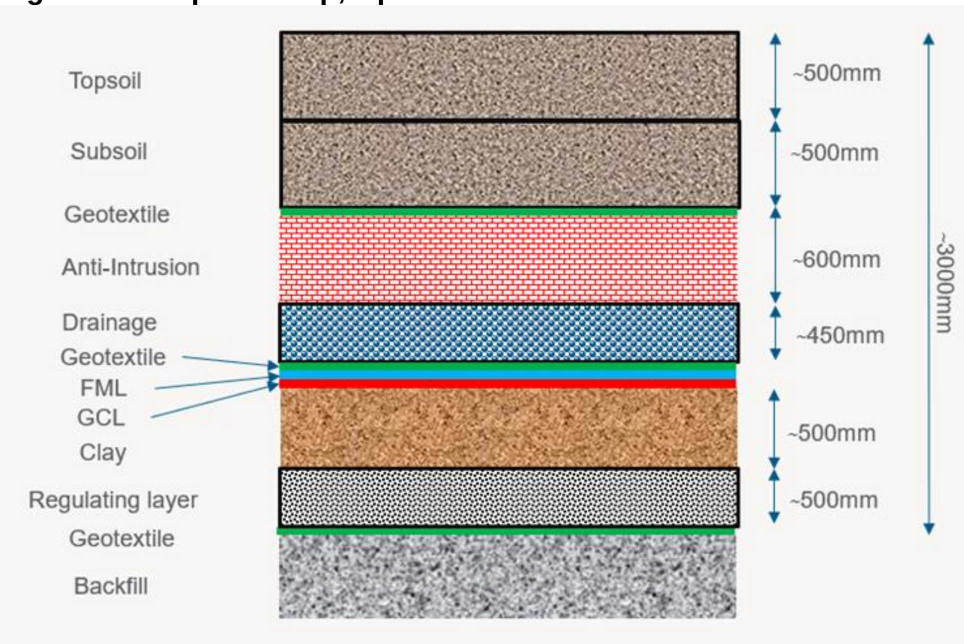


Table A2.3.2 Cap layer descriptions.

Cap materials	Layer description
Geotextile 1	A dense geotextile (typically less than 5mm thick) should be laid over the emplaced material prior to capping to provide separation and prevent loss of capping materials during installation.
Regulating layer	A regulating layer consisting of coarse gravel (grain size: 16-32mm) between 0.30-0.60m thick placed directly on top of the geotextile. This layer mitigates surface water breakout by providing a preferential horizontal flow path for water in the event of catastrophic cap failure resulting in full saturation of the below ground voids.
Mineral Liner	A clay mineral liner, of at least 0.50m thickness, formed by reworking/ compaction in defined layers of imported clays or mudstone, achieving a maximum air content of 5% to produce a liner with hydraulic conductivity less than 10-9 m/s.
Geosynthetic Clay Liner, GCL	A composite structure with a high internal shear strength. It is assumed it consists of a ~5mm layer of bentonite embedded between two needle punched layers of geotextile. The hydraulic conductivity for a GCL is typically in the range of 10-10 m/s to 10-12 m/s.
Flexible membrane liner, FML	A geomembrane of extruded polymer sheet of either low-density polyethylene or a high-density polyethylene with a thickness of <1 mm. Typical hydraulic conductivities of low density and high-density polyethylene geomembranes are ~ 10-14 m/s, but can be as low as 10-15 m/s.
Geotextile 2	A <5mm thick geotextile sits above the FML to minimise damage during the placement of overlying materials.

Cap materials	Layer description
Drainage layer	A minimum 0.30-0.45m thick drainage layer, of noncalcareous gravel (grain size 16-32mm), to achieve a permeability of no less than 10-4 m/s. The function of the drainage layer is to provide subsurface drainage above the low permeability barrier layers within the cap by promoting lateral drainage. The drainage layer must be graded to function without excessive clogging by sediments, chemical precipitation, biofouling, physical clogging. This means the potential for a standing head of water above the low hydraulic conductivity layer is minimised. It also maintains the stability of the cap by reducing and controlling pore water pressures at the interface with the underlying barrier layer. This is important where there is sufficient rainfall to potentially saturate the cover soil.
Anti-intrusion barrier	The function of the anti-intrusion layer is to prevent damage to the integrity of the low permeability barrier by burrowing animals, penetrating roots and accidental human intervention. The layer provides additional protection from erosion and serves to further discourage intrusion into the wastes. The layer should be constructed of compacted cobbles in the range 0.10-0.15m with a thickness of 0.30-0.60m to prevent intrusion by large burrowing mammals (e.g. badgers) and make accidental human intrusion difficult to achieve without specialist digging equipment. Because the layer will be poor in nutrients (relative to the base horizons of landscaping above) and free draining (relative to the drainage layer below), it should deter the intrusion of deeper rooting vegetation (i.e. trees) into the lower horizons and will serve a dual purpose of providing additional drainage capacity during storm events.
Geotextile 3	A dense geotextile is placed above the anti-intrusion barrier to minimise particle migration into the underlying anti-intrusion and drainage layers. This geotextile would not need to be a low permeability barrier like an FML or GCL.
Topsoil and subsoil	This is a layer of at least 0.50m of subsoil and 0.50m of topsoil to act as a substrate for vegetation.

It was assumed that the caps would have surface water infiltration through the cap increasing with time to represent the gradual cap deterioration. A constant rate of 50 mm y-1 for 100 years was used in the HRA and rad-PA modelling, doubling every 150 years reaching a maximum infiltration rate of 200 mm y-1 at 400 years. This represented an initial hydraulic conductivity that is likely to be higher than the cap manufacturer's stated values for the materials and so allows for some imperfections in the cap material or improper installation.

The outcome from this informed and guided the concept design, and in so doing the following FR have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR5	Consider the condition of the structure and identify any degradation mechanisms, current or future, that could give rise to direct discharges. Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.	
FR 9	Provide engineered caps above the disposals at SGHWR and Dragon to:	

	FR 9.1	Ensure structural integrity, including resistance to degradation, slumping and applied loading.
	FR 9.2	Provide a deterrent to accidental human intrusion, plants with deep roots and deep animal burrowing.
	FR 9.3	Prevent ponding on and around the caps by ensuring the caps are laid to appropriate falls and are connected to passive drainage systems.
	FR 9.4	Inhibit water ingress through the caps.
	FR 9.5	Prevent contaminated water breaking out on the ground surface.
	FR 9.6	Support colonisation of grasses and native plant species above the cap.

<u>Backfill</u>

The appraisal considered the types of backfill material available and its placement:

- The manner in which the material could be placed;
- Whether compaction is needed;
- Whether processing before placement is beneficial;
- If any grouting should be used;
- Issues around settlement.

It concluded that:

- Settlement of the backfill and the structural settlement of Dragon and SGHWR were expected to be acceptable and will not impact the performance of the cap;
- Low surface area concrete blocks reduce the formation of alkali leachate compared to high surface area rubble. Therefore, as a rule, large blocks of concrete and larger particles of rubble are preferred;
- Crushing of the demolition arisings and the rubble in the existing stockpiles is of little benefit and is likely to increase the risk of alkali leachate being generated;
- Segregation of the demolition arisings is of little benefit and would add significantly to the overall cost and duration of the demolition/backfilling process;
- There are advantages to layering backfill, where practicable to help minimise hydrogeological risk;
- Where possible, the largest concrete sections, i.e. concrete blocks, should be placed below the water table;
- Small rubble particles and fines should be minimised, where practicable and placed above the water table, where practicable;
- Grout is not required to fill voids in the backfill to control settlement or to provide stability but may be required to mitigate the risk of groundwater contamination. Whilst large scale grouting is a high-cost solution with a significant environmental impact carrying a conventional H&S risk associated with grout placement, its use may be beneficial in certain cases and should not be ruled out.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

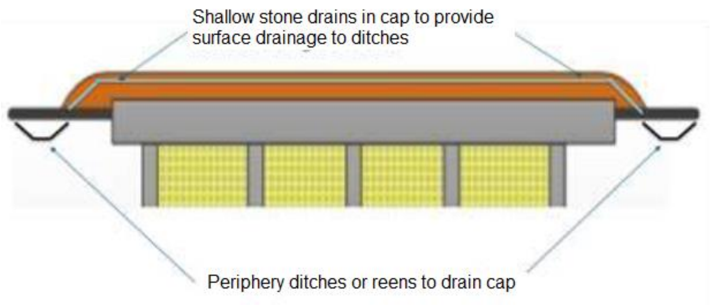
FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.

	FR 1.6	Consistently utilise relevant codes and standards.
FR 6	Maximise the use of concrete arisings from demolishing above ground section of SGHWR and Dragon reactors in order to fill below ground voids.	
FR 7	Maximise the use of the existing demolition rubble mounds to fill any remaining below ground voids after FR6 has been met.	
FR 8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).	

<u>Drainage and surface water management</u>

Surface water drainage from the caps is a necessity, but the type of drain used does not impact disposal performance. Several conventional, gravity drainage systems would be acceptable, and a simple drainage concept design was assumed: it is anticipated that a series of shallow stone drains will be positioned within the cap surface flowing to drainage ditches in the toe of the cap, shown in Figure A4.

Figure A5. Simple cap drainage arrangement



By draining water away from the cap, the drainage provides an additional layer of 'defence in depth' against rainwater ingress into the on-site disposals. The precise layout and size of the drains can be confirmed at the detailed design stage. In time, the ditches will take on a natural look that will be consistent with the site being restored. Runoff from the periphery ditches will flow into the water management scheme for the wider Winfrith site.

The proposed concept drainage design has sufficient flexibility to allow the drains and ditches to be increased in size to accommodate more extreme rainfall events.

The outcome from this informed and guided the concept design, and in so doing the following FRs have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR 9.3	Prevent ponding on and around the caps by ensuring the caps are laid to appropriate falls and are connected to passive drainage systems.	
FR 9.4	Inhibit water ingress through the caps.	

<u>Material use and waste generation</u>

A material balance was presented considering the available site-won materials and void spaces requiring infilling. Using site-won materials instead of importing primary raw materials or recycled materials will bring environmental and social benefits to the project, including:

- Maximising the reuse, recycling or recovery of materials and waste;
- Minimising waste sent to landfill;
- Reducing natural resource consumption;
- Reducing the carbon footprint of the works;
- Reducing HGV movements and the associated impacts.

It is expected that there will be a surplus of demolition materials produced on site and the options for managing this have been considered.

The appraisal considered other issues regarding waste materials, including:

- How surplus demolition and other waste materials could be managed;
- HGV movements for off-site removal of surplus bulk rubble;
- Recycling surplus material for use as secondary aggregates;
- Use of surplus material for restoration, i.e., cap and landscaping;
- Disposal to landfill;
- Environmental consents;
- Regulatory issues and waste permitting.

The main conclusions from this appraisal included:

- Material balance calculations show that there is sufficient demolition arisings and stockpiled material to fill the Dragon and SGHWR voids. In fact, there is an excess of material that will need to be managed via the SWMMP;
- There are several options available for how best to manage any remaining waste, including; recycling, use as restoration material and landfill;
- A BAT assessment undertaken by NRS (Ref. 49) makes the case for leaving “encast” and key structural steelwork in place;
- Above ground steelwork produced from demolition work will require segregation from the concrete demolition arisings;
- Consideration of the various non-RSR environmental consents has identified a bespoke waste recovery permit as the preferred option.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR 6	Maximise the use of concrete arisings from demolishing above ground section of SGHWR and Dragon reactors in order to fill below ground voids.	
FR 7	Maximise the use of the existing demolition rubble mounds to fill any remaining below ground voids after FR6 has been met.	

FR 8	Minimise the generation of wastes from SGHWR and Dragon reactor buildings which require off-site management (excluding those that do not meet the EAC and will require off-site management).
FR 9.6	Support colonisation of grasses and native plant species above the cap.

Landscape

The appraisal considered landscape and visual aspects. Careful consideration will be needed to all phases of end state construction to reduce, control and manage any potential impacts on the site landscape:

- Demolition. Methodologies and mitigations should be used to reduce effects on wider landscape, i.e., control of dust which could impact pH levels;
- Hydrogeology, drainage and water management to minimise effects on water quality;
- Capping, which should be suitable for seeding and the establishment of natural heathland.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR1	The engineering designs for disposals at SGHWR and Dragon will need to:	
	FR 1.1	Apply sound management and application of engineering best practice.
	FR 1.2	Ensure optimal approaches are used, thus confirming proportionality.
	FR 1.3	Maintain flexibility to allow change at subsequent decision-making hold points.
	FR 1.4	Adopt simple and established approaches as far as is practicable which are considered to minimise health and safety risks, costs and durations.
	FR 1.5	Entail passive rather than active controls after the IEP is achieved.
	FR 1.6	Consistently utilise relevant codes and standards.
FR 10	Provide a landscaped surface above the capped disposals that is consistent with the site's Restoration Management Plan, RMP and is suitable for use (both radiologically and non-radiologically) to a sufficient depth to be safe for public access.	

A3 Concrete hydraulic conductivity (28)

One of the critical aspects of the SGHWR and Dragon End States is the hydrogeological risk posed by the potential release of leachate containing contaminants into groundwater. Key to understanding these risks is the performance of the SGHWR reinforced concrete (RC) structure in terms of hydraulic conductivity and durability. Consequently, these parameters were investigated by Atkins, which reviewed factors which influence hydraulic conductivity and how this may change with time. Judgements and assumptions were considered as there will be uncertainty in estimating hydraulic conductivity in future. This assessment only considered SGHWR and its end state, but the arguments made are equally applicable to the Dragon Reactor and its end state.

A more recent assessment of concrete degradation was carried out as an input into the Conceptual Site Model (CSM) (Ref. 29, Ref. 36). This considered cracking caused by rebar corrosion and cement dissolution which can change the density, porosity and tortuosity of the concrete. This assessment sought to describe how the concepts would be described numerically in the HRA and the rad-PA, see Section A5.

Physical Characteristics of SGHWR Structural Concrete

A concrete specification for the SGHWR structure is not available. However, the SGHWR Primary Containment was designed to restrict the ingress of groundwater and the egress of pond water. Evidence also suggests that the SGHWR Primary Containment concrete had the water proofing agent, 'Prolapin', added to the mix. This is an admixture that is designed to reduce the hydraulic conductivity of the concrete.

For a typical concrete mix, hydraulic conductivity would be in the range of $1x10^{-10}$ to $1x10^{-12}$ m/s for freshly placed concrete. By way of comparison, LLWR stated that the 'as built' concrete hydraulic conductivity for Vault 9 would be between $1x10^{-11}$ m/s and $1x10^{-13}$ m/s, and these hydraulic conductivity values should be broadly applicable to SGHWR, although SGHWR was built in a different era to different standards. Nevertheless, it was concluded it is reasonable to assume that the current hydraulic conductivity of the SGHWR Primary Containment concrete will be in the range of $1x10^{-10}$ m/s up to $1x10^{-12}$ m/s.

Concrete Degradation Mechanisms

The earlier assessment considered how SGHWR concrete will degrade, and how hydraulic conductivity will increase over time. Physical and chemical degradation mechanisms were listed as:

- Abrasion/Erosion;
- Cavitation;
- Frost;
- Exfoliation;
- Fire;
- Sulphate attack;
- Acid attack;
- Carbonation;
- Decalcification;
- Corrosion of steel reinforcement.

Physical Observations

The key physical issues that impact hydraulic conductivity are:

- **Penetrations –** Several key penetrations exist in the Primary Containment that will need to be sealed ahead of demolition and backfilling. These include the large wall openings for the vent stack and the cooling water main in the Turbine Hall. It was recommended that penetrations that have already been sealed, are re-sealed to a higher specification to prevent water movement through the openings;
- **Construction joints –** Reference was made to the types of construction joints present in the SGHWR structure and it was predicted that some of the water bars used in these joints may have degraded, thereby resulting in elevated hydraulic conductivity at some joint locations. A separate construction joints review is included in Appendix A6;
- **Cracks in Primary Containment structure –** How cracks can form in concrete included flexural cracking, as well as thermal and shrinkage effects. Cracking will be limited by reinforcing steel, which is governed by design code and standards, some of which relate to water retaining structures. However, given the age of the Primary Containment, flexural cracking of the order of 0.3mm can be expected. Whilst such cracking will permit some water to enter the structure, it was concluded that water movement will be small and may only lead to damp patches being formed on the outer face of the structure. However, it should be noted that flexural cracking is caused by tensile forces on one side of a concrete member. On the other side of the member compressive forces will exist and these will prevent the crack formation, thereby reducing the tendency for water to flow through the member. Nevertheless, the presence of water within the concrete will lead to degradation and ultimately to failure, but this will take many years, probably hundreds of years, before it manifests itself;
- **North and South Annexe structures of SGHWR –** It was concluded that, given that the annexe structures lack robustness, it is not possible to make any claims on hydraulic conductivity. This will be particularly true when demolition commences, and damage may occur.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR4	Make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter ground water levels (current or assumed climate change scenarios). Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.

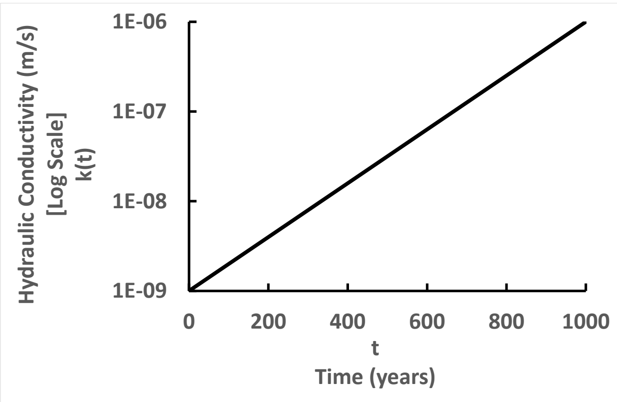
Hydraulic modelling

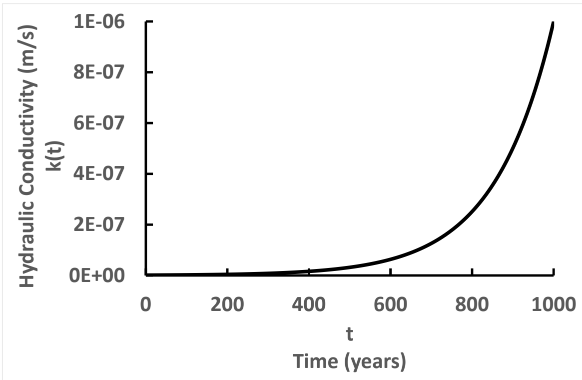
How the Primary Containment could be modelled in the performance assessments was considered, with two scenarios identified:

- A hydraulic model based on an 'impermeable barrier' for the Primary Containment with specific perforations to model leak paths into the structure, both in the current and future conditions. These leak paths increase with time, probably on an exponential scale, with an end point of 'full permeability' (i.e. comparable to the surrounding soil) after say 1,000 years. The effects of climate change and any associated groundwater level rise would need to be also considered;
- Modelling the Primary Containment using an 'effective hydraulic conductivity', based on best estimates:
- Current date, lower bound value $1x10^{-9}$ m/s, upper bound value $1x10^{-6}$ m/s;
- After 1,000 years, lower bound value $1x10^{-8}$ m/s, upper bound value $1x10^{-6}$ m/s;
- Climate change and groundwater level increases would need to be considered.

It was suggested that hydraulic conductivity could be $1x10^{-9}$ m/s at the present time (reduced from $1x10^{-10}$ m/s to allow for any degraded water bars), falling to $1x10^{-6}$ after 1000 years due to concrete degradation. Graphically, this is shown in Figure A5.

Figure A5: Suggested permeability change with time (logarithmic and linear)





Whilst this prediction is a reasonable estimate based on expert engineering judgement elsewhere, e.g., at LLWR, it was concluded that hydraulic conductivity' is difficult to accurately predict, and therefore the use of upper and lower bound values in the modelling to test sensitivity was appropriate.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR5	Consider the condition of the structure and identify any degradation mechanisms, current or future, that could give rise to direct discharges. Propose measures to address these mechanisms, where deemed appropriate.

A4 Concrete degradation and its representation in numerical models (Ref. 28, Ref. 35)

Concrete degradation was considered by WSP following comments on this by the independent peer reviewer of the Winfrith end state CSM, which underpins the HRA and rad-PA (Ref. 34). The review was carried out on how concrete degrades in the robust below ground and how it is represented in numerical models.

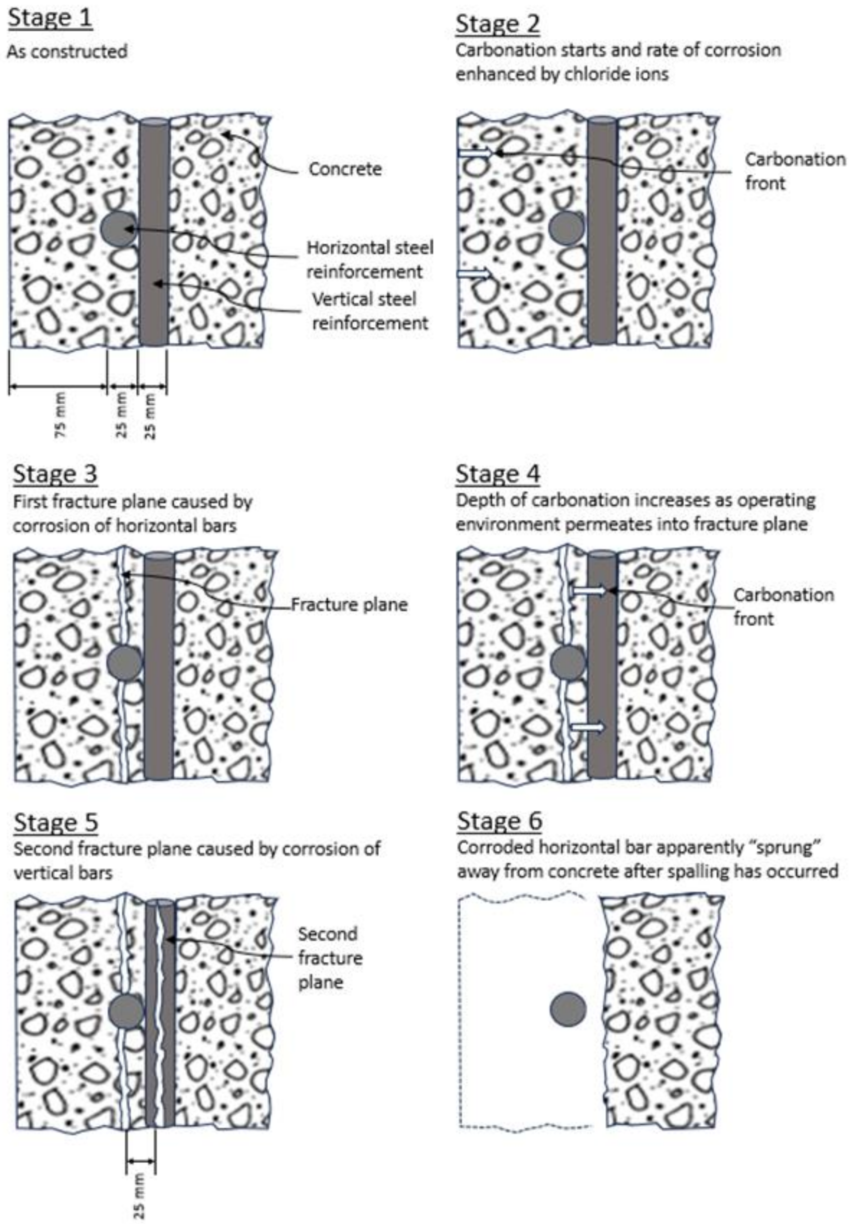
The concept for concrete degradation in the CSM was by:

- Cracking caused by rebar corrosion that increases the bulk hydraulic conductivity of the concrete over a few centuries until it provides no hydraulic resistance to the flow of water;
- Dissolution of the cement until all that remains is the concrete aggregate. This changes the density, porosity and tortuosity of the concrete over millennia.

Consideration of concrete cracking was only carried on SGHWR Primary Containment and the below ground wall of the Dragon reactor building. Figure A6 illustrates the conjectured six stages of concrete cracking and spalling, viz.:

- Stage 1: As constructed. The horizontal steel reinforcement is 75 mm from the internal face of the structure and is 25 mm thick. The vertical steel reinforcement is further from the internal face of the structure and abuts the horizontal steel reinforcement;
- Stage 2: Carbonation of concrete interpreted to have reached 150 mm after approximately 20 years. This destroys the corrosion inhibitive properties of the alkaline cement paste. 2% anhydrous calcium chloride is found in most concrete samples and was probably added to the cement mix to facilitate winter concreting. It likely increased the rate of corrosion;
- Stage 3: Increase in the radius of horizontal steel reinforcement causes the first fracture plane;
- Stage 4: The first fracture plane allows the operating environment to permeate the structure and increases the depth of carbonation;
- Stage 5: A second fracture plane is caused by the increase in radius of the vertical steel reinforcement by corrosion;
- Stage 6: Concrete spalls from the internal face of the structure giving the impression that the horizontal steel reinforcement has “sprung” away from the surface.

Figure A6 – Conjectured Model of Concrete Cracking and Spalling (after Wexham Developments Limited (Ref. 48))



It was concluded the basements of the SGHWR Primary containment and Dragon are robust structures and no mechanisms could be identified that could give rise to structural defects. On this basis the concrete could take hundreds, if not thousands, of years, to hydraulically degrade. Notwithstanding this, safety assessments for near-surface disposal facilities assume hydraulic degradation. The time assumed for the concrete to hydraulically degrade by the HRA, and rad-PA has therefore been assessed by reference to hydraulic degradation rates assumed for concrete barriers in safety assessments for near-surface disposal facilities. There are many differences between the designs and environments for the near-surface disposal facilities considered here (hence leading to the differences in degradation periods assumed), and between these purpose-built facilities and the extant SGHWR and Dragon structures, but the safety assessments are generally associated with pessimistic modelling assumptions, rather than attempted realism, and provide a benchmark to support development of the Winfrith assessments. The description of concrete degradation through this assessment has quantified how the porosity, density and tortuosity of concrete needs to be modelled as the cement leaches from the concrete in the HRA and rad-PA.

A5 Historic water ponding within SGHWR (Ref. 29)

Historically, water has ponded in some below ground areas of SGHWR. Following the SGHWR building roof repair in 2021, water ingress in all areas fell significantly and, in some areas, there was no longer a presence of water. The water ingress through the roof represented a significant proportion of the total arisings within SGHWR, whilst some water ponding within the structure was the result of drilling and cutting operations associated with the Core Segmentation Project. Historic water ingress was not attributed to groundwater ingress through the slabs and walls in the boundary structures in contact with groundwater.

To ensure that the uncertainty associated with water ingress and the potential for direct discharges continues to be considered in the development of the disposal designs, uncertainties have been identified by NRS in addition to those identified in the earlier concept appraisals viz. managing the risk of a direct discharge ahead of demolitions and ensuring timely repairs, and managing the uncertainty in structural integrity as decommissioning progresses.

A6 Construction joints and water bars (Ref. 31)

A study of below ground construction joints in SGHWR and Dragon Reactor has been undertaken. All concrete joints identified within the boundary structures have been shown to be construction joints with water bars, except for some keyed construction joints within the Effluent Vault in SGHWR. It was concluded that, due to the nature of their construction, none of the joints will give rise to direct discharges, even if the PVC water bars deteriorate over time. However, the optimal management of any joint deterioration will be considered following further decommissioning works and as part of end state detailed design.

The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been considered, but not yet closed out at the concept design stage:

FR4	Make reasonable endeavours to identify existing penetrations and other features in the boundary structures which could allow direct discharges into groundwater under typical winter ground water levels (current or assumed climate change scenarios). Optimise the design of remedial measures for any identified or potential direct discharge pathways to groundwater.

A7 Penetration Sealing (Ref. 31)

A preliminary assessment identified major locations where groundwater ingress has occurred, as well as listing penetration sealing options that could be incorporated into the final design of the disposals. Whilst the assessment only considered options for sealing penetrations through the SGHWR South Annexe base and walls, the sealing techniques identified could be employed elsewhere, particularly where there is a need to ensure prohibition of direct discharges. Figure A7 shows some potential penetration sealing techniques.

Figure A7: Potential penetration sealing techniques

A8 SGHWR & Dragon Basements Structural Integrity Assessment (ref. 32)

Building on previous work undertaken in 2018 and 2019, SNC Lavalin carried out a structural integrity assessment of the current SGHWR and Dragon Reactor buildings and future configurations. The aim was to demonstrate at a concept level that the structures would prohibit direct discharges. The assessment requirements were:

- The below ground structures of the SGHWR and Dragon reactors retain their structural integrity during proposed demolition configurations, and at their End States:
- The boundary structures can prevent the risk of a direct discharges of pollutants into the groundwater during the proposed demolition configurations and at their End States;
- Where structural integrity and direct discharge pathways cannot be demonstrated, some restrictions should be placed on the demolition methodology.

Engineering calculations were undertaken to cover the following areas:

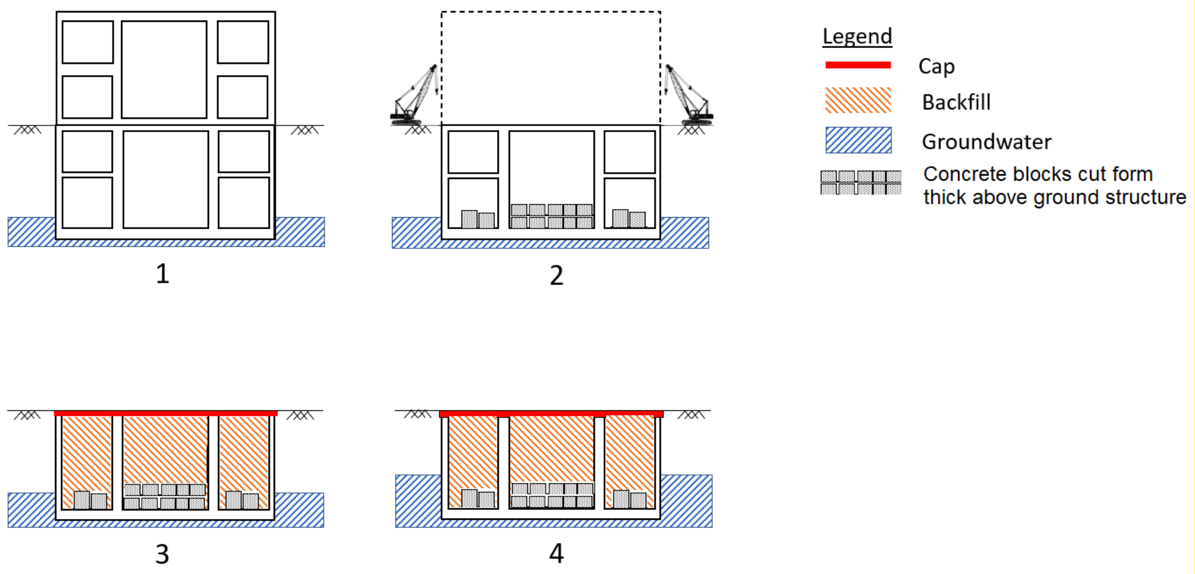
- Structural integrity of the boundary structure walls of the SGHWR and Dragon reactors were assessed in their interim demolition configurations and final End States. These structural integrity assessments were undertaken in accordance with Eurocode 2 (EC2) supported by Roark's formulas;
- Structural integrity of the ground bearing boundary structure slabs of the SGHWR and Dragon reactors were undertaken for the worst case non-uniform loading in accordance with the design guidance, TR34. They were also assessed for impact loading caused by the planned dropping of demolition arisings into the voids from ground level in accordance with the NRS design guidance, R3;
- For SGHWR, the below-ground structure was also assessed for buoyancy (flotation), assuming the above-ground structure was demolished, and the internals of the remaining structure was empty, i.e. no backfill mass. Dragon was not considered to be susceptible to buoyancy on the basis that the water table will always below the sub-structure prior to backfilling, and following backfilling, the weight of the disposal site will always be greater than the buoyancy effects.

For both SGHWR and Dragon Reactor buildings, the above assessments were carried out for the following demolition configurations:

- Configuration 1: Basic starting condition - post core segmentation;
- Configuration 2: Demolition - split into above-ground demolition and below-ground demolition;
- Configuration 3: End State - below-ground voids backfilled and capped, start of intended disposal site using the End State water level at time of completion;
- Configuration 4: End of life of the disposal permit, ground water level taken as the reasonable worst-case estimate for 2100.

These configurations are shown schematically in Figure A8.

Figure A8: Schematic diagram showing the four configurations used for assessment.



For SGHWR the assessments were only carried out for the Primary Containment and Turbine Hall because these are the only areas that possess deep, thick-walled basements that extend into the groundwater. The North and South Annexes were excluded from the structural integrity assessment because they are less robust, their basements are generally above groundwater level, and there are no SWESC claims on their integrity after demolition and backfilling.

The study showed that some SGHWR below ground retaining walls in the Primary Containment area potentially fail when internal supporting floor slabs are removed. However, the walls have been conservatively modelled, and detailed sensitivity analysis may present a case that the walls are sufficient under the given loading. If at the detailed design stage, the walls are shown not to have the structural capacity required, temporary propping will be needed. This can be readily achieved by maintaining certain internal floor slabs in discrete positions, thereby providing the necessary propping action to these walls. If this mitigation is required, it will be captured in the demolition plan. Nevertheless, with or without this mitigation for the Primary Containment walls, the integrity assessment generally demonstrated that the below-ground retaining walls in the Primary Containment and Turbine Hall will hold their integrity during demolition, i.e., they will not suffer any cracking or other damage which could give rise to a direct discharge pathway.

Furthermore, for SGHWR, the structural integrity report also concluded that:

- Propping of the external Delay Tank Room walls, below the South Annexe, will be required during demolition and backfilling, although this can be readily achieved by maintaining the propping provided by the roof slab. This propping action will be needed until sufficient backfill has been placed within this room;
- Backfill rubble should not contain large pieces of concrete as these can apply detrimental point loads to the external retaining walls or form large void spaces.
- Remediation of existing penetrations will be required, including those in the Delay Tank room walls;
- All sumps and gullies in the ground bearing slabs will need to be infilled with concrete to guard against water loss and to ensure uniform slab loading;
- The raft foundation of the Primary Containment can resist impact loads from dropping 1m^3 rubble into the void from ground level. The assessment found that the dropped rubble would not cause slab cracking;
- The floors slabs can resist non-uniform loading in accordance with TR34, indicative of the interim condition where a ground slab is loaded, whilst another part remains empty. The assessment found that the foundation slab is sufficiently robust to withstand the backfill

loading, though the assessment method was based on a simplified analysis, which will need to be reviewed at detailed design;

- Buoyancy will not occur in the Primary Containment or Turbine Hall, even with all internal structures removed and the remaining below ground voids unfilled, a theoretical worst-case scenario that is unlikely to occur;
- The external retaining walls around the Primary Containment are generally formed of thick reinforced concrete, strengthened by concrete buttresses. The area between the buttresses is enclosed by a brickwork wall on the outer face, thereby forming a cofferdam within, Figure A9. When constructed, the cofferdams were empty void spaces, but they have been backfilled with 20mm stone. The tops of the cofferdams can be accessed via steel hatch covers in the capping floor slab, Figure A10. It was recommended that these hatches are sealed so that any contaminated water within the on-site disposal cannot escape and form a direct discharge. This could be achieved by placing a concrete plug in the top of the cofferdams, but this will need to be determined at detailed stage. Whilst the external groundwater level, and hence the internal water level, should not reach the height of these hatches, it is believed that hatch sealing will provide additional strength in depth.

Figure A9: Diagram showing the access hatches above cofferdams which requiring sealing to prevent water leaving the on-site disposal.

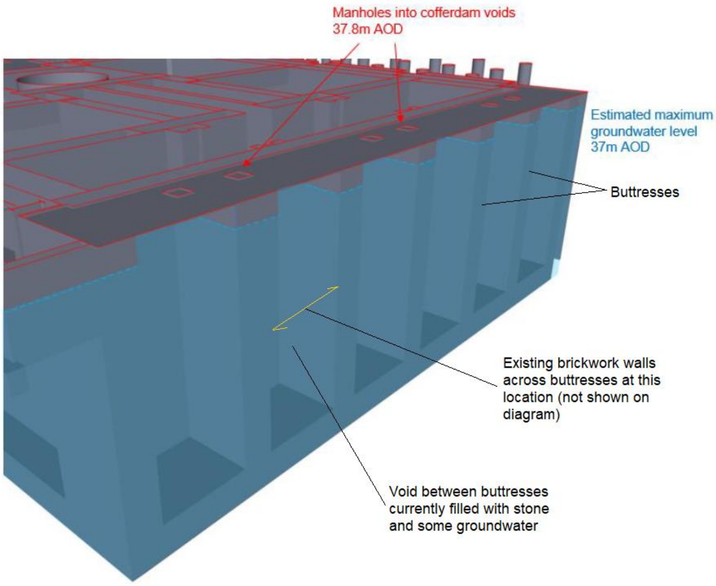
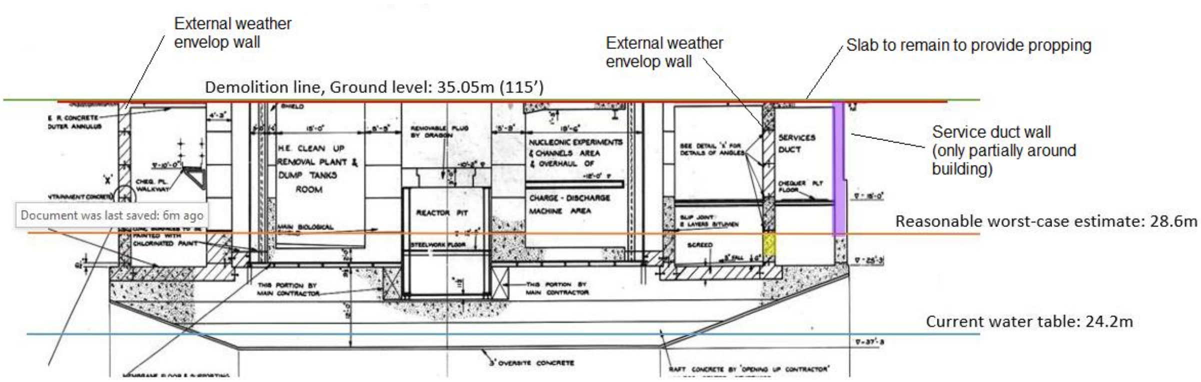


Figure A10: Typical manhole hatch above cofferdams. To be sealed as part of End State configuration.

For the Dragon Reactor, the structural integrity assessment concluded that:

- The external weather envelop walls can be reduced to ground level and act as retaining walls for the on-site disposals, Figure A11;
- The Service Duct wall, purple in Figure 11, which only partially surrounds the building, can be used to form the boundary structure, provided that some propping effect is maintained by the slab at ground level, until the void below is partially filled;
- Backfill rubble to is to meet agreed grading criteria (i.e., dust to 150mm max particle size) and place to prevent large voids occurring particularly adjacent to barrier walls.
- Remediation of existing penetrations is required;
- All sumps and gullies in the ground bearing slabs are to be infilled with concrete to guard against water loss and to ensure uniform slab loading;
- The boundary ground-bearing slab was assessed for non-uniform loading, which represents filling one end of the below-ground void before filling of the other is started. This is the worst-case loading pattern and covers the boundary slab in configurations 3 and 4. The assessment found that the boundary slab can withstand backfill loading in any load pattern arrangement;
- The boundary ground-bearing slab was also assessed for impact loads caused by the intentional dropping of rubble into the below-ground voids. Whilst the cone cracking check passes for the thicker foundations of the Dragon Reactor pit slab and internal containment slab, the assessment fails for the shallower foundations of the external containment slab and Service Duct slab. Therefore, it is recommended that acceptable maximum mass limits for hard backfill are specified and adhered to in order to prevent cone cracking in the slab.

Figure A11: Dragon Reactor. Configuration of walls for structural assessment (i.e., demolished to ground level with no support from backfill).



The outcome from this informed and guided the concept design, and in so doing the following Functional Requirements have been addressed and closed out at the concept design stage:

FR2	Minimise the demolition of the below ground structures at SGHWR and Dragon in order to reduce the production of waste requiring off-site disposal, reduce the amount of work and the resultant increased risks to worker health and safety and protection of the environment.	
FR3	Throughout all stages of demolition and construction of the disposals, maintain the structural integrity of ground bearing slabs and external walls which will form the disposal boundary structures such that direct discharges are prevented by:	
	FR 3.1	Avoid construction activities that may damage boundary structures, noting the relative performance of boundary structures is defined in the structural integrity assessment.

	FR 3.2	Ensure that demolition is controlled to avoid detrimental point loading of walls and slabs and also to restrict impact loading from falling demolition rubble to acceptable levels.

In summary, it was concluded that:

- SGHWR and Dragon reactor buildings are robust structures that will maintain their structural integrity both during demolition and backfilling operations and in their End State configurations and beyond, thereby eliminating the possibility that direct discharges of leachate to groundwater will occur from any wastes within the on-site disposals. This finding is subject to control measures being placed on the demolition process, but these measures are not onerous and will not impede demolition operations;
- No other mechanisms such as concrete degradation and failed structural joints that could give rise to direct discharges of leachate to groundwater from the disposals, have been found. This finding should be confirmed by surveys at detailed design stage. If issues are identified, simple repair solutions are available as discussed in the report.

Appendix 2: Engineering Uncertainties

Reference Number	Feature, Event or Process subject to Uncertainty	Description of Uncertainty	Treatment of Uncertainty / Statement of Assumption	Potential Significance Rating (Low, Medium, High)	Recommended Action
Engineering.01	Geotechnical assumptions	Ground conditions are based on historical boreholes along with recent results from GI for Mini-MILWEP project. The geotechnical parameters used in this assessment are derived based on BS 80002:2015 and from published tables.	Density of soil, and angle of internal friction have been derived based on BS 80002:2015. Modulus of subgrade reaction is determined from published tables. All values have been determined by chartered geotechnical engineers. The values used are considered suitably conservative.	Low	Further analysis of the existing modulus of subgrade reaction value is undertaken by a qualified geotechnical engineer using an approach which captures the interaction between ground and structure.
Engineering.02	Damage caused by demolition of above ground structure has not been assessed as it is outside the scope of the study.	Below ground structure may be compromised by initial above-ground demolition works (for example, uncontrolled demolition activities leading to adverse loading and impacts).	It is assumed damage to below ground structures is avoidable and/or preventable.	Medium	Requirement to be placed on demolition contractor to prevent damage to below ground structures.
Engineering.03	Accuracy of drawings	As-built structure may be different to the construction drawings used. Structural changes/ modifications may not have been accounted for.	Drawings are assumed to be accurate.	Low	Undertake walkdown to view any remaining areas of uncertainty.

Reference Number	**Feature, Event or Process subject to Uncertainty**	**Description of Uncertainty**	**Treatment of Uncertainty / Statement of Assumption**	**Potential Significance Rating (Low, Medium, High)**	**Recommended Action**
Engineering.04	Missing drawings	Some of the drawings held on file refer to drawings not held on file. It has not been possible to gather further drawings from site at time of writing.	Where necessary, the structure has been assumed to have the same details and properties as adjacent walls or similar thicknesses. A lack of drawings showing penetrations in walls has been assumed to indicate a lack of penetrations.	Medium	When possible, obtain more drawings from the drawing office. If deemed necessary, undertake Ferro-scanning or coring to ascertain missing structural information.
Engineering.05	Illegible drawings	Some of the drawings are illegible due to their age.	Where annotations are partly legible, judgements have been made on what seems reasonable for missing text. Where annotations are fully illegible, details and properties of adjacent legible details have been assumed.	Low	Undertake walkdown to confirm outstanding uncertainties. Where deemed necessary, undertake Ferro-scanning or coring.
Engineering.06	Properties of steel and concrete	Steel and concrete annotations on drawings do not give specific strength properties.	Properties have been assumed to be typical properties for 1960s construction.	Low	Assumption is considered reasonable, and no action is recommended.
Engineering.07	Current condition internal side of structures	No condition data, including decarbonisation and decalcification, has been provided.	Assessments do not account for degradation of concrete.	Medium	Full condition inspections to be carried out on the barrier walls, including consultation with materials expert.

Reference Number	Feature, Event or Process subject to Uncertainty	Description of Uncertainty	Treatment of Uncertainty / Statement of Assumption	Potential Significance Rating (Low, Medium, High)	Recommended Action
Engineering.08	Inability to inspect outside of below-ground walls.	Regardless of inspections, it is not possible to ascertain the condition of the external side of the structure without taking samples which would create openings in the barrier walls.	Assessments do not account for degradation of concrete.	Low	Coring and testing could be undertaken at higher levels of the building, i.e. 1m bgl, to provide indicative results, but these will not be representative of the actual condition of the basements of the Primary Containment and Turbine Hall.
Engineering.09	Engineered cap outside of scope	The engineered cap has not yet undergone detailed design. An Inadequate design may affect the cap properties, cap settlement, larger loads on the below ground components and allow greater hydraulic conductivity.	Cap design optimisation will be undertaken at the detailed design stage This will include reassessment of settlement using the proposed backfills, backfill material placement methodology and due consideration taken of water saturation of the backfill.	Low	Uncertainty to be addressed at detailed design stage. Cap quality will be assured by meeting construction quality assurance/ pre-operational conditions.
Engineering.10	Reliability of climate change data on groundwater level changes	Climate change data is based on current best estimates, but the rate of change may differ from that currently expected.	The data used is based on the best available estimates and is, therefore, as accurate as possible. The data is assumed to be correct.	Low	Groundwater level predictions to be updated as climate change rates shift or become better known.
Engineering.11	Lifespan of proprietary products used for remedial measures	Guarantees mean reduced chance of failure rather than no failure. The effectiveness of the products cannot be monitored once the disposal site is backfilled, and they cannot be fixed or replaced.	Failure will provide partial effectiveness, and discharge will be indirect rather than direct, i.e. discharge is “gradual, and there is potential for attenuation”.	Low	No action recommended.

Reference Number	Feature, Event or Process subject to Uncertainty	Description of Uncertainty	Treatment of Uncertainty / Statement of Assumption	Potential Significance Rating (Low, Medium, High)	Recommended Action
Engineering.12	Loss of information between now and achieving End State, for example, Generic.013.	Recommendations from this study get lost prior to demolition, and contractor deviates from recommendations made.	This study will feed into future works.	High	NRS to manage interfaces.
Engineering.13	Backfilling not executed as recommended by demolition site contractor	The recommendations made in the structural assessments are not carried out as required, thereby putting structural integrity of below ground structures at risk.	It is emphasised that NRS must make these recommendations accessible to the contractor.	High	NRS to establish a channel to communicate requirements to the contractor.
Engineering.14	Source of water ingress into the Region 1 octagonal sump, Region 1 corner sump, Region 2 Delay Tank Room.	There is a risk that the water found in SGHWR is groundwater, indicating that a direct discharge pathway could exist back into groundwater.	Early 2024 groundwater ingress followed high rainfall and is under-investigation. Where there is any identified or potential direct discharge pathways in boundary structures then they will be subject to optimisation. Structural integrity will be reassessed in the detailed design phase. It is assumed any repairs to ensure direct discharges cannot occur will be simple to enact and meet the prohibition requirement.	Medium As repairs will be necessary, integrity can still be claimed.	Monitor water levels in combination with rainfall patterns. Eliminate other sources. Carryout integrity repairs where necessary. Specify structural integrity requirement at the detailed design stage to ensure direct discharges to groundwater cannot occur for the life of the environmental permits. Only implement reactor end state when this requirement is met.

Reference Number	Feature, Event or Process subject to Uncertainty	Description of Uncertainty	Treatment of Uncertainty / Statement of Assumption	Potential Significance Rating (Low, Medium, High)	Recommended Action
Engineering.15	Source of water in the B72 building adjacent to the Dragon reactor may lead to water entering the reactor end state.	There is a risk that if water can enter the Dragon reactor basement, then a direct discharge pathway could exist back into groundwater.	Groundwater ingress into the B72 building must be considered a potential threat to compliance with the groundwater regulations. The penetration between B72 and the Dragon service duct may need to be sealed to ensure direct discharges cannot occur.	Medium As penetration sealing will be necessary, integrity can still be claimed.	Review requirement for sealing the Dragon service duct during the detailed design stage.
Engineering.16	SGHWR and Dragon end state structural integrity	Structural integrity calculations have been carried out based on existing structural layouts and best practice demolition methodologies. However, as the current decommissioning programme advances the SGHWR and Dragon structures may be changed in ways which undermine the structural integrity calculations and assumptions.	The structural integrity calculations for SGHWR and Dragon will need to be repeated at the detailed design stage before end state implementation.	Medium	Update the structural integrity calculations for SGHWR and Dragon at the detailed design stage before end state implementation.