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Hydrogeological Risk Assessment of the SGHWR and Dragon Reactor (and Mortuary Holes) End States

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GLOSSARY

Term	Explanation
AOD	Above Ordnance Datum.
BAT	Best Available Technique.
BTEX	Benzene, Toluene, Ethylbenzene, Xylene.
CL:AIRE	Contaminated Land: Applications in Real Environments.
Cr(III)	Chromium ion with a valency of 3+.
Cr(VI)	Chromium ion with a valency of 6+.
CSM	Conceptual Site Model.
DfR	Deposit for Recovery.
DQRA	Detailed Quantitative Risk Assessment.
EA	Environment Agency.
EPR 16	Environmental Permitting (England and Wales) Regulations 2016 (as amended).
EQS	Environmental Quality Standard.
GQRA	Generic Quantitative Risk Assessment.
GRR	"Guidance on the Requirements for Release" (Environment Agencies, 2018).
HRA	Hydrogeological Risk Assessment.
L/S	Liquid to Solid ratio.
LOQ	Limit Of Quantification.
MRV	Minimum Reporting Value.
NDA	Nuclear Decommissioning Authority.
NRS	Nuclear Restoration Services.
PAH	Polycyclic Aromatic Hydrocarbon.
РСВ	Polychlorinated biphenyl.
RSR	Radioactive Substances Regulation.
SAC	Special Area of Conservation.
SGHWR	Steam Generating Heavy Water Reactor.
SRS	Site Reference State.
SWESC	Site-Wide Environmental Safety Case.
ТРН	Total Petroleum Hydrocarbon.
TPH-CWG	Total Petroleum Hydrocarbon Criteria Working Group.

Term	Explanation
UCL95	Upper 95 th percent confidence limit.
UKTAG	United Kingdom Technical Adaptation Group.
WHO	World Health Organisation.
WMP	Waste Management Plan.

EXECUTIVE SUMMARY

This non-radiological hydrogeological risk assessment of the SGHWR and Dragon reactor End States supports NRS Winfrith applications to the regulator to vary the environmental permit for onsite disposals of radioactive wastes and to seek a Deposit for Recovery environmental permit.

Environment Agency hydrogeological risk assessment guidance encourages a tiered approach to risk assessment with more detailed assessment being undertaken where the risk of groundwater pollution is greater.

Tier 1 qualitative risk screening has been carried out on the components of the End States of the SGHWR and Dragon reactor. The potential discharge from the following components of the End States were identified as acceptable and these components need no further tiers of risk assessment:

- Contaminants bound within concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes monolith, with the exception of the hydroxide ion (that can generate high pH in water) leached from concrete blocks;
- Structural steel and rebar in concrete structures and blocks;
- Paint;
- Fibreglass;
- The following components of oil staining of structures: <C10 aromatic compounds (including benzene, toluene, ethylbenzene and xylene), >C16 aliphatic compounds and all 16 analysed polycyclic aromatic hydrocarbon species;
- Arsenic and mercury in demolition arisings; and
- Emplaced non-waste materials that will be used to implement the End State of the Dragon reactor mortuary holes as well as to prepare the structures for the disposals/deposits.

Porewater concentrations of contaminants in the demolition arisings have been calculated and compared with the compliance criteria as a Tier 2 generic quantitative risk assessment. The calculated porewater concentration of the following contaminants is lower than the selected compliance criteria: antimony, barium, cadmium, chloride, fluoride, molybdenum, nickel, selenium and sulphate. There is little likelihood of unacceptable inputs to groundwater from these contaminants and these contaminants need no further risk assessment.

Detailed quantitative risk assessment (Tier 3 risk assessment) of the SGHWR and Dragon reactor End States has been supported by numerical modelling using PHAST for alkalinity and GoldSim for substances other than alkalinity. Appendix A and Appendix B provide details of the modelling.

A reference scenario model has been constructed that is a cautious estimate of the predicted evolution of the End States. Parameter values have been based on site specific data where possible. Cautious parameter values have been adopted where there is uncertainty.

Modelling of the reference scenario has demonstrated the risk for all modelled contaminants is acceptable.

Assessment of cumulative effects has been undertaken because groundwater flow modelling has shown that, under some circumstances, groundwater flows from the SGHWR End State to beneath the Dragon reactor End State. The Tier 3 assessment has concluded that cumulative impacts will not cause an unacceptable risk to groundwater.

Conceptual, model and parameter uncertainty has been addressed by sensitivity analysis. The sensitivity analysis has been based on assumptions more pessimistic than those cautiously adopted in the reference scenario. The model results of the selected variant and alternative scenarios have demonstrated that, for all modelled contaminants, an acceptable risk to groundwater, thereby providing confidence the outcomes of the reference scenario are robust.

Based on the three tiers of risk assessment it is concluded that the non-radiological hydrogeological risk from the envisaged SGHWR and Dragon reactor End States is acceptable.

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APPENDICES

APPENDIX A

DETAILED DESCRIPTION OF MODELLING OF CONTAMINANT MIGRATION USING GOLDSIM

APPENDIX B

DETAILED DESCRIPTION OF MODELLING OF ALKALINITY MIGRATION USING PHAST

1 INTRODUCTION

1.1 BACKGROUND

For nuclear sites, such as Winfrith, disposals of radioactive waste (solid, liquid or gaseous) on or from the site are regulated under the Environmental Permitting (England and Wales) Regulations 2016 (as amended) (EPR 16). Release of a site from the radiological protection aspects of the regulations cannot take place until such disposals have ceased, and any radioactive wastes or radioactively contaminated ground remaining on the site have the necessary permission(s).

The condition of a site when it is fully compliant with the requirements for release from radioactive substances regulation is referred to as the Site Reference State (SRS). Nuclear Restoration Services (NRS) defines an end state that is reached following completion of all physical decommissioning and clean-up activities required for the next planned use of the site.

The Nuclear Decommissioning Authority (NDA), under its duties set out in the Energy Act 2004, has assessed end state options through formal community consultation and determined that the Winfrith site will target land suitable for heathland with public access as its next use.

NRS has subsequently considered facility end states to meet the agreed next planned land use whilst considering wider benefits and detriments of available options with input from stakeholders and representatives of the local community. The end states agreed through optimisation assessment and engagement with stakeholders include on-site disposals of radioactive waste, and deposits of recovered (non-radioactive) wastes at the Steam Generating Heavy Water Reactor (SGHWR) and Dragon reactor (including the mortuary holes). These disposals and deposits of wastes are currently envisaged by NRS as a combination of the following, using the terminology of the "Guidance on the Requirements for Release" (GRR, Environment Agencies, 2018) where applicable:

- Radioactive waste disposed in-situ;
- Radioactive waste disposed for a purpose; and
- Use of non-radioactive waste in a 'deposit for recovery' operation.

Works are currently underway to define and configure the Winfrith site for its End State.

NRS is now required to prepare applications to the Environment Agency (EA) for the necessary permissions. The GRR requires the operator (NRS) to prepare:

- A Waste Management Plan (WMP) which will deliver an acceptable optimised SRS following dismantling; and
- A supporting site-wide environmental safety case (SWESC) demonstrating acceptable risks to people and non-human organisms from radioactive substances in representative future scenarios of natural evolution, human intrusion and natural disruption, as well as protection of people and the environment against non-radiological hazardous associated with the radiological hazards.

A permit variation application for the 'disposal of radioactive waste in-situ and for a purpose' in accordance with the GRR WMP and SWESC will be required. Furthermore, a permit for a Deposit for Recovery (DfR) operation will be required for the use of non-radioactive waste. Both applications are required to be supported by assessment of non-radiological hazards associated with the disposals through a non-radiological hydrogeological risk assessment (HRA), and a radiological performance assessment for the reactor disposal concept designs. Both assessments are based on a conceptual site model (CSM) (NRS, 2024e) supported by a hydrogeological interpretation of present and future conditions (NRS, 2024b) and the reader is referred to these reports for underpinning to this HRA.

This non-radiological HRA supports the regulatory submissions as a Tier 2 document within the Winfrith end state permit variation and DfR application documents hierarchy (Figure 611/1).

Figure 611/1 - Winfrith End State GRR Permit Variation and Deposit for Recovery Application Documents Hierarchy



1.2 REGULATORY CONTEXT FOR THE DEVELOPMENT OF A HYDROGEOLOGICAL RISK ASSESSMENT

The envisaged End States of the SGHWR and Dragon reactor comprise:

- Disposal in-situ of radioactive below-ground structures (which are deemed to be radioactive waste);
- Disposal of radioactive waste (mainly blocks of concrete and broken concrete from demolition of the above ground building structures) for a purpose, namely infilling of unwanted below ground voids (for example in the SGHWR primary containment structure) as part of land restoration;
- Use of non-radioactive waste (aged and newly formed broken concrete) in a 'deposit for recovery' operation, also for the purpose of infilling unwanted below ground voids (for example in the SGHWR annexes) as part of delivering the next land use of heathland suitable for public access;
- Non-radioactive below-ground structures left in-situ, which are not waste; and
- Emplaced non-waste materials (e.g., granular fill, cementitious grout or other sealant) that may be used to implement the End State of the Dragon reactor mortuary holes as well as to prepare the structures for the disposals/deposits. Assuming these materials are placed for the specific purpose of "construction, civil engineering and building works" and they do not compromise certain objectives of the Water Framework Directive (preventing or limiting deterioration of groundwater bodies, reversing sustained upward trends in concentrations of pollutants etc) their use may be authorised.

Guidance from the EA in 2021 (EA, 2021) explains that where a below-ground structure is filled with radioactive waste, leaving the below-ground structure in-situ should be considered together with the waste disposals/deposits in determining whether a groundwater activity will occur. The EA provides hydrogeological risk assessment guidance for groundwater activities (EA, 2018) that encourages a tiered approach to risk assessment with more detailed assessment being undertaken where the risk of groundwater pollution is greater. The three tiers are:

- Tier 1 qualitative risk screening;
- Tier 2 generic quantitative risk assessment (GQRA); and
- Tier 3 detailed quantitative risk assessment (DQRA).

1.3 PURPOSE OF THIS REPORT

The purpose of this report is to present a tiered non-radiological hydrogeological risk assessment of the SGHWR and Dragon reactor End States.

1.4 SCOPE AND STRUCTURE OF THIS REPORT

This report is structured according to the tiered approach to risk assessment described in Section 1.2.

Tier 1 qualitative risk screening is presented in Section 2.0.

GQRA requires compliance criteria. Section 3.0 explains the compliance criteria that have been selected for each contaminant requiring GQRA and compliance points that are adopted for DQRA. Tier 2 GQRA is presented in Section 4.0.



DQRA is required for those contaminants that cannot be demonstrated by Tier 1 and Tier 2 risk assessment to pose an acceptable risk to groundwater quality. Numerical implementation of the DQRA is described in Section 5.0 and the results of the DQRA are presented in Section 6.0.

Conclusions of the report are presented in Section 7.0. Section 8.0 captures uncertainties associated with the risk assessment.

Section 9.0 lists referenced documents.

2

TIER 1 – QUALITATIVE RISK SCREENING

This Section presents Tier 1 qualitative risk screening of the disposals/deposits. EA (2018) explains that "*qualitative risk screening should assess whether the potential discharge from your activity is acceptable and so will not require further assessment*".

Possible reasons given for the potential discharge being acceptable are:

- "the discharge has acceptably low concentrations of hazardous substances, or in concentrations that are the same as the natural background levels in the groundwater (whichever is the higher concentration)
- the discharge has concentrations of non-hazardous pollutants that are within the relevant environmental standards, or in concentrations that are the same as the natural background levels in the groundwater
- there's a very low risk to groundwater-fed receptors due to the presence of unproductive drift or unproductive bedrock strata (and there are no aquifers present or near your activity) and remoteness from surface waters
- the volume or hydraulic loading rate of the discharge is so small such that only minimal dilution in underlying groundwater will be needed to avoid pollution by non-hazardous pollutants"

As with other tiers of risk assessment, a Tier 1 qualitative risk screen must be based on a conceptual model. NRS (2024e) is the conceptual site model of the SGHWR and Dragon reactor End States.

The End States of the SGHWR and Dragon reactor are comprised the following potentially contaminative components (NRS, 2024e):

- Concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes monolith;
- Barytes concrete;
- Structural steel and rebar in concrete structures and blocks;
- Paint;
- Fibreglass;
- Oil staining of structures;
- Concrete and masonry arisings from demolition of the reactor buildings and stockpiled demolition arisings from previously demolished structures; and
- Emplaced non-waste materials.

Section 2.1 to Section 2.8 assess each component of the End States and determine whether the potential discharge to groundwater is acceptable. Potential pollutant linkages between the components and groundwater receptors that require further tier(s) of risk assessment are summarised in Section 2.9.

2.1 CONCRETE IN REINFORCED CONCRETE STRUCTURES, CONCRETE BLOCKS AND THE DRAGON REACTOR MORTUARY HOLES MONOLITH

This Section is concerned with standard concrete in existing structures, as a void-filling material and in emplaced concrete blocks. It does not address barytes concrete that is the subject of Section 2.2.

Concrete is commonplace in the UK below the water table in the form of pipes, tunnel linings, building foundations and potable water tanks. Such features are routinely left in-situ on industrial sites in perpetuity and are not known as commonly having a detrimental effect on groundwater quality. Concrete structures left in-situ below the water table are therefore rarely, if ever, subject to hydrogeological risk assessment.

The reasons UK industry rarely, if ever, undertakes a HRA are because contaminant concentrations in concrete structures are similar to those in surrounding natural ground, the extremely low rate of concrete leaching, and little evidence that groundwater quality is ever affected. These three reasons are discussed in the context of the SGHWR and Dragon reactor End States in sub-sections 2.1.1 to 2.1.3. The reasoning is extended to concrete blocks and the Dragon reactor mortuary holes concrete monolith in sub-section 2.1.4.

2.1.1 COMPARISON OF THE SOLID PHASE CONCENTRATION OF CONTAMINANTS IN CONCRETE WITH BACKGROUND CONCENTRATIONS IN SOILS AT THE WINFRITH SITE

For several contaminants in concrete the solid phase concentration is lower than that in the natural material that makes up the soils at the Winfrith Site. This is demonstrated in Section 2.7 by comparison of the total concentration of contaminants in samples of the D630 stockpile and in cores taken from the SGHWR structure with background concentrations in soils at the Winfrith site.

2.1.2 COMPARISON OF LEACHABLE CONCENTRATIONS OF INORGANIC SUBSTANCES IN SAMPLES OF CONCRETE FROM THE SGHWR WITH THE LIMITS FOR ACCEPTANCE OF WASTE AT INERT LANDFILL SITES

Three samples of structural concrete sampled from Room 254 of the SGHWR (Building D60) were crushed and ground and subject to leach testing¹. The results of the leach testing are reproduced in NRS (2024e) and are compared with limits for acceptance of waste at inert landfill sites² in Table 611/1.

¹ The particle size of the crushed and ground material is not stated but the leach test referred to by EPR 2016 and Council Decision 2003/33/EC (BS EN12457-2) requires material to have a particle size less than 4 mm.

² As set out in Council decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC referred to by Schedule 10 of EPR 2016.

NSD

Table 611/1: Waste Acceptance Criteria Testing Results for Concrete from Building D60 Room 254 (all results mg/kg dry weight except where stated)

	Sample Lab Ref: GAU2938/11 ^b	Sample Lab Ref: GAU2955/1 ^b	Sample Lab Ref: GAU2955/1 ^b GAU2955/2 ^b					
Compositional Analysis (all results mg/kg dry weight except where stated)								
Mineral oil (C10 – C40)	(C10 - C40) < 50 94 < 50 500							
Loss on ignition (%)	11 %	12 %	2.8 %	No limit				
Total Organic Carbon (%)	1.9 %	< 1 %	< 1 %	3 %				
BTEX ³	< 5	< 5	< 5	6				
PCBs (7 congeners)	< 1	< 1	< 1	1				
PAH ⁴ compounds	< 10	< 10	< 10	100				
% Water (air drying)	< 1 %	< 1 %	< 1 %	No limit				
Leach Test Analysis (all r	Leach Test Analysis (all results mg leached per kg of dry material at a liquid to solid ratio of 10 l/kg)							
Arsenic	< 0.2	< 0.2	< 0.2	0.5				
Antimony	0.05	0.05	< 0.05	0.06				
Barium	0.4	2.7	0.70	20				
Cadmium	< 0.03	0.06	< 0.03	0.04				
Chromium (total)	0.42	0.38	< 0.3	0.5				
Copper	< 0.3	< 0.3	< 0.3	2				
Lead	< 0.2	< 0.2	< 0.2	0.5				
Mercury	< 0.01	< 0.01	< 0.01	0.01				
Molybdenum	< 0.2	< 0.2	< 0.2	0.5				
Nickel	< 0.2	< 0.2	< 0.2	0.4				
Selenium	< 0.1	< 0.1	< 0.1	0.1				
Zinc	< 0.2	< 0.2	< 0.2	4				
Sulphate	318	118	89	1000				

³ Benzene, Toluene, Ethylbenzene, Xylene.

⁴ Polycyclic Aromatic Hydrocarbon.

	Sample Lab Ref: GAU2938/11 ^b	Sample Lab Ref: GAU2955/1 ^b	Sample Lab Ref: GAU2955/2 ^b	Acceptance Criteria for Waste at Inert Landfills	
Fluoride	< 3	< 3	< 3	10	
Chloride	80	43	39	800	
Phenol index	< 1	< 1	< 1	1	
pH (pH units)	11.95	12.00	11.99	No limit	
Total dissolved solids	16500	18700	18400	4000	
Dissolved organic carbon	138	< 100	< 100	500	

Note a) Values in bold exceed the limit for waste acceptance at inert landfills. Note b) Taken from GAU, 2022.

Crushing and grinding increases the surface area of a material allowing it to leach inorganic substances more readily. The total dissolved solids results exceed the limit for acceptance of waste at inert landfill sites probably because of dissolution of sodium, potassium and calcium hydroxides from exposed concrete surfaces. Apart from slightly elevated cadmium in one sample, the leachable concentrations of all inorganic substances were less than the limits for acceptance of waste at inert landfill sites as should be expected given waste concrete can be accepted at an inert landfill site without testing. It is clear from the results of the leach tests on crushed and ground material that concrete in structures with a much smaller surface area to volume ratio will leach very little.

Whilst dissolution of concrete at Winfrith is anticipated over millennia (NRS, 2024e), the rate is so slow that a change in groundwater quality is not likely to be discernible.

2.1.3 EVIDENCE IN GROUNDWATER MONITORING DATA FOR WHETHER THE SGHWR STRUCTURE HAS AFFECTED GROUNDWATER QUALITY

By way of demonstration of the negligible effect of the below water table concrete structures on groundwater quality, groundwater monitoring data collected from boreholes downgradient of the SGHWR has been compared with that collected from upgradient boreholes.

Figure 611/2 shows groundwater contours near the SGHWR for September 2020 (Golder, 2021). The shape of the contours is similar for other points of time (e.g., as presented in NRS, 2024b).



Figure 611/2: September 2020 Groundwater Contours Near the SGHWR (Golder, 2021)

Figure 611/2 shows that boreholes OW17 and OW18 are upgradient or cross gradient of the SGHWR and boreholes OW19, OW20, OW27 and OW28 are downgradient of the SGHWR.

NRS (2024b) tabulates major ion concentrations in groundwater upgradient and downgradient of the SGHWR and interprets site-wide groundwater major ion chemistry. Samples of groundwater collected from boreholes in heathland areas are typically sodium-chloride type to sodium/calcium chloride/sulphate type. Samples of groundwater collected from boreholes in the east of the Winfrith site are calcium-bicarbonate type. Groundwater flowing from beneath the heathland onto the developed parts of the site transitions between the two water types and this occurs in the vicinity of the SGHWR. The major ion chemistry of groundwater sampled from boreholes around the SGHWR is dominated by the site-wide trends and there is no evidence that the SGHWR structure is affecting groundwater quality.

The D630 stockpiles of demolition material are located approximately 100 m south-east of the SGHWR and are described in NRS (2024e). NRS (2024b) shows the groundwater pH changes from around 5 on the upgradient side of the SGHWR to above 6 on its down gradient side and it explains that there is no evidence that the D630 stockpiles of demolition material are influencing groundwater pH. A similar change in groundwater pH does not occur at Dragon reactor, the concrete base of which extends approximately 1 m below the water table. Leaching of alkalinity from a material is favoured by a high surface area to volume. The stockpiles are therefore more likely to have affected groundwater quality than the SGHWR (and Dragon reactor) concrete

structures. From these observations it is interpreted that the SGHWR structure *per se* is not influencing groundwater pH.

A few minor inorganic compounds have been monitored in water samples collected from both upgradient and downgradient boreholes and the results of analysis are summarised in Table 611/2.

Table 611/2: Comparison	of Dissolved	Inorganic	Substances	in	Groundwater	Upgradient	or	Cross
Gradient and Downgradie	nt of the SGH	NR						

Contaminant	Upgradient or Cross Gradient				Units		
	Number	Minimum	Maximum	Number	Lowest	Highest	
Boron	3	<0.01	<0.08	2	<0.06	<0.08	mg/l
Cadmium	3	0.06	0.2	2	0.05	<0.2	µg/l
Chromium	3	2	3	2	2	2	µg/l
Cyanide	2	<0.01	<0.01	2	<0.01	<0.01	mg/l
Iron	2	<0.1	0.5	2	<0.1	0.5	mg/l
Lead	3	<1	1	2	<0.3	36	µg/l
Nickel	3	<0.3	3	2	<0.3	<4	µg/l

The number of samples that have been analysed for each parameter both upgradient and downgradient is small. Except for one of the two lead results, Table 611/2 shows no clear difference between upgradient and downgradient groundwater concentrations of minor inorganic substances. The higher of the two lead concentrations may be an analytical anomaly and no confident conclusions can be drawn about this value.

2.1.4 LINES OF EVIDENCE THAT THERE ARE NO POLLUTANT LINKAGES TO GROUNDWATER FROM CONCRETE BLOCKS AND THE DRAGON REACTOR MORTUARY HOLES

Concrete blocks cut from the buildings structure will be used to backfill the below ground voids as part of the Dragon and SGHWR End States. The cutting process could expose minerals that will dissolve from fresh surfaces as hydroxides thereby generating high pH in water. The lines of evidence for aged structural concrete not affecting water quality cannot therefore be extended to the concrete blocks used in backfilling with regards generation of alkalinity and this pollutant linkage requires a higher tier of risk assessment. GQRA methods are not available for confidently assessing this process and therefore the potential for generation of high pH water from concrete blocks will be assessed by DQRA.

Whilst potential contaminants bound within structural concrete have sufficiently low mobility that there is no pollutant linkage with groundwater, it needs to be demonstrated that the same conclusion can be drawn for structural concrete cut into blocks and the concrete monolith of the End State of the Dragon reactor mortuary holes. Leaching depends on the surface area to volume ratio of a material. The greater the surface area of the material, the greater the contact area with water over which chemical reactions can occur. Magnox (2020) describes the block size as up to 2.4 m³ but for the purpose of simplicity of assessment, the blocks are assumed to be cubic with a volume of 1 m³ (noting this is a conservative assumption). The surface areas per cubic metre of the Dragon

reactor mortuary holes monolith, structural concrete, concrete blocks and demolition arisings are set out in Table 611/3.

Component	Conceptualisation (NRS, 2024e)	Surface Area (m²) per Cubic Metre of Component
Mortuary holes ^a	Concrete monolith 6.40 m x 7.77 m x 4.72 m	1
Structural concrete	1 m thick wall or base slab	2
Structural concrete	0.5 m thick wall or base slab	4
Concrete blocks	Cubes with a volume of 2.4 m ³	4.5 ^b
Concrete blocks	Cubes with a volume of 1 m ³	6°
Demolition arisings	Spheres with a diameter of 15 mm packed to give a porosity of 30 $\%$ v/v.	280

Table 611/3: Comparison	n of Surface Area to	Volume Ratios o	f Components of the	e Disposals/Deposits

Note a) The external dimensions are taken from Magnox, 2024f. The effect on volume and surface area of the mortuary tubes within the concrete monolith is disregarded in the calculation of surface area per cubic metre because it is intended to fill the mortuary holes with cementitious grout.

Note b) A cube with a volume of 2.4 m^3 has a length dimension of 1.34 m. Each of its six faces has an area of 1.79 m^2 . The surface area per 1 m^3 is therefore (6 * 1.79 m^2)/2.4 m^3 = 4.5 m^2 .

Note c) A cube with a volume of 1 m^3 has a length dimension of 1 m. Each of its six faces has an area of 1 m^2 . The surface area per cubic metre is therefore (6 * 1 m^2)/1 $m^3 = 6 m^2$.

Table 611/3 shows that the surface area to volume ratio of the Dragon reactor mortuary holes concrete monolith is less than that of structural concrete. Leaching from the concrete monolith is therefore likely to be less than that from structural concrete. Further, this analysis of the surface area to volume ratio disregards the role of the encasing steel structure of the concrete monolith which will inhibit leaching of the concrete within it.

Table 611/3 shows that the surface area to volume ratio of concrete blocks is close to that of structural concrete and approximately 50 times lower than that of demolition arisings. Concrete blocks are therefore likely to leach in a similar manner to structural concrete. The 6,300 m³ of concrete blocks that are planned to be placed in the SGHWR have the same surface area as approximately 101 m³ of demolition arisings. The 400 m³ of concrete blocks that are planned to be placed in the Dragon reactor have the same surface area as approximately 6 m³ of demolition arisings. This is less than 1.5% of the total volume of demolition arisings expected to be placed in the two reactor basements. The effect of leaching of concrete blocks (and by extension structural concrete) is thereby small compared with the effect of the uncertainty in the volume of demolition arisings that will be used.

2.1.5 CONCLUSION

It is concluded that potential contaminants bound within concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes monolith have sufficiently low concentration and/or mobility that the discharge has acceptably low concentrations of pollutants and the potential discharge from these features is acceptable. This is because:

 Concrete structures are not known as commonly having a detrimental effect on groundwater quality;



- The solid phase concentration in concrete of some contaminants is lower than that found naturally in soils at the Winfrith Site (Section 2.1.1);
- Leachable concentrations of all inorganic substances in samples of concrete from the SGHWR are less than the limits for acceptance of waste at inert landfill sites (Section 2.1.2); and
- There is no persuasive evidence in groundwater monitoring data that the SGHWR structure has affected groundwater quality (Section 2.1.3).

Wireline cutting used to generate the concrete blocks could expose minerals that will dissolve from fresh surfaces as hydroxides thereby generating high pH in water. Whilst the effect of leaching of concrete blocks (and by extension structural concrete) is small compared with the effect of the uncertainty in the volume of demolition arisings that will be used, GQRA methods are not available for confidently assessing the process of generation of high pH water in this way and therefore, to ensure conservatism in the risk assessment, the potential for generation of high pH water from concrete blocks will be assessed by DQRA.

2.2 BARYTES CONCRETE

Barytes concrete, used at the SGHWR and Dragon reactor, is not commonly used in construction in the UK. Barytes concrete will contain more barium than the Poole Formation. The samples collected from Room 254 of the SGHWR were not of barytes concrete. Barium has not been monitored in groundwater both upgradient and downgradient of the SGHWR. The lines of evidence presented in Section 2.1 that there is no pollutant linkage with groundwater from concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes are not well evidenced for barytes concrete. There is insufficient confidence that based on these lines of evidence that potential discharge of dissolved barium and sulphate from barytes concrete is acceptable and barytes in barytes concrete therefore requires further tier(s) of risk assessment.

2.3 STRUCTURAL STEEL AND REBAR IN CONCRETE STRUCTURES AND BLOCKS

Corrosion of structural steel of the reactors' below-ground structures, rebar in concrete structures left in-situ and rebar in concrete blocks used to infill the below ground voids will release iron and lesser amounts of other metals (manganese, copper, nickel and chromium) and anions (sulphate and phosphate) to water. The pollutants could thereafter migrate to groundwater.

Structural steel can be expected to be protected from corrosion, at least initially, by paint. There is uncertainty about how long it will take for water to fully access the structural steel and initiate corrosion. The primary mechanism by which constituents of reinforcement will be released to water is also corrosion. The rebar will corrode when water permeates the concrete through microfractures or through demolition induced concrete fractures in the SGHWR annexe structures. Corrosion products have a greater volume than the rebar, and their generation increases stress within the concrete, causing cracking and increased exposure of the rebar to water.

LLWR (2011) presents a review of literature on the corrosion rate of mild steel and the findings of an expert elicitation on the subject. The median rate of corrosion under relatively high pH, generally anaerobic, saturated conditions is judged to be 1 μ m/yr and the range is judged to be 0.01 μ m/yr to 100 μ m/yr (LLWR, 2011). Faster rates of corrosion occur under aerobic conditions, but such conditions are unlikely to be sustained in the disposals/deposits because of the presence of the low permeability capping system mitigating against both infiltration of oxygenated rainwater and

exchange of air with the atmosphere. The LLWR review does not address aerobic saturated conditions but the review of corrosion in aerobic unsaturated conditions indicates that corrosion rates towards the upper end of the above range are appropriate to circumstances where aerobic groundwater contacts mild steel that might be present close to the external faces of the concrete structure.

Whilst the total surface area of structural steel and rebar is relatively large (NRS, 2024c provides estimates of 62,500 m² and 55,000 m² for the SGHWR and Dragon reactor, respectively), paint means that only a small fraction of the entire surface area of the structural steel will be exposed to water at any point in time. The main contaminant released from corrosion of structural steel and rebar will be iron and this can be expected to precipitate either in the unsaturated zone and/or in groundwater that has been shown by routine monitoring to be oxygenated (NRS, 2024b). Co-precipitation of other metals may occur.

A Best Available Technique (BAT) report about the potential options for management of encast and in-room metals has been produced (Magnox, 2018a). Magnox (2018a) cites similarly low rates of corrosion to LLWR (2011) and argues that pH and Eh changes will mitigate against an increase in dissolved iron concentration in groundwater. It points to marine and onshore analogues for disposing of metals associated with civil engineering structures:

- The best practicable environmental option for disposal of concrete gravity oil platforms in the North Sea is often to leave them in place because significant contamination of the marine environment is not expected; and
- It is the norm for pilings and foundations for buildings as well as tunnels and bunkers containing steel elements to be abandoned without the materials presenting a significant hazard to groundwater.

The discharge from the structural concrete and rebar in concrete structures and blocks is expected to have non-discernible concentrations of hazardous substances and concentrations of non-hazardous pollutants are expected to be well within relevant environmental standards. The non-radiological risk from structural steel and rebar associated with these disposals/deposits is therefore judged acceptable and no further tiers of risk assessment are necessary.

2.4 PAINT

Paint has been used to protect structural steel from corrosion and surfaces such as floors are painted, where water resistance is required. Paint has been removed from surfaces along with asbestos, but it is inevitable that a small mass of paint will be present in the disposals.

Water permeation beneath painted surfaces leads to paint blistering and in some circumstances, reaction between concrete and oil-based paints (saponification) can lead to paint dissolving.

A sample of paint scrapings from the secondary containment of the SGHWR has been analysed for metals and hydrocarbon compounds as well as by leaching testing. The results are presented in NRS (2024e).

Only one sample of paint has been analysed and the results should therefore be treated as broadly indicative of the contaminants that may be present and their mobility into water. The results indicate that, as expected, paint scrapings are comprised a complex mixture of hydrocarbon compounds and metals. Approximately ~10% by dry weight of the material can become dissolved organic carbon. Most of the metal content is not water available. Of the metals, antimony, cadmium and zinc are the



most available to water but only around 10% can be leached. The results of analysis of this sample align with the expectation, borne of the use of paint, that contaminants are not readily leached from it by water.

The mass of residual paint can be expected to be low and only a small fraction of it is water available. It is judged that the discharge of water that has contacted paint will have acceptably low concentrations of hazardous substances and concentrations of non-hazardous pollutants that are within the relevant environmental standards, or in concentrations that are the same as the natural background levels in the groundwater. No further tiers of risk assessment are necessary.

2.5 FIBREGLASS

The six fuel ponds located towards the eastern end of the turbine hall of the SGHWR are constructed from concrete and were lined with fibreglass in the 1960s. A BAT report about the potential options for management of the fibreglass has been prepared (Magnox, 2018b) and forms the basis for all information in this section.

Fibreglass comprises a fibre-reinforced polymer composite material, in which silica glass fibres are encapsulated within a thermosetting plastic such as epoxy/phenolic resin. The fibreglass in the fuel ponds was primarily applied to provide containment of the water used for storage of the nuclear fuel. The pond liners will be disposed of in-situ within the SGHWR structure in line with the outcome of optimisation assessment (Magnox, 2018b).

The base of the ponds is at 29 m AOD and the ground level at the east end of the turbine hall is approximately 41 m AOD. The lining of the ponds covers an area of 2,477 m². The lining is 3 mm thick, and if this is taken as the average, then the total fibreglass lining volume is 7.43 m³. This is equivalent to approximately 14.5 tonnes of the glass-polymer composite material if the material is assumed to have a specific gravity of approximately 1,950 kg/m³ (Magnox, 2018b).

Epoxy resin is commonly prepared from epichlorohydrin and bisphenol-A, in the presence of a sodium hydroxide catalyst, to produce the diglycidyl ether of bisphenol-A. Di-amines are frequently used as the curing agents. The resins are manufactured with a wide range of molecular weights, but the use of epoxy resins in the production of fibreglass usually requires a low molecular weight, low-viscosity resin to ensure complete penetration of the woven fibre component.

The glass fibre component is expected to be a silica-based glass with additional calcium, magnesium and sodium, and possibly boron.

According to Magnox (2018b) the fibreglass in the SGHWR has reached the end of its serviceable life . Epoxy resins are also, in general, highly resistant to environmental degradation, and show excellent resistance to aqueous alkalis and organic solvents but can be degraded by strong acids.

According to Magnox (2018b) physical aging reportedly does not appear to affect the fibre-resin interface, the strength of the composite or increase its permeability. Chemical aging can take place at elevated temperatures and oxidation can occur in an oxic environment. Hydrolysis at low water temperatures may not result in significant reaction or degradation of the resin. There is little long-term data on the environmental fate of epoxy resins, but current understanding indicates that, in a low-temperature, saturated environment, the polymer will only degrade slowly over a period of many decades to centuries, with hydrolysis initially giving rise to cracking that will expose the glass fibres to the surrounding porewater. In fresh, low-pH, meteoric-type groundwater, relatively little dissolution of the fibres might be expected, whereas a high-pH, cement-conditioned groundwater

would result in a greater extent of dissolution. Magnox (2018b) explains that radiation can damage epoxy resin but reduction in physical properties requires higher doses than expected to be experienced given the low inventory remaining in the SGHWR and hence epoxy resins are used to encapsulate certain types of radioactive waste.

The BAT report concludes that "It seems unlikely that degradation of the epoxy resins will result in large-scale production of organic molecules that could act as complexants for radionuclides, nor in the large-scale production of gas". It also concludes that "No contamination or impact is particularly associated with the fibreglass and, therefore, there is no obvious potential benefit in chemically or physically treating the material in some manner to retain contaminants or in backfilling around the fibreglass with any particular material to address any potential adverse effects".

On consideration of the information presented in the BAT report it is concluded that the potential contaminants bound within the fibreglass have sufficiently low mobility that there is no pollutant linkage with groundwater. The potential discharge from fibreglass is acceptable.

2.6 OIL STAINING OF THE SGHWR REGIONS 1 AND 2 STRUCTURE

Laboratory analysis of targeted samples (i.e., samples collected directly from concrete visually impacted by oil) has been undertaken to determine the hydrocarbon fractions that comprise the oil staining of concrete in the SGHWR Regions 1 and 2 (below ground level areas⁵). The mass of each fraction has been calculated using the upper 95th percent confidence limit (UCL95) of the mean concentration from the analytical dataset (NRS, 2024e). The calculated masses are thereby cautious estimates. This approach cautiously disregards decontamination of the structure surfaces before demolition that will remove much of the water available and soluble hydrocarbon compounds of the oil staining.

Based on the inventory mass calculated in NRS (2024e) the oil staining is predominantly composed of heavy end hydrocarbon fractions with very low concentrations of BTEX and PAH. This is consistent with the staining being a lubrication oil.

Of the BTEX compounds, only xylene is detected from the analysis undertaken and, with a single exception, the concentration of xylene was within an order of magnitude of the detection limit for each sample analysed. The resultant xylene inventory within the SGHWR Regions 1 and 2 structure is trivial (significantly less than 1g). As described in NRS (2024e), water will flow into the SGHWR Regions 1 and 2 structure following the End Point until eventually the water level inside the structure is at least as high as the external groundwater level. Even if the entire mass of xylene were instantaneously water available, there is confidence that the dilution afforded by the volume of water accumulated in the Regions 1 and 2 structure will result in acceptably low concentrations of xylene in water. No further tiers of risk assessment are considered to be required for xylene.

Of the PAH compounds, only 4 have been detected of the 16 analysed (naphthalene, phenanthrene, fluoranthene and pyrene). Naphthalene is a non-hazardous pollutant. Pyrene, fluoranthene⁶ and phenanthrene are of low solubility and mobility according to CL:AIRE (2017). The concentration of the each of the PAH compounds was determined to be within one order of

⁵ Oil staining of the above ground SGHWR structure will be removed for off-site management where practicable to do so.

⁶ Fluoranthene is not listed in CL:AIRE (2017) but it is the same mass as pyrene and is by extension assumed to be of similar mobility and solubility.

magnitude of the detection limit for each sample analysed. The concentrations of PAH in the oilstained samples are lower than the maximum concentration for acceptance of waste at inert landfill sites, indicating that, in general, the PAH left within the structure poses a low risk to water quality. Decontamination is expected to further reduce the PAH inventory. No further tiers of risk assessment are considered to be required for the PAH species.

Aliphatic hydrocarbon compounds in the range >C16–C44 have a very low solubility in water (no greater than 0.003 μ g/l according to CL:AIRE, 2017) and very low mobility in water (K_{oc} no less than 6.3E8 l/kg, according to CL:AIRE, 2017). WHO (2008) draws on toxicity information from TPH-CWG⁷ (1997) that describes the >C16-C21 and >C21-C35 aliphatic fractions as follows:

These oils are essentially pure aliphatic hydrocarbons with virtually no aromatic components or other contaminants. They are approved by the Food and Drug Administration as direct food additives and used extensively in foods, cosmetics, and pharmaceutical products.

The absence of a WHO drinking water guideline value either for the >C21-C35 or >C35-C44 aliphatic fractions also reflects the low toxicity of these hydrocarbon compounds. Aliphatic hydrocarbon compounds are unlikely to be hazardous substances. On the basis of their toxicity, combined with their low solubility and mobility in water, >C16-C21, >C21-C35 and >C35-C44 aliphatic fractions will not be considered further. There is insufficient confidence in the same judgment with respect to hydrocarbons in the >C8-C16 aliphatic range due to their higher published solubility and mobility. Therefore >C8-C16 aliphatic fractions will be considered further in the Tier 2 assessment.

According to CL:AIRE (2017) aromatic hydrocarbon fractions are of greater toxicity, mobility and solubility in groundwater than aliphatic hydrocarbons of equivalent banding. The inventory of the >C8-10 aromatic fraction is significantly less than 1g. Xylene is a >C8-C10 aromatic therefore, based on the calculated mass, the composition of the >C8-C10 aromatic fraction is likely predominantly xylene. Even if the entire mass of the >C8-C10 aromatic fraction were instantaneously water available, there is confidence that the dilution afforded by the volume of water accumulated in the Regions 1 and 2 structure will result in acceptably low concentrations of the >C8-C10 aromatic compounds in water. No further tiers of risk assessment are considered to be required for the >C8-C10 aromatic fraction.

Whilst the solubility and mobility of >C21-C44 aromatic compounds are described as very low in CL:AIRE (2017), given the calculated inventory mass and the solubility (6.6 μ g/l for the >C21-35 aromatic fraction in CL:AIRE, 2017) there is insufficient confidence that the risk to groundwater can be dismissed on the basis of qualitative judgment. Therefore, the remaining aromatic fractions (>C10-C44) will be considered further in the Tier 2 assessment.

2.7 DEMOLITION ARISINGS

The upper 95th percentile confidence limit of the mean concentration of each contaminant in the demolition arisings has been calculated using CL:AIRE (2020) guidance (Table 611/4).

The stockpiles contain between 19% and 30% brick. If the brick contributes to the contaminant concentrations like concrete, then the reported concentrations apply equally to the demolition arisings that will be generated by demolition of the above ground parts of the SGHWR. If brick is

⁷ Total Petroleum Hydrocarbon Criteria Working Group

assumed not to contain contaminants, then the demolition arisings' contaminant concentrations need correcting for brick content before they are representative of the SGHWR concrete. This correction is explained in NRS (2024e) and the results are shown in Table 611/4.

The total concentration of contaminants in concrete has been determined in fifteen cores (NRS, 2024e). The results of the analysis for those contaminants determined in the analysis of the demolition arisings are shown in Table 611/4.

The concentrations of contaminants present naturally in soils on Winfrith site have been determined in a NRS report (NRS, 2024d) and are compared with the concentrations of inorganic contaminants in demolition arisings in Table 611/4.

The concentrations of arsenic and mercury in concrete (even when correcting in a conservative manner for brick) shown in Table 611/4 are judged at or below the background concentration in soils. On this basis these contaminants do not require further tiers of risk assessment. Other contaminants (antimony, barium, cadmium, chromium, copper, lead, molybdenum, nickel, selenium and zinc) require further tier(s) of risk assessment.

The background concentrations of anions in soils at Winfrith have not been defined and therefore a satisfactory risk cannot be demonstrated by Tier 1 assessment. Sulphate, fluoride and chloride require further tier(s) of risk assessment.

The leachate produced from fresh concrete and demolition arisings is alkaline (e.g. NDA, 2019). Elevated alkalinity (quantified using pH) is expected in the porewater and requires further tier(s) of risk assessment.

The TPH⁸ and total PAH⁹ assessment inventory of demolition arisings is assumed to be derived from the tar/bitumen foreign material described in Magnox (2019). The concentrations of both TPH and PAH in the ten samples of the D630 stockpile (Magnox, 2019) are lower than the maximum concentration for acceptance of waste at inert landfill sites. The requirements for engineering to protect groundwater at inert landfill sites are not onerous. The landfill sides and base must consist of a mineral layer that provides protection at least equivalent to 1 m thickness with a permeability of 1x10⁻⁷ m/s. Since the equivalent thickness and permeability of the concrete structure of the SGHWR and Dragon reactor basements provides greater protection than this standard these results indicate that, in general, the TPH and PAH in demolition arisings pose a low risk to water quality.

The D630 stockpile was further characterised for TPH and PAH in 2022 by analysing samples of stockpiled demolition arisings for hydrocarbon compounds split by aromatic and aliphatic compounds and carbon banding; and speciated PAH. The results are presented in NRS (2024e). Lighter aromatic and aliphatic compounds are rarely detected and detected concentrations are within an order of magnitude of the limit of detection¹⁰. The frequency of detection of aliphatic and aromatic hydrocarbon compounds generally increases with the size of the compounds. The heaviest fractions (>C21-C35 and >C35-C44 aliphatic and >C21-C35 aromatic and >C35-C44 aromatic) are detected in approximately half the samples. Lighter PAH compounds are generally not detected whereas heavier PAH compounds in the >C21-C35 aromatic and >C35-C44 aromatic

⁸ Total petroleum hydrocarbon compounds.

⁹ Polycyclic aromatic hydrocarbon compounds.

¹⁰ The laboratory error when detected concentrations are close to the limit of detection is relatively high.

carbon band ranges are present. The results are consistent with the presence of the tar/bitumen foreign material described in Magnox (2019).

CL:AIRE (2017) assesses the partitioning to organic carbon and the aqueous solubility of carbon band ranges and concludes that the mobility of these carbon band ranges is 'very low'. Since the discharge from the bitumen in demolition arisings is expected to have non-discernible concentrations of hazardous substances and concentrations of non-hazardous pollutants are expected to be well within relevant environmental standards, the non-radiological risk associated with these disposals/deposits is judged acceptable and no further tiers of risk assessment are necessary.

The concentrations of PCB compounds in the ten samples of the D630 stockpile (Magnox, 2019) are lower than the maximum concentration for acceptance of waste at inert landfill sites and indicate that the concentrations are not of high environmental significance. Nevertheless, PCB compounds, which are classified as hazardous substances, are soluble in water and the EA has established very low minimum reporting values for congeners (EA, 2017b) since the inert waste acceptance criteria were developed. There is therefore insufficient confidence that the discharge from the demolition arisings will contain acceptably low concentrations of hazardous substances, and they are judged to require further tier(s) of risk assessment.

	Demolition Arisings (Magnox, 2019)			Demolition Arisings Corrected for Brick ^c			Concrete cores (NRS, 2024e)		Background (NRS, 2024d)				
	Minimum	Maximum	95% UCL of Mean ^a	Minimum	Maximum	95% UCL of Mean ^a	Minimum	Maximum	95% UCL of Mean ^a	Mean	Standard Deviation	Maximum	95% Upper Confidence Level
Antimony	<1	2	1.1	n/a	2.5	1.4	1.5	7.3	4.4				
Arsenic	5	9	6.7	6.2	11	8.4	<5	<5	<5	1.7	2.1	<30	5.1
Barium	42	1300 ^d	601	52	1616	747	20.9	781.9	198				
Cadmium	<1	1	0.7	n/a	1.2	0.8	<1	6.8	1.9	0.068	0.145	<2.0	0.16
Chromium	12	34	22	15	42	27	7.3	23.4	15	5.8	6.9	21	17.15
Copper	8	42	25	9.9	52	31	2.1	24.4	11.2	2.9	5.6	19	12.11
Lead	25	390	208	31	485	259	<1	36.5	14.9	5.1 ^e	2.1 ^e	21	17.28
Mercury	<1	<1	0.5	n/a	n/a	0.6	<1	<1	<1			<10	
Molybdenum	<2	3	1.7	n/a	3.7	2.1	<1	1.4	0.70	0.13	0.16	<2.0	0.39
Nickel	7	32	18	8.7	40	22	4.1	15.0	9.5	2.9	5.4	21	11.78
Selenium	<3	<3	1.5	n/a	n/a	1.9	<5	<5	<5	f	f	f	f
Zinc	41	160	124	51	199	154	16.4	75.5	41.3	8.6 ^e	3.04 ^e	66	53.74

Table 611/4: Comparison of Contaminant Concentrations (mg/kg) in Demolition Arisings and Concrete with Background Soils

Note a) Where concentration is reported as less than the laboratory limit of detection, the mean concentration, 95th percentile and 95% UCL (upper confidence level) of the mean concentrations have been calculated using a value of half of the limit of detection.

Note b) Blank cells indicate that no data is available. n/a indicates that no attempt has been made to calculate the value from concentrations less than the limit of detection.

Note c) If the proportion of concrete in the D630 stockpile is 70% and in the above ground SGHWR structure is 87%, the proportion by mass of concrete in demolition arisings from the SGHWR will be 100*(87-70)/70 = 24% higher than in the D630 stockpile material. The proportion by mass of concrete in demolition arisings from the Dragon reactor will be higher but the correction for the SGHWR is shown here to allow comparison with the SGHWR concrete cores.

Note d) The maximum barium concentration of 1300 mg/kg appears an outlier compared to the other barium results in the dataset. However, conservatively, it has not been treated as an outlier in the calculation of the UCL95 of the mean.

Note e) The values shown are the median concentration (mg/kg) and the geometric standard deviation that has a dimensionless unit.

Note f) No statistical analysis was performed for selenium due to the only two results reported appearing anomalous when compared to the limit of detection values presented for the other 50 samples in the dataset (0.5 - 30mg/kg). No meaningful statistics can therefore be calculated; the only available data not appearing to be representative.

2.8 EMPLACED NON-WASTE MATERIALS

Grouts, sealants and the like may be used to prepare the structures for the disposals/deposits and will also be used to fill the Dragon reactor mortuary holes. It is assumed that emplaced non-waste materials will be selected on the basis they are demonstrably non-polluting.

2.9 POTENTIAL POLLUTANT LINKAGES THAT REQUIRE FURTHER TIER(S) OF RISK ASSESSMENT

The potential discharge from the following components of the End States has been identified as acceptable and these components need no further tiers of risk assessment:

- Contaminants bound within concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes monolith, with the exception of the hydroxide ion (that can generate high pH in water) leached from concrete blocks;
- Structural steel and rebar in concrete structures and blocks;
- Paint;
- Fibreglass;
- The following components of oil staining of structures: <C10 aromatic compounds (including BTEX), >C16 aliphatic compounds and all 16 analysed PAH species;
- Arsenic and mercury in demolition arisings; and
- Emplaced non-waste materials that will be used to implement the End State of the Dragon reactor mortuary holes as well as to prepare the structures for the disposals/deposits.

Table 611/5 summarises potential pollutant linkages from the SGHWR and Dragon reactor End States. These pollutant linkages require further tier(s) of risk assessment.

Location	Components with Assessment Inventory	Pathways	Receptors		
SGHWR	Barytes concrete	Basement concrete	Groundwater Surface water Ecological habitats		
	Demolition arisings	structure, unsaturated zone, saturated zone			
	Concrete blocks				
	Oil staining of the Regions 1 and 2 structure				
Dragon reactor	Barytes concrete				
	Demolition arisings				
	Concrete blocks				
Mortuary holes	None				

Table 611/5: Potential Pollutant Linkages

3 COMPLIANCE POINTS AND COMPLIANCE CRITERIA

3.1 **REGULATORY GUIDANCE ABOUT COMPLIANCE POINTS**

The required approach for establishing compliance points for activities permitted under EPR 2016 is set out in EA guidance "Groundwater risk assessment for your environmental permit" (EA, 2018).

EA guidance (EA, 2018) states:

"If there is a potential risk to groundwater and specific receptors, you need to assess how to protect receptors through the use of compliance points."

"The compliance point is the point along the groundwater flow pathway where the defined target concentration (compliance limit or value) must not be exceeded, as this would represent an unacceptable risk of harm to the receptor. The compliance point may be the receptor itself or a specified point along the source–pathway–receptor linkage (for example, within an aquifer nearer to the contamination source). Alternatively, it may represent pore water in the soil zone.

The location of the compliance point will depend on the circumstances, the level of assessment and the sensitivity of the receptor. The compliance point may be a virtual point for the purpose of predictive assessments (modelling) or it may be a physical monitoring point (such as a borehole or spring)."

"You can set a limit on your compliance points which can be used as a value to trigger action (at a physical monitoring point). If the limit is exceeded you must take action because there is evidence of a polluting discharge that could result in a breach of a compliance limit."

3.1.1 COMPLIANCE POINT FOR GQRA

A GQRA involves a relatively simple assessment of the effect an activity may have on water quality, including groundwater. Generic quantitative risk assessments use hydrogeological calculations which are typically analytical solutions solved in a deterministic fashion. They use conservative (worst case) assumptions (EA, 2018).

In this HRA, to adopt a demonstrably conservative approach, the compliance point for GQRA will be water in the disposals/deposits.

3.1.2 DQRA COMPLIANCE POINTS FOR GROUNDWATER ACTIVITIES

EA (2018) goes on to discuss where to put compliance points:

"You can set a compliance point at the receptor itself but this may not be possible or desirable. You may want to set the compliance point between the point of discharge and the receptor. If so, you should assess it using criteria that predict the effects of dilution, attenuation and degradation, to protect the downstream receptors.

If your compliance point is also your physical monitoring point, you may need to site it closer to the discharge than the receptor to:

- be sure the monitoring takes place near enough to the discharge's zone of influence (the area of aquifer that has the potential to be impacted by the discharge)
- get advance warning of the development of any contaminant plume data can then be gathered on the contaminant flux to protect the receptor before any environmental threshold is breached
- overcome constraints you have on accessing any sampling points



If the receptor is not an abstraction point, but could be one in future, you should set a compliance point that protects the nearest point where you reasonably expect abstraction could take place. This may be subject to practical constraints.

Where there is no plausible use of groundwater closer to the point of discharge use the following to form your pollution assessment:

- existing abstractions
- natural discharges
- other passive uses of groundwater"

The difference between the 'prevent' and 'limit' requirements means a compliance point for hazardous substances does not have to be in the same location as the compliance point for non-hazardous pollutants:

- The compliance point for hazardous substances will be established below the water table in the Poole Formation immediately downgradient of the disposals/deposits. This is also where the EA has requested that a hypothetical abstraction well is located to assess risk from potentially migrating radionuclides (classified as hazardous substances) in the radiological performance assessment in accordance with Requirement R10 of the GRR (Environment Agencies, 2018).
- The compliance point for non-hazardous pollutants will be established below the water table in the Poole Formation between the disposals/deposits and the nearest groundwater receptor. which is surface water, or the root zone of a groundwater fed ecological system. The location of plausible future abstraction points is required to be considered by EA (2018) when establishing compliance points. The Poole Formation is a Secondary A aquifer that could be exploited in future although given the relatively thin saturated zone and the intention to return the land to open heathland this seems unlikely. Nevertheless, the compliance point for non-hazardous pollutants will be established 50 m from the downgradient boundary of the SGHWR and Dragon reactor. Whilst 50 m is an arbitrary distance in the context of permitting a groundwater activity, the default compliance point distance for resource protection from a source is 50 metres for land contamination risk assessment of all hazardous substances in all aquifers for contaminants already in the groundwater and for non-hazardous pollutants in groundwater with strategic resource potential. A distance greater than 50 m may be agreed with the EA for land contamination risk assessment of non-hazardous pollutants in groundwater with local resource potential (EA, 2017a). The selected 50 m distance to the non-hazardous pollutant compliance point is therefore reasonable when considered in the context of land contamination risk assessment guidance.

Groundwater is not interpreted to flow downwards from the Poole Formation down hydraulic gradient of the SGHWR and Dragon reactor (NRS, 2024b). Both the compliance point for hazardous substances and the compliance point for non-hazardous pollutants are therefore also protective of groundwater in the Portsdown Chalk that is at depth beneath the Winfrith site.

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3.2 COMPLIANCE LIMITS (TARGET CONCENTRATIONS) FOR NON-RADIOLOGICAL CONTAMINANTS

EA (2018) explains:

"The target concentration (also known as a compliance limit) is a concentration at the compliance point that must not be exceeded. Provided the target concentration is met, the relevant environmental standard for the receptors should also be met or complied with.

Where the compliance point is the receptor, the target concentration will be set as the relevant environmental standard or natural background groundwater quality

A compliance value can be:

- *theoretical if used during predictive modelling* [and this is the relevant choice in the current circumstances at Winfrith]
- a limit set in a permit for physical monitoring"

For groundwater activities, the compliance limits at the hazardous substances' compliance point will be the higher of the minimum reporting value of each non-radiological hazardous substance, and the natural background concentration of the non-radiological hazardous substance. This is because compliance points will be established at locations where no discernible concentrations of hazardous substances are allowed if an input of hazardous substances is to be prevented. The compliance limit is set to the minimum reporting value to assess the results of modelling that does not take into account the background concentration of a hazardous substance.

For non-hazardous pollutants, EA (2018) provides guidance on appropriate standards and refers to drinking water standards and surface water Environmental Quality Standards. It states that values for assessing the status of groundwater bodies set out in The Water Framework Directive (standards and classification) Directions (England and Wales) 2015 should not be used, although it acknowledges that these values *"may, however, prove useful as overall indicators of groundwater guality when protecting groundwater dependent wetlands"*.

For some pollutants in some situations, deterioration in groundwater quality to the environmental standards would not be acceptable and EA (2018) states:

"You may need to set the target concentrations at a level between an appropriate environmental standard and natural background level dependent on sensitivity of the site to sufficiently protect water quality for good quality aquifers which are either:

- extensively developed for potable supplies
- providing a significant flow component to surface water"

Judgement is required to establish appropriate compliance limits for compliance points downgradient of the Winfrith disposals/deposits. Given the environmental setting, the values should, by default, be surface water environmental quality standards, but 'sense checked' against:

- Values in the Water Framework Directive (standards and classification) Directions (England and Wales) 2015;
- Background groundwater quality; and
- To a lesser degree, UK drinking water quality standards.

Assessment is required of the risk associated with a change in groundwater pH brought about by water migrating from the deposits/disposals that has contacted demolition arisings. Groundwater from around the SGHWR is interpreted to discharge to an area west of the Monterey roundabout. This area has a M16 National Vegetation Classification community (*Erica tetralix – Sphagnum compactum* wet heath) that is part of the wet heaths that are a 'qualifying feature' of the Dorset Heaths Special Area of Conservation (SAC). *Sphagnum* acts as an 'ecosystem engineer', and currently maintains a low pH environment in the near surface of this area of mire (Atkins, 2024). Atkins (2024) explains that decommissioning the Winfrith site's rubble drains could allow bicarbonate rich deeper groundwater to discharge into the mire endangering the *Sphagnum*. This, as well as the effects of future climate change, will alter groundwater pH in the vicinity of the mire. Atkins (2024) therefore recommends that when assessing the sensitivity of the M16 wet heath to an increase in pH within the rootzone that *Sphagnum* is assumed not to be acting as an ecosystem engineer and should not be relied upon to maintain the low pH.

Atkins (2024) explains that an increase in pH in the rootzone to 7 would support habitats associated with broadly neutral conditions albeit the designated habitats will be reduced in the affected areas with a likely increase in species which are not components of the qualifying feature habitats. Atkins (2024) explains the transition to habitats that can tolerate groundwater with neutral pH could, in theory, result in a community that is of high ecological value (as present elsewhere within the SAC).

On this basis pH compliance for groundwater has been assessed to avoid the pH at the mire exceeding 7. Groundwater flowing from Dragon reactor discharges into, and close to, the River Frome that is less sensitive to pH than the acid mire. Nevertheless, for reasons of consistency and simplicity, the pH compliance limit established for the SGHWR is also used for groundwater pathway downgradient of Dragon reactor. The compliance limit established for the groundwater pathway from the SGHWR is therefore protective of receptors downgradient of the Dragon reactor.

pH is shown in Table 611/6 along with contaminants associated with components for which a satisfactory hydrogeological risk could not be demonstrated through Tier 1 risk assessment (Section 2.0). It also includes arsenic and mercury in demolition arisings even though the total concentration of these contaminants in demolition arisings has been demonstrated to be similar to natural background soils. This provides reassurance that the tiered risk assessment has been applied robustly.

Table 611/6 shows the compliance limit selected for each contaminant based on the contaminant classification, water quality standards and background groundwater quality. This compliance limit will be used for GQRA. The compliance limits for dissolved substances (i.e. not pH) are conservative because the guidance (EA, 2018) allows for the compliance limit at a compliance point established between the disposals/deposits and the nearest receptor to be higher than the acceptable concentration at the receptor by an amount that takes account of attenuation of the pollutant between the compliance point and the receptor. The DQRA compliance limit may therefore be increased to take account of attenuation between the compliance point shown in Table 611/6 and the receptor. The compliance limit for pH in Table 611/6 is for groundwater at the mire.
Table 611/6: Compliance Limits (Target Concentrations)

Contaminant	Component	Contaminant Classification	Complianc e Point Location Down Gradient of the SGHWR or Dragon reactor	Freshwater Annual Average EQS (µg/l) or Minimum Reporting Value (µg/l except for pH)ª	Drinking Water Standard (µg/l) where there is no EQS ⁹	Mean Concentration in Background Groundwater Quality (µg/I except for pH) (NRS, 2024d)	Selected Compliance Limit Concentration (µg/l except for pH)
рН	Demolition arisings and blocks	Non-hazardous	50 m	6-9 (95th percentile)		5.75	7 ^b
Antimony	Demolition arisings	Non-hazardous	50 m		5	n/a	5
Arsenic	Demolition arisings	Hazardous	0 m	5°		4	4
Barium	Demolition arisings	Non-hazardous	50 m		1300	n/a	1300
Cadmium	Demolition arisings	Non-hazardous	50 m	0.08 ^f		n/a	0.08
Chromium III	Demolition arisings	Non-hazardous	50 m	4.7		3	4.7
Chromium VI	Demolition arisings	Hazardous	0 m	1 ^c		n/a	1
Copper	Demolition arisings	Non-hazardous	50 m	1 (bioavailable)		12	12
Lead	Demolition arisings	Hazardous	0 m	0.2°		3	0.2
Mercury	Demolition arisings	Hazardous	0 m	0.01		0.2	0.01
Molybdenum	Demolition arisings	Non-hazardous	50 m		70 ⁱ	n/a	70
Nickel	Demolition arisings	Non-hazardous	50 m	4 (bioavailable)		14	14
Selenium	Demolition arisings	Non-hazardous	50 m		10	n/a	10
Zinc	Demolition arisings	Non-hazardous	50 m	10.9 (bioavailable)		33	33

Contaminant	Component	Contaminant Classification	Complianc e Point Location Down Gradient of the SGHWR or Dragon reactor	Freshwater Annual Average EQS (µg/l) or Minimum Reporting Value (µg/l except for pH)ª	Drinking Water Standard (µg/l) where there is no EQS ⁹	Mean Concentration in Background Groundwater Quality (μg/l except for pH) (NRS, 2024d)	Selected Compliance Limit Concentration (µg/l except for pH)
Sulphate	Demolition arisings	Non-hazardous	50 m	400,000	250,000 ^j	n/a	250,000 ^j
Fluoride	Demolition arisings	Non-hazardous	50 m	1,000 ^e		n/a	1,000
Chloride	Demolition arisings	Non-hazardous	50 m	250,000		36,900	250,000
PCB-101	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-118	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-138	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-153	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-180	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-28	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
PCB-52	Demolition arisings	Hazardous	0 m	0.001		n/a	0.001
>C8-C10 (aliphatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Non-hazardous	50 m		300 ^k	n/a	300
>C10-C12 (aliphatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Non-hazardous	50 m		300 ^k	n/a	300
>C12-C16 (aliphatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Non-hazardous	50 m		300 ^k	n/a	300

Contaminant	Component	Contaminant Classification	Complianc e Point Location Down Gradient of the SGHWR or Dragon reactor	Freshwater Annual Average EQS (μg/l) or Minimum Reporting Value (μg/l except for pH)ª	Drinking Water Standard (μg/l) where there is no EQS ^g	Mean Concentration in Background Groundwater Quality (µg/l except for pH) (NRS, 2024d)	Selected Compliance Limit Concentration (µg/l except for pH)
>C10-C12 (aromatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Hazardous	0 m	10 ¹		n/a	10
>C12-C16 (aromatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Hazardous	0 m	10		n/a	10
>C16-C21 (aromatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Hazardous	0 m	10		n/a	10
>C21-C35 (aromatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Hazardous	0 m	10		n/a	10
>C35-C44 (aromatic)	Oil-stained concrete (SGHWR Regions 1 and 2)	Hazardous	0 m	10		n/a	10

Note a) This column presents the minimum reporting value for hazardous substances and the freshwater environmental quality standard for non-hazardous pollutants.

Note b) The reason for selection of this value is explained in the text before this table.

Note c) Limit of quantification (UKTAG, 2017).

Note d) n/a means not available.

Note e) Value appropriate where there is less than 50 mg/l calcium carbonate.

Note f) Value appropriate where there is less than 40 mg/l calcium carbonate.

Note g) Selected preferentially from The Water Supply (Water Quality) Regulations 2016 SI2016/614 and then World Health Organisation, 2022.

Note h) The tabulated compliance limit for pH is for groundwater at the mire. Otherwise, the compliance limits are for the prescribed compliance points for hazardous substances and non-hazardous pollutants. The selected compliance limit does not include for attenuation between the compliance point and the receptor. It is appropriate for GQRA. The compliance limit for DQRA may include for attenuation between the compliance point and the receptor.

Note i) There is no drinking water standard for molybdenum. This is a health-based value cited by WHO (2022).

Note j) The compliance limit has been selected as the lowest of the EQS and drinking water standard in recognition of the Secondary A aquifer status.

Note k) CL:AIRE (2017) drinking water standards for aliphatic fractions from WHO (2008).

Note I) There is no MRV or LOQ for TPH-CWG aromatic fractions therefore the standard limit of detection reported from routine groundwater monitoring at Winfrith has been used. Note m) Modelling to support the Tier 2 and Tier 3 risk assessments has not taken into account background concentrations and the compliance limit is therefore based on the minimum reporting value or laboratory limit of quantification.

4 TIER 2 – GENERIC QUANTITATIVE RISK ASSESSMENT

This Section presents a GQRA for those components of the disposals/deposits for which a satisfactory risk could not be determined by Tier 1 qualitative risk screening. EA (2018) explains that a "generic quantitative risk assessment involves a relatively simple assessment of the impact your activity may have on water quality, including groundwater" and to carry it out "You must use conservative (worst case) assumptions".

The GQRA in this Section involves calculation of the concentrations of contaminants in water in the disposals/deposits and then comparison with generic assessment criteria. It seeks to meet the requirements of a GQRA set out in EA (2018) and "*demonstrate that the proposal poses little likelihood of unacceptable inputs to groundwater*".

4.1 GQRA OF BARYTES IN BARYTES CONCRETE

Barytes concrete was used in the construction of the SGHWR and Dragon reactor. The solubility of barytes (barium sulphate) is approximately 2 mg/l (NIOSH, 2007). The concentration of barium in a saturated solution of barytes is therefore approximately 1.2 mg/l. This is less than the compliance criterion (WHO drinking guideline value) for barium of 1.3 mg/l. Even if water became fully saturated with barytes, it would remain potable with respect to barium. The barytes in barytes concrete therefore poses little likelihood of unacceptable inputs to groundwater and requires no further tiers of risk assessment.

Dissolution of barytes allows sulphate into solution as well as barium. The concentration of sulphate in a saturated solution of barytes is approximately 0.8 mg/l. This is low compared with the background concentration in groundwater (around 20 mg/l according to NRS, 2024b) and the compliance limit concentration (Table 611/6). The sulphate in barytes concrete therefore poses little likelihood of unacceptable inputs to groundwater and requires no further tiers of risk assessment.

4.2 GQRA OF DEMOLITION ARISINGS

4.2.1 CALCULATION OF INORGANIC CONTAMINANT CONCENTRATIONS IN DEMOLITION ARISINGS POREWATER

Inorganic contaminants are progressively flushed by water from a granular material by the process of leaching. Leaching decreases the concentration of a contaminant in a material and also the concentration of the contaminant in the intergranular porewater. The greater the volume of water that has passed through a given mass of material, the greater is the material leached. The leaching of several (but not all) inorganic contaminants in an equilibrium-controlled system may be described as resulting in an initial or early peak concentration of the substance in the leachate followed by an exponential decrease of the concentration with time. The ratio of the volume of water that has leached a material to the mass of the material is referred to as the liquid to solid ratio (L/S). The evolution of leachate concentration through leaching is approximated mathematically as an exponentially decreasing function of L/S, using a contaminant-specific constant, kappa (κ).

$$C = C_0 e^{-\kappa L/S}$$

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Where:

- Co is the initial peak concentration of the contaminant in the leachate (mg/l);
- L/S is the accumulated liquid to solid ratio corresponding to the concentration C (l/kg). In a laboratory batch leaching test, such as carried out on samples of the D630 stockpile (Magnox, 2019), L/S is based on the total amount of water added to the solid;
- κ is a kinetic constant describing the rate of decrease of the concentration as a function of L/S for a given material and a given component (kg/l). κ may be estimated from laboratory leaching data and is for this purpose assumed independent of the L/S.

This description of leaching was used when setting emission limit values at L/S = 2 I/kg and L/S = 10 I/kg for acceptance of waste for landfilling in Council Decision 2003/33/EC referred to by Schedule 10 of EPR 2016. It is embedded in EA's risk assessment tool LandSim (EA, 2003), which is used to describe the change in concentration of leachate in landfill sites.

Assuming equilibrium-controlled leaching is conservative if, for instance, mass transfer limitations, such as slow intraparticle diffusion, prevail. This may occur if large clasts of concrete are included in otherwise finer-grained demolition arisings.

By integrating the above expression, the amount of the substance released per unit mass of material, E (in mg/kg), over the period of time it takes for L/S to increase from 0 l/kg to a specific value of the liquid to solid ratio, can be calculated:

$$E = \frac{C_0}{\kappa} \left[1 - e^{-(L/S)\kappa} \right]$$

Rearranging this equation provides a means of calculating the initial concentration, C₀:

$$C_0 = \frac{E \kappa}{[1 - e^{-(L/S)\kappa}]}$$

The amount (*E*) of several contaminants released at a liquid to solid ratio of 10 has been determined for the D630 stockpile using BS EN 12457-2. The laboratory results are in Magnox (2019).

The values of kappa used in developing waste acceptance criteria for inert landfills were the average values based on column leaching tests performed on construction materials taken from Aalbers et al (1996). They have been subsequently used elsewhere in Europe for modelling leaching of demolition arisings and developing end of waste criteria (e.g., Hjelmar, 2016) and are listed in Table 611/7.

4.2.2 COMPARISON OF POREWATER CONCENTRATIONS WITH COMPLIANCE CRITERIA

Table 611/7 tabulates contaminant kappa values and average emission concentrations. It also shows the calculated initial porewater concentrations and lists the compliance concentrations for comparison.

Contaminant	Kappa Value (kg/l)	UCL95 of Mean Emission (mg/kg) at L/S=10 I/kg (from Magnox, 2019) ^a	UCL95 of Mean Emission (mg/kg) at L/S=10 I/kg Accounting for Brick in Stockpile ^c	Initial Porewater Concentration (µg/l)	Compliance Concentration (µg/l) (Table 611/6)
Antimony	0.11	0.013	0.019	3.1	5
Arsenic	0.03	0.015	0.022	2.5	4
Barium	0.15	0.82	1.18	227	1300
Cadmium	0.50	0.0001	0.0001	0.07	0.08
Chloride	0.57	15	21	12,024	250,000
Chromium	0.18	0.15	0.22	47	4.7 / 1 ^b
Copper	0.28	0.043	0.061	18	12
Fluoride	0.22	1.9	2.8	685	1,000
Lead	0.27	0.0080	0.011	3.3	0.2
Mercury	0.05	0.00047	0.00067	0.08	0.01
Molybdenum	0.35	0.015	0.022	7.9	70
Nickel	0.29	0.013	0.018	5.7	14
Selenium	0.38	0.0033	0.0048	1.9	10
Sulphate	0.33	461	659	225,851	250,000
Zinc	0.28	0.13	0.18	54	33

 Table 611/7: Calculation of Porewater Concentration

Note a) Where the emission value was reported as less than the limit of detection, the average has been calculated using a value at half the limit of detection.

Note b) Values are for Cr (III) and for Cr (VI).

Note c) The degree to which each of the concrete and the brick proportions contribute to the inorganic contaminant concentrations reported for the D630 stockpile is uncertain. In using the D630 stockpile analysis to derive an inorganic contaminant assessment inventory for components of the End States other than stockpile material, account must be taken of the possibility that the inorganic contaminants are present predominantly within the stockpile concrete and not the brick. Because the arisings generated by demolition of the above ground parts of the SGHWR and Dragon reactor buildings will contain a higher proportion of concrete than the stockpile material, it is conservative to assume the brick does not contribute to the inorganic contaminant concentrations in the stockpile. The reported inorganic contaminants in the stockpile material have therefore been increased to account for the proportion of brick before they are used to represent the concentrations of inorganic contaminants in the demolition arisings generated in-situ. The proportion by mass of concrete in the Dragon reactor demolition material will be up to 43% higher than in the D630 stockpile whereas the concentrations of inorganic contaminants in demolition arisings from the SGHWR could be up to 24% higher (NRS, 2024e). The emissions shown here are for the Dragon reactor because they are higher than those that would be calculated for the SGHWR.

For completeness Table 611/7 includes arsenic and mercury that are judged to have concentrations in concrete at or below the background concentration in soils (Section 2.6) and that do not require risk assessment beyond Tier 1. The calculated initial porewater concentration of arsenic is less than the compliance concentration reinforcing the conclusion of the Tier 1 risk assessment that these substances do not require DQRA. The calculated initial porewater concentration of mercury is higher than the compliance concentration. Mercury was not detected in the solid phase of any of the analysed ten samples of the D630 stockpile (Magnox, 2019). The limit of detection was 1 mg/kg, much lower than the concentration of 40 mg/kg inorganic mercury deemed suitable for use in residential gardens with homegrown produce (Nathanail et al, 2015). Its concentration in demolition arisings is judged indifferent to background soils (Section 2.6). Mercury was not detected in the leachate of eight of the ten samples. Use of half of the laboratory limit of detection for mercury in leachate has led to the initial porewater concentration being calculated higher than the compliance concentration, but mercury is not considered to need DQRA.

The calculated initial porewater concentrations of chromium, copper, lead and zinc exceed the compliance concentrations for these metals. Chromium (as Cr(III) and Cr(VI)), copper, lead and zinc require DQRA. The calculated initial porewater concentrations of other inorganic substances are less than the compliance concentrations and there is therefore little likelihood of unacceptable inputs to groundwater. They do not therefore require a further tier of risk assessment to determine whether there is a satisfactory risk.

4.2.3 ALKALINITY IN DEMOLITION ARISINGS POREWATER

The pH of water in contact with newly generated demolition arisings is expected to exceed the freshwater EQS (between 6 and 9 for 95% of the time). Water alkalinity (high pH) associated with leaching of the demolition arisings therefore requires DQRA.

4.2.4 ORGANIC CONTAMINANT CONCENTRATIONS IN DEMOLITION ARISINGS POREWATER

Sampling and analysis indicates that the stockpiled demolition arisings contain PCB compounds. The solubility of the seven PCB compounds analysed in the D630 stockpile samples (Magnox, 2019) is shown in Table 611/8. Also shown is the calculated PCB concentration in porewater in equilibrium with the UCL95 of the mean concentration in stockpile samples.



Table 611/8: PCB Solubility and Calculation of Concentration in Porewater in Equilibrium with	Stockpile
Samples	

PCB Congeners	Solubility (µg/l) (World Health Organisation, 2003)	Log Koc (l/kg) (Panagopoulos et al, 2017)	UCL95 of Mean Concentration in Stockpile Samples (µg/kg) (Magnox, 2019) ^a	Concentration in Porewater in Equilibrium with UCL95 of Mean Concentration in Stockpile Samples (µg/I) ^b	Compliance Concentration (µg/l)
PCB-101	Not available	5.47	99	0.097	0.001
PCB-118	13.4	5.78	67	0.032	0.001
PCB-138	15.9	5.79	120	0.056	0.001
PCB-153	0.91	5.94	89	0.030	0.001
PCB-180	0.23	Not available	63	-	0.001
PCB-28	Not available	5.33	21	0.029	0.001
PCB-52	Not available	5.32	25	0.034	0.001

Note a) Where the concentration was reported as less than the limit of detection, the UCL95 of the mean has been calculated using a value at half the limit of detection.

Note b) The calculations use the average total organic carbon content of the samples of the D630 stockpile (Magnox, 2019) of 0.35% by mass.

The calculated concentrations are sufficiently low that there is unlikely to be solubility limitation on the partitioning of the compounds into water and the calculated concentrations exceed the compliance concentration. PCB compounds therefore require DQRA.

4.3 GQRA OF OIL STAINING OF THE SGHWR REGIONS 1 AND 2

Table 611/9 shows the solubilities of >C8-C16 aliphatic fractions and >C10-C44 aromatic fractions and compares them with their compliance concentrations. Further, it shows the calculated concentration of each hydrocarbon fraction were the entire inventory mass diluted in the volume of water that could accumulate in the SGHWR Regions 1 and 2 structure prior to leakage/outflow occurring. This volume of water will be no less than 2,000 m³ based on the geometry of Regions 1 and 2, and the void space in the blocks and broken demolition arisings.



Table 611/9: Hydrocarbon Solubility, Maximum Concentration in Regions 1 and 2 Water and Compl	iance
Concentrations	

Hydrocarbon Fraction	Solubility (µg/l) CL:AIRE (2017)	Calculated Inventory Mass (kg) NRS (2024e)	Maximum Concentration in Regions 1 and 2 Waterª (µg/l)	Compliance Concentration (µg/l)
>C8-C10 aliphatic	430	0.038	19	300
>C10-C12 aliphatic	34	0.059	29.5	300
>C12-C16 aliphatic	0.76	0.14	0.76	300
>C10-C12 aromatic	25000	0.6	300	10
>C12-C16 aromatic	5800	0.19	95	10
>C16-C21 aromatic	650	0.55	275	10
>C21-C35 aromatic	6.6	119	6.6	10
>C35-C44 aromatic	6.6 ^b	3.9	6.6	10

Note a) Inventory mass of contaminant (kg) dissolved in 2,000 m³ water.

Note b) Solubility not published in CL:AIRE (2017). Assumed to be no greater than that of the >C21-C35 aromatic fraction. Note c) Bold denotes concentrations that exceed the compliance concentration for the hydrocarbon fraction. Note d) Italics denote calculated concentrations that are solubility limited.

Table 611/9 demonstrates that, regardless of the water available mass, >C12-16 aliphatic compounds, >C21-C35 aromatic compounds and >C35-C44 aromatic compounds are insufficiently soluble in water to exceed their compliance concentrations. Further, the table demonstrates that, although not limited by solubility, the calculated maximum concentrations in water of the >C8-C10 and >C10-C12 aliphatic fractions are significantly below their compliance concentration. These fractions will not be considered further.

Table 611/9 shows the calculated maximum concentrations of >C10-C12, >C12-C16 and >C16-C21 aromatic hydrocarbon fractions exceed their compliance concentration. These simple calculations are insufficient to demonstrate an acceptable risk from these hydrocarbon fractions. Therefore >C10-C12, >C12-C16 and >C16-C21 aromatic hydrocarbon fractions require DQRA.

4.4 SUMMARY OF CONTAMINANTS REQUIRING DQRA

Table 611/10 summarises the contaminants requiring DQRA.

Table 611/10: Summary of Contaminants Requiring DQRA

Component in the SGHWR and Dragon Reactor	Contaminants		
Concrete blocks	Alkalinity (pH)		
Demolition arisings	Alkalinity (pH) Chromium (as Cr(III) and Cr (VI)), copper, lead and zind PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, PCE 153 and PCB-180		
Oil-stained concrete (SGHWR Regions 1 and 2 only)	TPH-CWG >C10-C12, >C12-C16 and >C16-C21 aromatic fractions		

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5 TIER 3 - DETAILED QUANTITATIVE RISK ASSESSMENT – IMPLEMENTATION

5.1 RISK ASSESSMENT TOOL (MODEL) SELECTION

5.1.1 ASSESSMENT OF DISSOLVED SPECIES OTHER THAN ALKALINITY – GOLDSIM

GoldSim has been used to model concentrations of substances other than alkalinity. GoldSim is a modelling platform for visualising and dynamically simulating complex systems. GoldSim is like a "visual spreadsheet" that allows the user to visually create and manipulate data and equations to simulate a system that changes with time. The user describes the equations and rules that control the system's behaviour, and GoldSim then simulates (predicts) the future behaviour of the system at each specified timestep.

GoldSim is considered an appropriate choice of software for this work given its capability in modelling time varying events and processes. The key features of GoldSim directly applicable to the modelling of the Winfrith end states include the capability to:

- Superimpose the occurrence and consequences of discrete events onto continuously varying systems;
- Build top-down models using hierarchical containers that facilitate the simulation of large, complex systems while keeping them easy to understand and navigate;
- Model first order decay of contaminants; and
- Dynamically link to spreadsheets.

GoldSim has been used routinely in the past to support Environment Agency projects, for example validation of LandSim v2.5 (EA, 2003) and development of Waste Acceptance Criteria for landfill.

GoldSim is used routinely in the nuclear industry for performance assessment and hydrogeological risk assessment and was initially developed to assess nuclear repository performance. The parallel radiological performance assessment of the Winfrith end states is implemented in GoldSim.

GoldSim version 14 has been used to construct the models used by this assessment.

5.1.2 ASSESSMENT OF ALKALINITY – PHAST

PHAST is a computer program developed by the U.S. Geological Survey. PHAST simulates multicomponent, reactive solute transport in three-dimensional saturated groundwater flow systems. PHAST uses an embedded version of PHREEQC for all geochemical thermodynamic calculations. PHREEQC is designed to perform a wide variety of aqueous geochemical calculations including speciation and saturation-index. It is therefore suited to the calculation of the effects on the pH of groundwater when alkaline leachates are discharged into the environment. A summary of the relevant capabilities of the PHAST code to modelling the Winfrith end states is set out as follows.

PHAST is applicable to the study of natural and contaminated groundwater systems at a variety of scales ranging from laboratory experiments to local and regional field scales. It is suited therefore to modelling alkalinity release from the Winfrith end states to groundwater and alkalinity attenuation in the Poole Formation saturated pathway over several 100s of metres.

- A variety of hydraulic boundary conditions are available in PHAST to simulate flow, including specified-head. It allows confined or, as is the case for the Poole Formation saturated pathway at Winfrith, unconfined groundwater conditions to be modelled.
- A variety of chemistry boundary conditions are available in PHAST enabling mixing of leachate with upgradient groundwater and downgradient mixing of groundwater with rainfall recharge to be modelled.
- It allows modelling of equilibria between the aqueous solution and minerals, ion exchange, and surface complexation.
- Its graphical capabilities allow model results to be conveyed to a wide audience of stakeholders.

PHREEQC is used routinely in the nuclear industry to simulate reactions in water and between water and geological materials. The thermodynamic database that has been used (ThermoChimie) was developed by Andra (the French national radioactive waste management agency) in 1995. It is now maintained by a consortium that includes Nuclear Waste Services. PHAST has been used to model contaminant migration from radioactive waste disposal sites in Europe and to support assessment of uranium release from the Low Level Waste Repository in the UK.

PHAST version 3 has been used to construct the models used by this assessment.

5.2 NUMERICAL IMPLEMENTATION OF THE CSM

The construction of the GoldSim model to assess the risk to groundwater from pollutants other than alkalinity is described in Appendix A. The construction of the PHAST model to assess the risk to groundwater from alkalinity is described in Appendix B.

There are two aspects to the GoldSim model:

- Hydraulics the flow of water into, within and out of the disposals; and
- Contaminant transport the movement of dissolved contaminants in water.

A forward modelling approach has been implemented in both models to calculate time variant concentrations of contaminants in groundwater downgradient of the disposals/deposits immediately following the End Point.

In GoldSim, the concentrations of contaminants released from the disposals have been calculated at a compliance point in groundwater immediately (0.1 m) downgradient of each reactor basement. Using the compliance point that is suitable for hazardous substances for both hazardous substances and non-hazardous pollutants is cautious because the compliance point for non-hazardous pollutants is 50 m downgradient of the source (Section 3.1.2). The model assumes contaminants are not present in upgradient groundwater.

PHAST allows concentrations to be calculated at any grid point within the model domain. The grid domain has been constructed with dimensions sufficient to calculate pH 50 m directly downgradient of each reactor basement (i.e., at the compliance point for non-hazardous pollutants) and at locations representative of receptors downgradient of each reactor basement (NRS, 2024e).

For the purposes of modelling the different hydraulic performances the geometry of the SGHWR End State in both the PHAST and GoldSim models has been subdivided into three distinct regions: the south annexe, the north annexe and Regions 1 and 2 as shown in Figure 611/3. No subdivision has been required to model the Dragon reactor End State.

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Figure 611/3: Modelled Regions of the SGHWR End State (South Annexe, Regions 1 and 2 and North Annexe)



The SGHWR and Dragon reactor End States, whilst in the same GoldSim model file, are numerically distinct. Whilst they share some common parameters (for example cap infiltration rate) there are no direct links or dependencies modelled between the End States. Cumulative impacts are not modelled.

The PHAST models for each End State are contained in distinct model files. Water flows from the disposals/deposits in the PHAST model are taken from the calculations carried out by the GoldSim model.

Modelling by its nature concerns simplification of reality. In carrying out GoldSim and PHAST modelling, simplification of aspects of the conceptual site model has been required to construct a numerical representation. In doing so model assumptions have been made. For example, the geometry of Regions 1 and 2 of the SGHWR is too complex to be faithfully reproduced in a model. Regions 1 and 2 have therefore been assumed to be a regular cuboid with dimensions proportioned so the plan area and void volume are correctly represented, and the model thereby accurately calculates the water level within the demolition arisings.

Where there is model uncertainty, for example about how the cap will degrade and therefore the modelled infiltration rate through the cap, cautious assumptions have been adopted. Where there is uncertainty about the value of a model parameter, the values have been cautiously defined.

Model assumptions are described more fully in Appendix A and Appendix B, including those required for the purpose of selecting values for parameters. However, several of the cautious simplifying assumptions are summarised here to illustrate the conservatism incorporated in the numerical implementation:

- The GoldSim modelling assumes instantaneous and immediate release of hydrocarbon compounds from oil staining and PCB congeners from demolition arisings into water. The oil stains are soaked into structural concrete and the PCB congeners are likely bound into extraneous constituents within the demolition arisings. In reality, the release of oil will be spread over a period of time as it diffuses from the concrete. Similarly, the release of PCBs will be delayed until the extraneous constituents within the demolition arisings start to degrade and then the release will be spread over the time for complete degradation to take place. Spreading the release of the oil and PCBs will lower the peak concentration in water in the disposals/deposits and thereby in downgradient groundwater.
- The PHAST modelling does not calculate leaching of alkalinity from the solid material and does not take account of the source depletion (leaching of portlandite) and carbonation of portlandite. Instead, it assumes the water in the demolition arisings is permanently saturated with portlandite and has a pH of approximately 12.5.
- The PHAST modelling makes a bounding assumption that the demolition arisings within the voids are composed entirely of broken demolition arisings, including in locations where concrete blocks (that can be expected to have significantly lower leachability) are to be emplaced.
- No transverse or vertical dispersion of contaminants in the groundwater pathway downgradient of the disposals/deposits is assumed in the GoldSim model and vertical dispersion is ignored by the PHAST model.
- The PHAST model does not couple flow and mineral dissolution and precipitation. Mineral
 precipitation at the interface of the concrete structures and Poole Formation may restrict leakage
 from the disposals/deposits.
- The PHAST model does not allow for alteration of minerals exposed to high pH values close the disposals/deposits. The modelled extent of raised pH downgradient is thereby overestimated.
- No account is taken in either model of the attenuation of contaminants in the unsaturated zone likely to be regularly present beneath the SGHWR south annexe and the Dragon reactor.

5.3 SELECTION OF MODEL SIMULATION SCENARIOS

5.3.1 REFERENCE SCENARIO

The reference scenario is a cautious representation of the evolution of the system (see Section 5.2) and its parameterisation. Parameters and their values for the reference scenario are set out in Appendix A and Appendix B.

5.3.2 ALTERNATIVE AND VARIANT SCENARIOS FOR SENSITIVITY ANALYSIS

Uncertainties with respect to the description of the evolution of the End States (and their surrounds) and their parametrisation were captured in NRS (2024e). These uncertainties can be categorised as:

- Conceptual uncertainties including uncertainty in how the disposals/deposits and their environment will evolve;
- Uncertainties in how a feature, event or process should be modelled, i.e., model uncertainty; and
- Uncertainties in the parameter values that should be chosen, i.e., parameter uncertainty.

A cautious approach to these uncertainties has been adopted by the reference scenario. In addition, an understanding of the extent to which conceptual, model and parameter uncertainties affect the modelled outcome of the reference scenario has been established by way of sensitivity analysis. The variant scenarios defined to assess model uncertainty are described in Table 611/11 and the alternative scenario defined to assess sensitivity to conceptual uncertainty is described in Table 611/12. Required changes to the reference scenario model (including parameterisation) to support the alternative and variant scenarios is described in Appendix A and Appendix B.

Uncertainty	Reference scenario	Variant scenario to support sensitivity analysis
Evolution of the effective hydraulic conductivity of the concrete structures	Model with a cautious estimate of the rate of concrete degradation of the SGHWR Regions 1 and 2 compared to the reference scenario as described in NRS (2024e).	Two variant scenarios: Model with faster early time rate of concrete degradation of the SGHWR Regions 1 and 2 structure compared to the reference scenario as described in NRS (2024e). Model with slower early time rate of concrete degradation of SGHWR Regions 1 and 2 structure compared to the reference scenario as described in NRS (2024e).
Evolution of the rate of infiltration to the cap	Model with a cautious estimate of the rate of degradation of the caps over the SGHWR and Dragon reactor End States as described in NRS (2024e).	Model with faster rate of cap degradation compared to the reference scenario as described in NRS (2024e).
Frequency and extent of groundwater inundation to the SGHWR south annexe and to the Dragon reactor basement	Groundwater rises above the SGHWR south annexe and Dragon reactor base to a level and with a frequency consistent with that of a cautious central estimate of future recharge calculated assuming a scenario of medium future global atmospheric emissions.	Groundwater rises above the SGHWR south annexe and Dragon reactor base to a level and with a frequency consistent with that of a 'reasonable worst case' of future recharge calculated assuming a scenario of medium future global atmospheric emissions.
Volumetric porosity of the demolition arisings ¹¹	30% v/v, which is based on the void space between packed spherical particles.	22% v/v, which is based on an assumed bulking factor of the demolition arisings of 1.22.

Table 611/11	Variant Scenarios	selected to :	assess sensitivitv t	to model uncertainty
			abbeed sensitivity	to model uncertainty

¹¹ Strictly, this is a parameter uncertainty, but it is included here because, like the other listed aspects of model uncertainty, it potentially affects the rate of water level change in the demolition arisings.



Table 611/12: Alternative Scenario se	elected to assess sensitivity	to conceptual uncertainty
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Uncertainty	Reference Scenario	Alternative scenario to support sensitivity analysis
Frequency and extent of groundwater inundation to the SGHWR south annexe and to the Dragon reactor basement under the worst possible conditions of climate change.	Groundwater rises above the SGHWR south annexe and Dragon reactor base to a level and with a frequency consistent with that of a cautious central estimate of future recharge calculated assuming a scenario of medium future global atmospheric emissions.	Assume an alternative scenario in which groundwater rises above (and subsequently falls below) the SGHWR south annexe and Dragon reactor base to the maximum modelled water level every year.

5.3.3 ASSESSMENT OF PARAMETER VALUE UNCERTAINTY

The risk posed by each group of contaminants (metals, PCBs, hydrocarbon fractions and alkalinity) is mitigated by different attenuation factors and processes. Table 611/13 lists these.

Component and contaminants in the SGHWR and Dragon Reactor	Risk Mitigating Factors and Attenuation Processes
Demolition arisings: PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, PCB-153 and PCB-180	 Inventory mass. Partition with the demolition arisings. Dilution. Partition with the unsaturated and saturated Poole Formation. Biodegradation in the unsaturated and saturated Poole Formation.
Demolition arisings: Chromium (as Cr (III) and Cr (VI)), copper, lead and zinc	 Inventory mass. Partition with the demolition arisings. Dilution. Partition with the unsaturated and saturated Poole Formation.
Oil stains (SGHWR only): >C10-C12, >C12-C16 and >C16-C21 aromatic hydrocarbon fractions	 Inventory mass. Dilution. Partition with the unsaturated and saturated Poole Formation.
Demolition arisings: alkalinity	 Dilution and reaction of leachate with upgradient groundwater; Dilution and reaction of groundwater with rainfall recharge in the downgradient saturated pathway; Adsorption and desorption (surface complexation) of alkalinity to minerals in the downgradient saturated pathway; Mineral precipitation; and Cation exchange.

 Table 611/13: Summary of mitigating factors and attenuation processes in the reference scenario

Sensitivity analysis has focussed on the model parameters that are used to represent these attenuation factors and processes.

The reference case uses metal partition coefficients taken from the conservative end of a published range. Less conservative values (ten times higher) could have reasonably been selected from the range. The results of models with these higher values would show the risk is even lower. Modelling of sensitivity to the magnitude of metal partition coefficients has therefore not been carried out.

Partition of organic compounds (PCBs and hydrocarbon fractions) depends on the assumed fraction of organic carbon. The reference case uses the lower 95% confidence on the mean of the measured values of the fraction of organic carbon in the demolition arisings and in the Poole Formation. There is confidence the selected values are sufficiently cautious and modelling of the sensitivity to the assumed fraction of organic carbon has therefore not been carried out.

Dilution is the ratio of groundwater flow to leakage. Groundwater flow is well understood, and the rate is constrained because the groundwater catchment area upgradient of both reactors is small and well defined. Sensitivity to dilution is explored with the variant case that assumes more leakage from the south annexe and Dragon reactor because of the effects of future climate change (Section 5.3.2).

Pessimistic biodegradation rates for PCBs in the Poole Formation have been derived from literature and are used in the reference scenario model. Sensitivity to selection of PCB biodegradation values has been assessed by assuming no biodegradation of PCBs in the Poole Formation. No PCB breakdown over centuries or millennia is not credible but making such an assumption allows a bounding assessment to be made.

The assessed inventory mass of hydrocarbon compounds used in the reference scenario has been calculated using cautious assumptions about the mass concentration and depth of oil penetration into the structure and it is more than ten times the mass estimate in NRS (2024a) made using average mass concentrations and the observed depth of oil penetration. The assessment does not account for the cleaning of the SGHWR structure as part of End State preparations, that will seek to remove the staining and therefore substantially reduce the inventory mass. There is therefore confidence the inventory mass of hydrocarbon compounds used by the reference scenario is sufficiently cautious and modelling of the sensitivity to a higher mass is unnecessary and has not been carried out.

A scenario has been assessed in which the reference case mass of PCBs and metals in the demolition arisings placed in both End States is doubled. This is highly cautious because the chemical composition of the stockpiles has been characterised by sampling and analysis and is a greater increase in inventory than can be achieved by decreasing the volumetric porosity of the demolition arisings (by decreasing the bulking factor).

In assessing the effects of groundwater and recharge chemistry on alkalinity attenuation and the effects of Poole Formation composition on sorption, the SGHWR reference scenario model has been used as it is assumed it will provide a bounding sensitivity analysis of the same parameters in the Dragon reactor model. The model assumption of instantaneous equilibrium between solutes and mineral phases is cautious and there is therefore no need to test the model sensitivity to mineral precipitation.

The model of the SGHWR reference scenario uses for upgradient groundwater and recharge chemistry monitored groundwater sampled from an upgradient borehole with the highest pH (5.75) and alkalinity. This is expected to be cautious. Nevertheless, a variant scenario has been modelled using the chemistry of a groundwater sample, taken from the same upgradient borehole, with the lowest pH (5.05) and alkalinity to assess the sensitivity of modelled downgradient pH to assumed upgradient groundwater and recharge chemistry.

Sensitivity of modelled alkalinity in groundwater to assumed adsorption and desorption has been assessed using the minimum measured gibbsite and ferrihydrite concentrations in samples of the Poole Formation. Similarly, the sensitivity of modelled alkalinity in groundwater to the assumed cation exchange capacity of the Poole Formation has been assessed by a variant scenario that assumes there is no CEC in the downgradient groundwater pathway.

5.4 SELECTION OF THE DURATION OF MODEL SIMULATION

The modelled cap degradation and the modelled degradation of the concrete structures is complete after 1,000 years and the modelled water flows become invariant shortly thereafter. The GoldSim model has been run for 20,000 years from the End Point with contaminant transport results reported on an annual timestep. The run time of 20,000 years allows for the peak concentration of each contaminant to be realised at the model compliance point as demonstrated by the model results presented in Section 6. A 20,000-year simulation time is also used by LandSim (EA, 2003), the EA software developed for the purpose of assessing non-radiological risks from solid waste disposals.

The PHAST model has been run until the modelled pH in groundwater downgradient of the End States has increased and become steady. Because the model is run with a time invariant leachate chemistry, it is not numerically possible for groundwater pH to fall after it reaches peak pH.

5.5 SELECTION OF MODEL SETTINGS

Both the PHAST and GoldSim models have been run deterministically, i.e., parameters are assigned a single value and single value, non-stochastic, outputs are returned from the model calculations. Uncertainty in the assessment has been considered by way of sensitivity analysis.

6 TIER 3 – DETAILED QUANTITATIVE RISK ASSESSMENT – RESULTS

This Section summarises the results of the DQRA. GoldSim and PHAST model results for all modelled scenarios are provided in Appendix A and Appendix B, respectively.

6.1 **RESULTS FOR THE REFERENCE SCENARIO**

Results of the GoldSim modelling for the reference scenario are summarised in Table 611/14 and Table 611/15 for the SGHWR and Dragon reactor End States, respectively. The last column in each table shows the ratio of the compliance limit for each parameter to its modelled peak concentration and is therefore a measure of the factor of safety.

Results of the PHAST modelling for the reference scenario are summarised in Figure 611/4 and Figure 611/5 for the SGHWR and Dragon reactor End States, respectively.

 Table 611/14: Modelled peak concentrations of contaminants other than alkalinity in groundwater at the compliance point for the SGHWR in the reference scenario

Parameter	Peak Concentration (mg/l)	Time of Peak (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
PCB-28	2.9E-08	1435	1.0E-06	34.8
PCB-52	4.2E-08	1429	1.0E-06	23.6
PCB-101	3.4E-08	1527	1.0E-06	29.2
PCB-118	1.7E-09	1934	1.0E-06	602
PCB-138	2.6E-09	1961	1.0E-06	391
PCB-153	4.1E-10	2499	1.0E-06	2445
PCB-180	6.5E-12	4607	1.0E-06	154335
Chromium(III)	5.1E-04	996	4.7E-03	9.3
Chromium(VI)	5.1E-04	996	1.0E-03	2.0
Copper	3.0E-06	11778	1.2E-02	4045
Lead	1.5E-06	8598	2.0E-04	135
Zinc	1.0E-05	6453	2.7E-02	2599
>C10-C12 Aromatics	6.1E-05	761	1.0E-02	163
>C12-C16 Aromatics	1.4E-05	1003	1.0E-02	717
>C16-C21 Aromatics	1.8E-05	1029	1.0E-02	557

Table 611/15: Modelled peak concentration of contaminants other than alkalinity in groundwater at the Dragon reactor compliance point for the reference scenario

Parameter	Peak Concentration (mg/l)	Time of Peak (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
PCB-28	4.8E-08	1204	1.0E-06	20.9
PCB-52	6.9E-08	1201	1.0E-06	14.5
PCB-101	8.9E-08	1251	1.0E-06	11.3
PCB-118	1.7E-08	1355	1.0E-06	60.4
PCB-138	2.7E-08	1358	1.0E-06	37.2
PCB-153	1.1E-08	1409	1.0E-06	92.3
PCB-180	2.2E-09	1608	1.0E-06	448
Chromium(III)	2.2E-04	589	4.7E-03	21
Chromium(VI)	2.2E-04	589	1.0E-03	4.5
Copper	6.5E-07	1092	1.2E-02	18501
Lead	4.2E-07	3569	2.0E-04	471
Zinc	1.9E-06	1037	2.7E-02	13869

Figure 611/4: Modelled groundwater pH downgradient of the SGHWR disposals for the reference scenario

	11.0 9.69 8.38 7.06 5.75
 50m Downgradient pH: 9.33 100m Downgradient pH: 8.73 500m Downgradient pH: 6.35 	

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Figure 611/5: Modelled groundwater pH downgradient of the Dragon disposals for the reference scenario

	6.00 5.90 5.80 5.70 5.60
 50m Downgradient pH: 5.70 100m Downgradient pH: 5.68 500m Downgradient pH: 5.65 	

The model results demonstrate that concentrations in groundwater of all modelled contaminants in either End State are well below compliance criteria¹².

Of the modelled metals, the peak concentration of chromium (VI) in groundwater downgradient of the SGHWR is calculated to be closest to its compliance limit. Despite cautiously assuming all the leachable chromium inventory is instantly water available and that all the chromium in the arisings is chromium (VI), the calculated peak concentration in groundwater immediately downgradient of the SGHWR is approximately half of the compliance limit. The results also demonstrate that chromium is so heavily retarded that it will take approximately 1,000 years for the peak concentration in groundwater immediately downgradient of the disposals/deposits to occur.

With respect to the modelled hydrocarbon fractions associated with oil staining in the SGHWR Regions 1 and 2, the highest peak concentration calculated in groundwater at the compliance point is for the >C10-C12 aromatic fraction. No biodegradation is assumed, and no account is made of the dispersed breakthrough likely to be caused by the slow release of the hydrocarbon mixture from the concrete structure. Regardless of this, the modelled peak concentration of the >C10-C12 aromatic fraction is 163 times less than the compliance limit. The peak concentration is calculated to take over 750 years to become manifest at the compliance point, emphasising the degree of caution attached to assuming hydrocarbon compounds do not biodegrade¹³.

¹² Compliance criteria in the context of this assessment are the compliance limits at the relevant hazardous substance or non-hazardous pollutant compliance points as set out in Section 3.2.

¹³ Even biodegradation half-lives of several decades would reduce concentrations by orders of magnitude given the long travel times.

PCB-52 downgradient of the SGHWR has the highest modelled peak concentration in groundwater of all modelled PCBs. Despite being bound in solid material within the deposited arisings the entire PCB inventory mass is assumed to be instantly water available. Regardless of this, the calculated peak concentration of PCB-52 is 24 times less than the 1E-6 mg/l compliance limit immediately downgradient of the SGHWR. The PCB compounds are so heavily retarded that it is calculated to take at least 1,400 years for the peak concentration of any PCB migrating through groundwater to be observed at the compliance point. For PCB-180, the concentration is calculated to peak after 4,600 years at the compliance point immediately downgradient of the SGHWR. Despite these timescales, extending over several millennia, no loss of PCBs to the atmosphere by volatilisation (the oft cause of PCB reduction in soils, e.g. EA, 2007) has been assumed as part of the modelling.

With respect to alkalinity released from the SGHWR and Dragon reactor End States, the PHAST modelling results demonstrate that the maximum pH in the groundwater pathway is significantly lower than the compliance criterion¹⁴. This is despite the modelling assuming a source of alkalinity that does not deplete throughout the lifetime of the simulation. Further, the modelling takes no account of unsaturated zone attenuation, and it assumes the more readily leachable broken demolition arisings fill the voids even in the locations below the water table where less leachable blocks could be placed.

Interpretation of the model shows that mixing and dilution of high pH leachate with groundwater that has flowed from upgradient of the disposals/deposits and with recharge of rainfall downgradient of the disposals/deposits results in calcite supersaturation. The consequent calcite precipitation is the principal process that attenuates alkalinity in the leachate close to the disposals/deposits. Dilution by recharge of rainfall downgradient of the disposals/deposits is important for progressive reduction in groundwater pH with distance downgradient.

Groundwater flow modelling shows that in some circumstances, groundwater can flow from the SGHWR End State and pass beneath the Dragon reactor End State. A variant of the reference scenario has been modelled in PHAST to assess the effect of cumulative impacts from alkalinity release. The variant model assumes that the modelled reference scenario steady state groundwater chemistry 500 m downgradient of the SGHWR is the upgradient boundary condition groundwater quality for a model of the Dragon reactor. This is a highly cautious bounding assumption because the maximum modelled pH in groundwater of the SGHWR reference scenario occurs after 3,180 years, but for the purpose of this variant model it is assumed to occur upgradient of the Dragon reactor at the onset of the simulation. The variant model also cautiously assumes all the groundwater from beneath the SGHWR End State passes beneath the Dragon End State. The calculated maximum pH in the groundwater pathway 500 m downgradient of the Dragon reactor (a pH value of 6.46) is above the background groundwater pH, but despite the highly pessimistic

¹⁴ The selected compliance point for pH is 50 m downgradient of the disposals. The environmental standard at the nearest downgradient groundwater receptor is 7 pH units. A compliance point has been established between the disposals/deposits and the receptor. EA guidance (EA, 2017a) allows for the compliance limit at the compliance point to the higher than the environmental standard to take account of attenuation between the compliance point and the receptor. The closest groundwater receptor to the SGHWR is the wet heath/acid mire habitat established in emergent groundwater approximately 500 m down gradient of the End State. The closest groundwater receptor to the Dragon reactor is the River Frome and its environs, 900 m downgradient. The modelled pH is well below 7 at 500 m and therefore, by extension, the modelled pH at the 50 m compliance point is acceptable.

assumptions including with the effects of source depletion being disregarded, it remains lower than the compliance criterion.

The results of the reference scenario have demonstrated that the modelled concentrations of metals, hydrocarbon compounds and PCBs in groundwater immediately downgradient of the SGHWR are so far below compliance limits that no further modelling is considered necessary for it to be concluded that cumulative impacts from both End States will not cause these substances to exceed compliance criteria in groundwater.

6.2 RESULTS OF SENSITIVITY ANALYSES IN GOLDSIM AND PHAST

6.2.1 RESULTS OF THE ASSESSMENT OF MODEL UNCERTAINTY

Model uncertainty has been addressed by assessing the model sensitivity to pessimistic variant scenarios of cap infiltration rate, concrete degradation and climate change.

Assuming a cap which degrades more quickly than that of the reference scenario is pessimistic because more water is allowed into the disposals/deposits increasing contaminant leaching and the flow of water to the saturated zone. Model results demonstrate for both End States that the concentrations of all contaminants in groundwater are well below compliance criteria even when assuming a cap that degrades twice as quickly as in the reference scenario. Furthermore, other than for the most mobile hydrocarbon fraction, the modelled contaminant concentrations in groundwater vary little from those of the reference scenario model.

The effects of assuming a faster or slower rate of concrete degradation in Regions 1 and 2 of the SGHWR than the cautious representation of concrete degradation by the reference scenario have been assessed using variant models. The modelled contaminant peak concentrations at the compliance point for the two variants are invariant from the reference scenario because peak concentrations occur once the concrete is completely degraded. There is no increased risk to groundwater with faster or slower concrete degradation and confidence that the modelled risk associated with the cautious estimate of concrete degradation rate in the reference scenario is robustly determined.

If rainfall recharge is higher than assumed by the reference scenario, groundwater levels could be higher and inundation of the SGHWR south annexe and the Dragon reactor basement could be increased causing a higher rate of leaching of demolition arisings and outflow of contaminants to the water table. A variant model assuming a 'reasonable worst case' of higher climate driven recharge has been assessed. Despite a cautious and pessimistic approach being taken to the effects of climate change, peak modelled concentrations of all contaminants are less than compliance criteria and vary little from the reference scenario.

Reducing the assumed volumetric porosity of the demolition arisings causes modelled water levels to rise more quickly than for the reference scenario, but the highest modelled water levels are little different to those of the reference scenario and do not overtop the structures of Regions 1 and 2 of the SGHWR.

In summary, when areas of model uncertainty are addressed by assessment of demonstrably conservative variant models, the model results indicate there is little or no increased risk to groundwater. This provides confidence that the findings of the reference scenario, which adopts cautious assumptions for the aspects of the model that are uncertain, are robust.

6.2.2 RESULTS OF THE ASSESSMENT OF CONCEPTUAL UNCERTAINTY - ALTERNATIVE CONCEPT OF CLIMATE CHANGE

Conceptual uncertainty has been addressed through consideration of an alternative scenario in which groundwater rises above (and subsequently falls below) the SGHWR south annexe and Dragon reactor base to the maximum modelled water level every year. Under these conditions, groundwater inundates the SGHWR south annexe and the Dragon reactor basement every year. Even under this highly pessimistic assumption about groundwater inundation to the SGHWR south annexe and to the Dragon reactor basement, concentrations of all modelled contaminants were well below compliance criteria. This alternative model provides confidence that the even though the effect of climate change on rainfall recharge is uncertain, the risk to groundwater quality from non-radiological contaminants is acceptable.

6.2.3 RESULTS OF THE ASSESSMENT OF PARAMETER VALUE UNCERTAINTY

Sensitivity to selection of PCB biodegradation values has been assessed by assuming no biodegradation of PCBs in the Poole Formation. No PCB breakdown over centuries or millennia is not credible but making such an assumption allows a bounding assessment to be made. With this assumption, the peak concentrations of all but one PCB congener (PCB-101) are lower than the compliance criterion with the peak PCB-101 concentration becoming manifest after over 3,600 years and remaining close to the compliance criterion. The model remains conservative because the entire mass of PCBs is assumed to be immediately water available and, despite the extended travel timescales, no account is made for the volatility of PCBs. The risk from PCBs to groundwater is therefore considered acceptable regardless of the value of PCB biodegradation rate.

A scenario has been assessed in which the reference case mass of PCBs and metals in the demolition arisings placed in both End States is doubled. Despite the assumed higher inventory, the modelled peak concentrations of metals and PCBs remain below compliance criteria. This provides confidence that the risk associated with slight variations in the demolition arisings bulking factor; and/or concentrations of metals and PCBs in the demolition arisings derived from the D630 stockpile or from the reactor structures, would be acceptable.

In assessing the effects of groundwater and recharge chemistry on alkalinity attenuation, a variant scenario of the SGHWR has been modelled using the chemistry of a groundwater sample with the lowest pH and alkalinity taken from the same upgradient borehole from which the chemistry of groundwater in the reference scenario has been derived. In the variant scenario, the modelled peak pH in groundwater downgradient of the SGHWR End State (pH value of 5.58, compared to a pH value of 6.35 in the reference scenario) remains well below the compliance criterion. For the range of monitored upgradient pH and alkalinity, the modelling demonstrates that the reference scenario is cautious and, whilst mixing and dilution with upgradient groundwater and recharge water is an important attenuation process, that modelled downgradient pH is insensitive to the monitored variation in upgradient groundwater and recharge chemistry. Modelling using the other end of the range of monitored groundwater pH and alkalinity to that used by the reference scenario, as well as the well understood rates of groundwater flow and recharge of rainfall, provides confidence in the results of the reference scenario.

۱۱SD

Sensitivity of modelled alkalinity in groundwater to assumed adsorption and desorption has been assessed using the minimum measured gibbsite and ferrihydrite concentrations in samples of the Poole Formation. The modelled peak pH in groundwater downgradient of the SGHWR End State (pH of 6.35) again remains below the compliance criterion and shows the modelled results are insensitive to the assumed gibbsite and ferrihydrite concentrations and thereby the process of mineral adsorption and desorption. Similarly, the model sensitivity to the assumed cation exchange capacity has been assessed by assuming there is no cation exchange in the downgradient groundwater. The modelled peak pH in groundwater downgradient of the SGHWR End State is invariant from the reference case and shows that the modelled groundwater pH downgradient of the SGHWR is not sensitive to the process of cation exchange capacity in the Poole Formation.

7

CONCLUSIONS OF THE HYDROGEOLOGICAL RISK ASSESSMENT

EA hydrogeological risk assessment guidance encourages a tiered approach to risk assessment with more detailed assessment being undertaken where the risk of groundwater pollution is greater. Conclusions of the tier 1 (Section 7.1), tier 2 (Section 7.2) and tier 3 (Section 7.3) risk assessments follow.

7.1 TIER 1

Tier 1 qualitative risk screening has been carried out on the components of the End States of the SGHWR and Dragon reactor.

Concrete is commonplace in the UK below the water table in the form of pipes, tunnel linings, building foundations and potable water tanks. Such features are routinely left in-situ on industrial sites in perpetuity and are not known as commonly having a detrimental effect on groundwater quality. Concrete structures left in-situ below the water table are therefore rarely, if ever, subject to hydrogeological risk assessment. There is no evidence from many years of routine groundwater monitoring that the SGHWR structure is affecting groundwater quality.

The surface area to volume ratio of the Dragon reactor mortuary holes concrete monolith is less than that of structural concrete. Leaching from the concrete monolith is therefore likely to be even less than that from structural concrete.

Structural steel and rebar corrode at low rates releasing iron that can be expected to precipitate either in the unsaturated zone and/or in groundwater that has been shown by routine monitoring to be oxygenated. There are marine and onshore analogues for disposing of metals associated with civil engineering structures such as concrete gravity oil platforms in the North Sea because significant contamination of the marine environment is not expected; and pilings and foundations for buildings as well as tunnels and bunkers containing steel elements abandoned without the materials presenting a significant hazard to groundwater.

Paint has been used to protect structural steel from corrosion and on surfaces such as floors, where water resistance is required. Similarly, fibreglass in the fuel ponds was primarily applied to provide containment of the water used for storage of the nuclear fuel. Paint and fibreglass are inherently not leachable.

The potential discharge from the following components of the End States were identified as acceptable and these components need no further tiers of risk assessment:

- Contaminants bound within concrete in reinforced concrete structures, concrete blocks and the Dragon reactor mortuary holes monolith, with the exception of the hydroxide ion (that can generate high pH in water) leached from concrete blocks;
- Structural steel and rebar in concrete structures and blocks;
- Paint;
- Fibreglass;
- The following components of oil staining of structures: <C10 aromatic compounds (including BTEX), >C16 aliphatic compounds and all 16 analysed PAH species;



- Arsenic and mercury in demolition arisings; and
- Emplaced non-waste materials that will be used to implement the End State of the Dragon reactor mortuary holes as well as to prepare the structures for the disposals/deposits.

7.2 COMPLIANCE POINTS AND COMPLIANCE LIMITS

Compliance points have been identified with reference to EA guidance as follows:

- The compliance point for hazardous substances has been established firstly in the discharge (i.e., water that will accumulate within the disposals/deposits) and then below the water table in the Poole Formation immediately downgradient of the disposals/deposits.
- The compliance point for non-hazardous pollutants has been established 50 m from the downgradient boundary of the SGHWR and Dragon reactor.

Compliance limits have been identified for contaminants associated with the components of the End States requiring Tier 2 GQRA and Tier 3 DQRA.

7.3 TIER 2

Where it can be carried out with confidence, porewater concentrations of contaminants in the demolition arisings have been calculated and compared with the compliance criteria as a Tier 2 GQRA.

The calculated porewater concentration of the following contaminants is lower than the selected compliance criteria: antimony, barium, cadmium, chloride, fluoride, molybdenum, nickel, selenium and sulphate. There is little likelihood of unacceptable inputs to groundwater from these contaminants and these contaminants need no further risk assessment.

Preliminary risk assessment and GQRA has not demonstrated acceptable hydrogeological risk associated with the other contaminants associated with components shown in Table 611/10 and these have been included in a Tier 3 DQRA.

7.4 TIER 3

DQRA of the SGHWR and Dragon reactor End States has been supported by numerical modelling using PHAST for alkalinity and GoldSim for substances other than alkalinity.

A reference scenario model has been constructed that is a cautious estimate of the projected evolution of the End States. Parameter values have been based on site specific data where possible. Cautious parameter values have been adopted where there is uncertainty. Whilst this is a best practice approach to build confidence risks are low, it is important that this is considered if the results are used in the future to inform further optimisation decisions as cautious assumptions can lead to 'overengineering'.

Modelling of the reference scenario has demonstrated the risk for all modelled contaminants is acceptable.

Assessment of cumulative effects has been undertaken because groundwater flow modelling has shown that, under some circumstances, groundwater flows from the SGHWR End State to beneath the Dragon reactor End State. The Tier 3 assessment has concluded that cumulative impacts will not cause an unacceptable risk to groundwater.

Conceptual (which includes uncertainty in how the disposals/deposits and their environment will evolve), model and parameter uncertainty has been addressed by sensitivity analysis. The sensitivity analysis has been based on assumptions more pessimistic than those cautiously adopted in the reference scenario. The model results of the selected variant and alternative scenarios have demonstrated, for all modelled contaminants, an acceptable risk to groundwater, thereby providing confidence the outcomes of the reference scenario are robust.

Interpretation of the PHAST model shows that mixing and dilution of high pH leachate with groundwater that has flowed from upgradient of the disposals/deposits and with recharge of rainfall downgradient of the disposals/deposits results in calcite supersaturation. The consequent calcite precipitation is the principal process that attenuates alkalinity in the leachate close to the disposals/deposits. Dilution by recharge of rainfall downgradient of the disposals/deposits is important for progressive reduction in groundwater pH with distance downgradient.

An acid mire is the principal groundwater receptor downgradient of the SGHWR. Factors such as the decommissioning of the drainage network and climate change will also affect the mire. Atkins (2024) conclude, "Should the M16 wet heath be resilient to decommissioning of the drainage network and climate change then it is highly likely that it will be resilient to a relatively modest further increase in groundwater pH arising from the SGHWR disposal." The modelled pH change in groundwater at the mire downgradient of the SGHWR is modest.

Based on the three tiers of risk assessment it is concluded that the non-radiological hydrogeological risk from the envisaged SGHWR and Dragon reactor End States is acceptable.

8 UNCERTAINTIES

Magnox (2023) demonstrates how NRS meets the GRR requirements for uncertainty management. Uncertainty is defined in the GRR glossary as a "*Lack of certainty*. A state of limited knowledge that precludes an exact or complete description of past, present or future."

Magnox (2023) explains that the potential significance of uncertainties, assumptions and gaps should be rated as Low, Medium or High defined as follows:

- Low:
 - If the uncertainty is not reduced, additional practical mitigation measure(s) is/are unlikely to be necessary in the near term¹⁵; and/or
 - The magnitude of uncertainty is currently such that robust demonstration of environmental safety (including optimisation) over the site life-cycle will be straightforward.
- Medium:
 - If the uncertainty is not reduced, additional practical mitigation measure(s)¹⁶ might be necessary in the near term; and/or
 - The magnitude of uncertainty is currently such that robust demonstration of environmental safety (including optimisation) over the site life-cycle could be somewhat difficult.
- High:
 - If the uncertainty is not reduced, additional practical mitigation measure(s) is/are certain or very likely to be necessary in the near term; and/or
 - The magnitude of uncertainty is currently such that robust demonstration of environmental safety (including optimisation) over the site life-cycle is likely to be impossible or very difficult.

Table 611/16 outlines the uncertainties inherent in the risk assessment.

¹⁵ In this context, "the near term" covers the timescale for any Radioactive Substances Regulation (RSR) permit variation application for onsite disposal under the GRR that is in progress or planned in the next decade, as well as the timescale for demonstrating that a satisfactory SWESC is in place where no such application is planned.

¹⁶ In this context, "additional practical mitigation measure(s) … necessary in the near term" could include measure(s) required (if the uncertainty cannot be reduced) in order to: comply with extant RSR permit conditions (including conditions on implementing any permitted on-site disposals); make a successful RSR permit variation application; and/or be able to demonstrate a satisfactory SWESC. Such measures are "additional" in the sense that they would be over and above mitigation measure(s) needed regardless of the magnitude of uncertainty.

Table 611/16: Hydrogeological Risk Assessment Uncertainties

Contractor Reference Number	Feature, Event or Process Subject to Uncertainty	Description of Uncertainty	Treatment of Uncertainty / Statement of Assumption	Rating of Potential Significan
HRA-1	Conceptual uncertainty	The effect that climate change will have on the frequency and level of inundation to the disposals/deposits. This is described in NRS (2024e).	An alternative scenario has been developed in which groundwater inundates the SGHWR south annexe and Dragon reactor basement every year and is described in Section 6.2.2. The model results of the alternative scenario demonstrate an acceptable risk to groundwater.	Low
HRA-2	Model uncertainty	 Uncertainty in how a feature, event or process should be numerically implemented within the HRA. Specific model uncertainties are how to implement: The effect on infiltration to the disposals/deposits of cap degradation; The effect on the effective hydraulic conductivity of the structures of Regions 1 and 2 of the SGHWR of concrete degradation; and The effect of climate change on groundwater inundation of the SGHWR south annexe and Dragon reactor. These uncertainties are described in NRS (2024e). 	Variant scenarios of the reference scenario have been modelled in GoldSim and PHAST as described in Section 6.2.1. The results of the variant models demonstrate an acceptable risk to groundwater.	Low
HRA-3	Parameter uncertainty	Uncertainty in the value of model parameters. These uncertainties are listed in Appendix A and Appendix B.	Variant scenarios of the reference case have been modelled in GoldSim and PHAST as described in Section 6.2.3. The results of the variant models demonstrate an acceptable risk to groundwater.	Low
HRA-4	Upgradient groundwater quality	The quality of upgradient groundwater is uncertain.	Contaminants are assumed not to be present in upgradient groundwater. Modelled concentrations of contaminants at compliance points down gradient of both the SGHWR and Dragon reactor End States have been compared with compliance limits.	Low Sources of PCBs and hydroo not present upgradient of the the model assumption is the Metals may be a natural con groundwater. However, the of metals in groundwater as from the disposals/deposits a laboratory detection limits ar upgradient concentrations, a compliance limits to be exce

ce (Low, Medium, High)	Recommended Action
	None
	None
	None
	None.
carbon compounds are disposals/deposits and refore appropriate.	
ponent of upgradient modelled concentrations a result of migration are below typical d, when added to re unlikely to cause eded.	

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Appendix A

DETAILED DESCRIPTION OF MODELLING OF CONTAMINANT MIGRATION USING GOLDSIM



Nuclear Restoration Services

WINFRITH SITE

Appendix A: Detailed Description of Modelling of Contaminant Migration Using GoldSim

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this appendix is to describe the implementation of a numerical model in GoldSim that calculates the concentrations in groundwater, at the compliance point, of non-radiological contaminants released from the SGHWR and Dragon reactor End States.

1.2 OVERVIEW AND STRUCTURE OF THIS APPENDIX

As described in NRS (2024c), the active processes required to be modelled using GoldSim are summarised as follows:

- Mixing and dilution of contaminants released from the End States with groundwater in the Poole Formation;
- Dispersion of dissolved contaminants along the Poole Formation unsaturated and saturated pathways;
- Partition of contaminants between the solid material of the Poole Formation and groundwater; and
- Biodegradation of organic contaminants.

This appendix describes the numerical implementation of the SGHWR and Dragon reactor End States concept. To model the processes identified in NRS (2024c), a GoldSim model is required which provides:

- A numerical representation of time variant water flow (groundwater flow in the Poole Formation, groundwater flooding, cap infiltration and leachate leakage), storage and level; and
- A numerical representation of contaminant mass transport (by water) from the source via the groundwater pathway to the compliance point.

This appendix is structured into eight main sections:

- Section 2 describes how the hydraulics aspects are implemented in the model of the SGHWR and Dragon reactor End States, including aspects of model implementation for the purpose of assessing the effects of an alternative scenario;
- Section 3 describes how aqueous release and transport of the SGHWR and Dragon End States non-radiological contaminant inventory has been modelled;
- Section 4 lists the values of parameters used in the reference scenario model;
- Section 5 describes the changes to the model required to model the alternative and variant scenarios to address conceptual and model uncertainty;
- Section 6 presents the results of the reference scenario model, including assessment of cumulative effects. It also identifies parameters selected for sensitivity analysis;
- Section 7 presents the results of the models of the alternative and variant scenarios as well as variant models used to assess parameter value uncertainty;
- Section 8 provides a summary of the modelling; and
- Section 9 lists the references used in this appendix.

2 MODEL HYDRAULICS

2.1 NUMERICAL IMPLEMENTATION OF A WATER BALANCE

Components of water flow that underpin the contaminant fate and transport calculations are the degree of saturation of the deposits/disposals, the outflow rate of water from the End States and the flow rate in the saturated Poole Formation pathway.

In line with the concept described in NRS (2024c), the rate of water entering and leaving the End States must balance, except in the SGHWR Regions 1 and 2 where any imbalance is accounted for by the change in the volume of water that has accumulated within the void.

Similarly, groundwater flow entering the modelled Poole Formation saturated pathway at the upgradient boundary must balance with groundwater flow leaving it after accounting for leakage from the End States. The concept, and its implementation, does not include inflows from rainfall infiltration along the downgradient saturated pathway. This is cautious as it excludes the additional dilution that would be afforded by the recharge.

Water that episodically inundates the SGHWR South Annexe and the Dragon reactor basement is assumed to inflow from all sides of the structures and not just from upgradient. No attempt has been made to determine how much of the water that inundates the deposits/disposals inflows from upgradient of the deposits/disposals (and how much of the groundwater flow into the deposits/disposals comes from cross-gradient and/or downgradient). In determining the flow rate in the Poole Formation pathway downgradient of the deposits/disposals appropriate to maintaining a flow balance, it has been assumed that none of the inundating water comes from upgradient. The rate of inundation of water to the deposits/disposals has therefore been added to the flow in the Poole Formation pathway downgradient of both End States to maintain the flow balance. This is described in Figure 611/A1 using the South Annexe as an example. Since the rate of water inundation of the deposits/disposals is less than approximately 1% of the groundwater flow rate, the assumption about the provenance of the inundating water has negligible consequences for modelled contaminant dilution and migration rate in groundwater.

The water balance implemented in the model is summarised in Figure 611/A2 and Figure 611/A3 for the SGHWR and Dragon reactor End States, respectively. The double blue line within Regions 1 and 2 of the SGHWR illustrates the requirement to calculate the volume of water accumulated in the structure.

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Figure 611/A1: Illustration of Implemented Water Balance during South Annexe Inundation by Groundwater



Figure 611/A2: SGHWR Water Balance for Implementation in GoldSim



Figure 611/A3: Dragon Water Balance for Implementation in GoldSim

2.2 CALCULATION OF FLOW RATES AND CHANGES IN WATER LEVEL FOR THE REGIONS OF THE SGHWR

2.2.1 MODELLING CAP INFILTRATION

The calculation of inflow through the cap for all regions of the SGHWR and the Dragon reactor accounts for time variant infiltration as the cap degrades (as described in Table 611/A7).

2.2.2 NORTH ANNEXE

No claims are made about the capability of the North Annexe to retain water and on that basis the infiltration which enters the cap is modelled to flow unimpeded through the base of the annexe. Therefore, the rate of outflow from the North Annexe is equal to the rate of inflow via infiltration through the cap and there is no requirement to calculate water storage within the deposits/disposals. The water inflow rate is calculated as the product of the North Annexe plan area and the cap infiltration rate, and the outflow is set equal to this inflow rate. The flow of water from the North Annexe is modelled to enter the unsaturated zone beneath the North Annexe base. The water is modelled to flow through the unsaturated zone and enter the Poole Formation saturated pathway.

2.2.3 SOUTH ANNEXE

Like the North Annexe, no claims are made about the capability of the South Annexe to retain water and therefore inflow from cap infiltration is modelled to flow unimpeded from the structure.

Unlike the North Annexe, under conditions of climate change in some winters, groundwater levels are projected to rise into the base of the South Annexe. Therefore, the outflow rate of water which leaves the basement when winter groundwater levels return to below the basal level must be added to the outflow rate derived from infiltration.

The water outflow rate from infiltration is calculated as the product of the South Annexe plan area and the cap infiltration rate.

The water outflow rate from groundwater flooding into and out of the South Annexe basement is calculated as: (flooding probability * groundwater height above base * base plan area * available porosity of the demolition arisings¹) / 1 year. This gives an outflow rate with dimensions of [L3/T]. The flooding probability is expressed as the number of winters (years) within the modelled 21-year period when groundwater is projected to rise above the South Annexe floor slab as described in Table 611/A8.

Whilst an unsaturated zone might be present beneath the South Annexe for some or most of the year, it is cautiously disregarded within the model. The flow of water from the South Annexe is modelled to enter the saturated zone of the Poole Formation.

2.2.4 REGIONS 1 AND 2

As summarised in NRS (2024c), the base of Regions 1 and 2 of the SGHWR extends such that part of the structure is permanently beneath the groundwater level in the Poole Formation. Unlike the North and South Annexe, the concept for the Regions 1 and 2 structure walls and base is that they will retain their integrity following placement of blocks and broken demolition arisings but will progressively degrade thereafter resulting in changes to inflow and outflow rates of water.

The internal water level will vary during the evolution of Regions 1 and 2 as described by NRS (2024c). This (by virtue of the established hydraulic gradient between internal and external water levels) will affect the inflow and outflow rate of water which, in turn, will affect the internal water level. Water inflow and outflow rates and internal water level are fundamental controls on the release rate of contaminants from Regions 1 and 2. It is necessary to calculate the time variant internal water level because unsaturated and saturated demolition arisings leach at different rates and the water level defines the degree of saturation of the demolition arisings.

A GoldSim 'Pool' element is used to manage water inflows and outflows and track the volume of water in Regions 1 and 2 on each timestep. The Pool element can manage the continuous recursive loop between inflow, outflow and water level.

The Pool element has a lower and upper water volume bound defined. The minimum (lower bound) has been defined as the water held in the demolition arisings at field capacity. The maximum (upper bound) has been defined as the combined, weighted average, void space within the broken demolition arisings and blocks. There is an implicit assumption in the model that this void space is uniformly distributed, whereas the distribution of the void space in the demolition arisings will be heterogenous, and dependent on the locations of blocks and broken concrete. If the tracked water

¹ The available porosity is the empty pore space of the demolition arisings when they are at their field capacity. The field capacity is the maximum amount of water retained in the pore space of the demolition arisings that does not drain away by gravity.

volume reaches the upper bound, the Pool element directs all inflowing water to overflow (this is labelled as R1&R2 overflow in Figure 611/A2).

The inflow rate to the Pool element has been defined as:

- The inflow rate due to cap infiltration (plan area multiplied by cap infiltration rate); and
- The Darcy calculated groundwater inflow rate under conditions of an inward hydraulic gradient.

The outflow rate from the Pool element has been defined as:

- The Darcy calculated groundwater outflow rate under conditions of an outward hydraulic gradient; and
- The overflow rate under conditions where the upper volume bound is reached.

The calculations of water inflow and outflow rates account for time variant external groundwater levels (as described in Table 611/A7) and the increase in hydraulic conductivity of the degrading Regions 1 and 2 walls (described in Table 611/A1).

The geometry of the Regions 1 and 2 structure is irregular. Simplification is required to numerically represent water level rise and fall and the wall area through which water flows into and out of the structure (the wetted area). The Regions 1 and 2 structure has been simplified to a cuboid. The cuboid volume is faithful to the Regions 1 and 2 void volume. The wall height represents the true wall height, so the overflow height is correctly modelled. The cuboid plan area has been adjusted from the 'true' plan area to that of the equivalent cuboid of correct wall height and void volume. This is illustrated in Figure 611/A4. There is no effect of the adjusted plan area on the modelled cap infiltration rate as the 'true' plan area is used to calculate the inflow.

The wetted area calculation assumes the average height of the internal and external water levels and multiplies this by the perimeter length of all four faces of the cuboid.



Figure 611/A4 – Simplification of the Geometry of Regions 1 and 2

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Calculations are included within the model to prevent numerical oscillation in the volume of the Pool element as a result of the recursive loop between water volume and calculated water inflow and outflow rates. Numerical instability can occur as the outflow rates become very small (because the internal water level is similar to the groundwater level) and arise because calculated water flows on successive timesteps alternate between negative (inflow) and positive (outflow) values. A trigger has been specified in the model that sets the outflow rate equal to the infiltration rate when the conditions that give rise to oscillations are detected. This removes the recursive loop and prevents the oscillation. The trigger is only realised when the calculated outflow rate is within 0.001 m³/d of the infiltration rate and there is no possibility of further water accumulation.

2.3 CALCULATION OF FLOW RATES AND CHANGES IN WATER LEVEL AND VOLUME FOR THE DRAGON REACTOR

No claims are made as to the capability of the inner or outer walls of the basement of the Dragon reactor to impede water flow. On this basis all inflow from cap infiltration is modelled to flow unimpeded from the outer edges of the structure. As described in NRS (2024c), under conditions of climate change during wetter periods, groundwater levels are projected to rise into the base of the Dragon reactor. Therefore, like the SGHWR South Annexe, the outflow rate of groundwater that has inundated the lower parts of the deposits/disposals in the Dragon reactor basement must be added to the outflow rate derived from infiltration.

2.4 CALCULATION OF GEOSPHERE FLOWS

The groundwater flow rates in the Poole Formation upgradient of the Dragon reactor and the SGHWR are based on catchment recharge. Upgradient flow through the Poole Formation pathway is calculated as the product of the upgradient catchment length and width of the respective End State multiplied by the catchment recharge rate. The values of these parameters are defined in Table 611/A2 (width of the SGHWR), Table 611/A3 (width of the Dragon reactor) and Table 611/A7 (recharge rate and catchment lengths).

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3 MODELLING AQUEOUS RELEASE AND CONTAMINANT TRANSPORT FROM THE SGHWR DEPOSITS/DISPOSALS

Modelling the aqueous release, fate and transport of contaminants in the deposits/disposals uses the GoldSim Contaminant Transport or 'CT' Environment. This allows environmental media to be defined and specialised elements to be used which model contaminant transport, including 'Pipe' and 'Cell' pathways.

All water inflow to, and outflow from, the End States and saturation levels (for Regions 1 and 2) are derived from the hydraulics calculations in Section 2.

3.1 MASS RELEASE FROM THE SGHWR ANNEXES

The deposits/disposals in the annexes are modelled using GoldSim mixing cells. The mass of solid material in the cell is defined as the volume of the annexe void available for demolition arisings multiplied by the demolition arisings' dry bulk density. The annexes are assumed to be continuously unsaturated. The volume of water in the cell is defined as the volume of void available for demolition arisings multiplied by the demolition arisings' volumetric moisture content. The selected value for volumetric moisture content assumes the demolition arisings are at field capacity.

The modelled inventory of the annexes comprises specific metals and PCBs in the demolition arisings. The metals are bound in the fabric of the demolition arisings' concrete whilst the PCBs are most likely contained within solid material (such as paint) adhered to the concrete or as loose debris that will only decompose over long periods of time. Nevertheless, the entire PCB inventory mass is cautiously represented within the model as being water available from the beginning of the simulation.

Partitioning of contaminants between the demolition arisings and the water that is modelled to flow through and out of the annexes (in accordance with the rates calculated as described in Sections 2.2.1 and 2.2.3) is modelled in the GoldSim cells. Contaminant partition between the aqueous phase and the concrete structure is cautiously disregarded. The inventory mass of all modelled substances in the demolition arisings has been specified as an initial mass, and as such it depletes with time as the contaminants leach to the water and migrate from the annexes.

The modelled demolition arisings in both annexes are unsaturated. The water flow rate through the base of the North Annexe is set as the infiltration rate through the cap. Two flow rates are specified from the base of the South Annexe: the infiltration rate (like the North Annexe) plus the outflow rate of water that periodically inundates and then exits the basement. The outflow rate of inundated water, whilst in reality is episodic, is time averaged to occur on every timestep. An attempt to quantify the rate of water rise and fall during inundation (and therefore the changing saturation level) has not been made. The outflow rate is based on the depth to which the demolition arisings are assumed to be inundated with groundwater as set out in Section 2.2.3. For simplification both outflow rates have been applied to a single cell representing all the demolition arisings in the South Annexe.

3.2 MASS RELEASE FROM REGIONS 1 AND 2 OF THE SGHWR

Unlike in the annexes, the water level in Regions 1 and 2 of the SGHWR is modelled to change through time. Two GoldSim cells are required to adequately represent movement of contaminant mass in Regions 1 and 2: one that represents saturated demolition arisings; and one that represents unsaturated demolition arisings. Each cell is a subdivision of Regions 1 and 2 with the cells together representing the inventory mass, the amount of demolition arisings and the volume of water. This is illustrated in Figure 611/A5.

The calculation of the amount of solid demolition arisings in Regions 1 and 2 is based on the void available for placement of broken demolition arisings only. The blocks are disregarded which is cautious as it reduces the capacity for sorption of contaminants to solid materials. The calculated volume of water in saturated demolition arisings assumes both broken arisings and blocks are present, although when calculating the volume of water in unsaturated demolition arisings, only the broken arisings are assumed to retain water (at field capacity) and the void space between the placed blocks is assumed to be fully drained.

The volume of demolition arisings and water calculated to be in each of the two cells is a function of the water level (calculated as described in Section 2.2.4) throughout the simulation. The demolition arisings are unsaturated at the beginning of the simulation and therefore the entire modelled inventory mass of the demolition arisings (PCBs and metals) is specified as being present in the unsaturated cell. The initial amount of solid in this cell is the entire mass of demolition arisings within Regions 1 and 2 and the volume of water is the entire volume of demolition arisings multiplied by the field capacity of broken demolition arisings.

Conversely, the entire mass of modelled hydrocarbon fractions in the oil staining is set to be initially present in the saturated cell. As for the contaminants associated with the demolition arisings, this cautiously assumes that all the hydrocarbon inventory is instantly water available, whereas in reality release of hydrocarbon compounds will be spread over a period of time as they diffuse from the concrete. The oil staining is assumed to remain in the saturated zone and in contact with water. The progressive inundation of Regions 1 and 2 is modelled, with the dissolved hydrocarbon fractions allowed to partition with the broken concrete.

As the modelled water level in the SGHWR Regions 1 and 2 rises and falls and the degree of saturation changes, the change in water level on each time step is used by GoldSim to correctly update the amounts of solid material, water and inventory mass in the saturated and unsaturated cells. Mass is moved between the two cells on each timestep using a direct transfer function between the two GoldSim cells. The transfer rate and direction is based on the change of volume of the saturated and unsaturated cells caused by the rising or falling water level.

Contaminants are modelled to partition between the water and the demolition arisings and to migrate from Regions 1 and 2 dissolved in water. The inventory mass is moved by the modelled infiltration through the cap from the unsaturated cell to the underlying saturated cell according to the flow rate calculated in Section 2.2.4. The inventory mass is transported from the saturated cell to the saturated pathway of the Poole Formation according to the flow rate calculated using Darcy's Law as set out in Section 2.2.4.

Contaminant partition between the aqueous phase and the concrete structure is cautiously disregarded.



Figure 611/A5 – Saturated and Unsaturated Cells in Regions 1 and 2 of the SGHWR

3.3 MASS RELEASE FROM THE DRAGON REACTOR

The modelling of mass release from the Dragon reactor is like that of the SGHWR South Annexe. A single GoldSim mixing cell is used to represent the End State. The mass of demolition arisings in the cell is defined as the volume of the Dragon reactor void available for demolition arisings multiplied by the demolition arisings dry bulk density. Blocks are cautiously disregarded. The volume of water in the cell is defined as the volume of void available for demolition arisings multiplied by the broken demolition arisings' moisture content (assumed to be at field capacity). The demolition arisings are modelled as continuously unsaturated.

In the Dragon reactor End State, the inventory comprises metals and PCBs in the demolition arisings. Like for the annexes of the SGHWR:

- The entire masses of the modelled metals and PCB are cautiously represented as being water available from the start of the simulation; and
- The inventory masses of all modelled substances in the demolition arisings have been specified such that the inventories deplete through time as the contaminants leach to the water and migrate from the demolition arisings.

Contaminants in the inventory partition between the demolition arisings and the water that is modelled to flow through, and out of, the Dragon reactor End State in accordance with the rates calculated in Section 2.3. Like the South Annexe, whilst only the lower part of the Dragon reactor basement is expected to be episodically in contact with groundwater, a simplification is made for the purposes of modelling that outflow both from cap infiltration and from groundwater inundation is applied to a single cell containing the entire inventory.

Contaminant partition between the aqueous phase and the concrete structure is cautiously disregarded.

3.4 MASS TRANSPORT IN THE POOLE FORMATION UNSATURATED PATHWAY

The only unsaturated pathway that is modelled is that beneath the SGHWR North Annexe. It is modelled as a GoldSim 'Pipe' pathway. The pipe pathway length is defined as the difference between the elevation of the bottom of the North Annexe base and the groundwater elevation. Contaminant mass enters the pathway, dissolved in water, from the overlying North Annexe and is subject to dispersion as it migrates along the vertical pathway. The infiltrating water moves the mass through the pipe. The flow rate of water leaving the pipe is the same as that entering it and it is as calculated in Section 2.2.1. Both metals and PCBs are modelled to partition between the unsaturated Poole Formation and the flowing water and this process retards contaminant migration. PCBs are assumed to biodegrade in this pathway.

3.5 MASS TRANSPORT IN THE POOLE FORMATION SATURATED PATHWAY

3.5.1 SGHWR

GoldSim pipe pathways are used in the model to represent contaminant transport in the saturated pathway beneath the SGHWR Annexes. The component of the pathway associated with groundwater flow bypassing Regions 1 and 2 has been conservatively disregarded, thereby shortening the path length for attenuation. The length of the pipe below the South Annexe is the same as the South Annexe footprint length in the direction of groundwater flow. Contaminant mass from the overlying South Annexe is modelled to enter the pipe pathway uniformly along its entire length.

Ensuring contaminant mass transport is represented adequately beneath the North Annexe requires two pipe pathways. This is because the same pipe cannot have contaminant mass entering over more than one defined length. The lengths of both pipes below the North Annexe are the same as the length of the North Annexe footprint in the direction of groundwater flow. One pipe is set to receive mass inputs from the hydraulically upgradient saturated pathway (comprising leakage from Regions 1 and 2 and inputs from the pathway beneath the South Annexe) and these enter the pipe at its upgradient end. The second pipe is set to receive mass input from the overlying North Annexe, and this enters the pipe uniformly along its entire length.

Water flow rates into and out of the North Annexe and South Annexe groundwater pipe pathways are defined according to the calculations in Section 2. Dilution, as a result of the inputs of the dissolved substances from each region of the End State mixing with flowing groundwater, is modelled.

Contaminant mass is subject to longitudinal dispersion in the pipe pathways. The metals, PCBs and hydrocarbon fractions are modelled to partition between the solid material of the Poole Formation and the water, leading to retarded migration. PCBs are assumed to biodegrade in the pathway.

Both the pipes beneath the North Annexe are set to outflow to a GoldSim pipe nominally 0.1 m long representing the groundwater compliance point. It is from this pipe that contaminant concentrations at the SGHWR compliance point are reported.

3.5.2 DRAGON REACTOR

A single pipe pathway is used to model contaminant mass transport in the Poole Formation saturated pathway beneath the Dragon reactor End State. The pipe pathway length is set equal to the diameter of the Dragon reactor End State base. The input of contamination from the overlying Dragon reactor is specified to be distributed evenly along the entire length of the pipe. The approaches to dilution, dispersion, retardation and biodegradation are consistent with those assumed for the SGHWR.

The pipe pathway representing the Poole Formation beneath the Dragon reactor outflows to a GoldSim pipe nominally 0.1 m long representing the groundwater compliance point.

4 PARAMETERISATION OF THE NUMERICAL MODEL FOR THE REFERENCE SCENARIO

The numerical representation of the conceptual model, described in Section 2 and Section 3, is constructed of parameters. This section sets out the values assigned to the parameters in the model of the reference scenario.

4.1 HYDRAULIC CONDUCTIVITY OF THE REGIONS 1 AND 2 STRUCTURE

The values of parameters used to model the hydraulic conductivity of the SGHWR Regions 1 and 2 structure, as described in NRS (2024c), are summarised in Table 611/A1. The hydraulic conductivity is used to calculate water inflows to, and outflows from, Regions 1 and 2 and is time invariant after the first 1,000 years of the simulation.

Parameter	Unit	Value	Justification/Reference		
Log K for SGHWR Regions 1 and 2 structural concrete at 0 years	- (m/s)	-10.36 (4.4E-11)	NRS (2024c). Uppermost value in cell to left: exponent of base 10.		
Log K for SGHWR Regions 1 and 2 structural concrete at 1,000 years	- (m/s)	-3.568 (2.7E-4)	Lowermost value in cell to left (in brackets): value of hydraulic conductivity. To model a log K - linear t change, GoldSim		
Log K for SGHWR Regions 1 and 2 structural concrete at 100,000 years	- (m/s)	-3.568 (2.7E-4)	performs linear interpolation across the three values as a function of t in a time series data element. The interpolated values are then anti-logged for onward use in the model.		

Table 611/A1: Values of Hydraulic Conductivity for the SGHWR Regions 1 and 2 Structure

4.2 GEOMETRY OF THE SGHWR

The parameters used to describe the geometry of the SGHWR in the model are summarised in Table 611/A2.

Table 611/A2: Values of Parameters Used to Describe the Geometry of the SGHWR

Parameter	Unit	Value	Justification/Reference	
Regions 1 and 2				
Plan area for calculating infiltration inflow	m²	1,883	NRS (2024c) Section 2.	
Basal elevation	mAOD	28.8	NRS (2024c) Section 2. Lowest elevation of Regions 1 and 2 (basal elevation of Region 1).	

Parameter	Unit	Value	Justification/Reference		
Top of fill elevation (1 mbgl)	mAOD	40.61	NRS (2024c) Section 2.		
Wall thickness	m	1.2	Minimum wall thickness from NRS (2024c) Section 4.		
Width perpendicular to groundwater flow direction for calculating upgradient groundwater flow rate	m	81.2	Measured from NRS (2024c) Figure 606/2 assuming the flow direction is as shown in NRS (2024c) Figure 606/32.		
North Annexe					
Plan area for calculating infiltration inflow	m²	1,593	NRS (2024c) Table 606/4.		
South Annexe					
Plan area for calculating infiltration inflow	m²	2,202	NRS (2024c) Table 606/4.		

4.3 GEOMETRY OF THE DRAGON REACTOR

The values of parameters used to describe the geometry of the Dragon reactor in the model are summarised in Table 611/A3.

Table 611/A3: Values of Parameters Used to Describe the Geometry of the Dragon Reactor

Parameter	Unit	Value	ustification/Reference		
Top fill elevation (ground level)	d mAOD 35.05		NRS (2024c).		
Basal elevation (top of base slab)	mAOD	27.34	NRS (2024c) Section 2.		
Internal diameter of the outer Wall A for calculating upgradient groundwater flow rate, cap infiltration and leachate leakage	m	32.31	NRS (2024c) Section 2.		

4.4 DEMOLITION ARISINGS AND BLOCKS

4.4.1 COMMON DATA

The values of parameters describing the broken demolition arisings and blocks common to both the SGHWR and Dragon reactor models are summarised in Table 611/A4.

Table 611/A4: Values of Parameters Used to Describe Properties of Blocks and Demolition Arisings

Parameter	Unit	Value	Justification/Reference
Demolition arisings intraparticle porosity	m³/m³	0.3	NRS (2024c) Table 606/6.
Dry density of concrete	kg/m³	2,400	NRS (2024c) Table 606/6.
Water density	kg/m³	1,000	Average density of water (required to convert moisture content mass/mass to moisture content volume/volume).
Demolition arisings moisture content by mass	kg/kg	0.094	Mean value from analytical data in Magnox (2019) Appendix C.
Intra-block porosity (void space)	m³/m³	0.1	NRS (2024c) Table 606/5.

4.4.2 SGHWR

The modelled volumes of demolition arisings and blocks to be placed in the SGHWR are summarised in Table 611/A5.

Table 611/A5: Modelled Volumes of Demolition Arisings and Blocks (SGHWR)

Parameter	Unit	Value	Justification/Reference
Volume occupied by demolition arisings in Regions 1 and 2	m³	8,774	NRS (2024c) Table 606/7.
Volume occupied by demolition arisings in the North Annexe	m³	4,164	
Volume occupied by demolition arisings in the South Annexe	m³	10,501	
Volume occupied by blocks in Regions 1 and 2	m³	6,300	

4.4.3 DRAGON REACTOR

The modelled volumes of demolition arisings and blocks to be placed in the Dragon reactor are summarised in Table 611/A6.

Table 611/A6: Modelled Volumes of Demolition Arisings and Blocks (Dragon)

Parameter	Unit	Value	Justification/Reference
Volume occupied by demolition arisings outside Wall C	m³	4,412	NRS (2024c) Table 606/7.
Volume occupied by demolition arisings inside Wall C	m³	1,732	
Volume occupied by blocks	m³	400	

4.5 HYDROGEOLOGY, SATURATED PATHWAY AND UNSATURATED PATHWAY PARAMETERS

Values of parameters describing groundwater level, infiltration rate, saturated and unsaturated pathway properties, catchment and pathway dimensions are summarised in Table 611/A7.

Table 611/A7: Values of Hydrogeology and Saturated/Unsaturated Pathway Parameters

Parameter	Unit	Value	Justification/Reference
External groundwater level – SGHWR at 0 years (January 2032)	mAOD	33.1	NRS (2024c).
External groundwater level – SGHWR at 18 years	mAOD	33.6	NRS (2024c). Value for 2050s used for 2050 timestep at t = 18 years ² .
External groundwater level – SGHWR at 48 years	mAOD	34	NRS (2024c). Value for 2080s used for 2080 timestep at t = 48 years.
External groundwater level – SGHWR at 100,000 years	mAOD	34	NRS (2024c). Value for 2080s used for timestep at t = 100,000 years.
External groundwater level – Dragon at 0 years (January 2029)	mAOD	24.5	NRS (2024c).

² The "t = x years" nomenclature used in this table and subsequent tables refers to the model elapsed time.

Parameter	Unit	Value	Justification/Reference
External groundwater level – Dragon at 21 years	mAOD	24.9	NRS (2024c). Value for 2050s used for 2050 timestep at t = 21 years.
External groundwater level – Dragon at 51 years	mAOD	25.1	NRS (2024c). Value for 2080s used for 2080 timestep at t = 51 years.
External groundwater level – Dragon at 100,000 years	mAOD	25.1	NRS (2024c). Value for 2080s used for timestep at t = 100,000 years.
Cap infiltration rate at 0 years	mm/yr	5	NRS (2024c) Section 5.3. The cap will be designed to reduce the infiltration rate to less than 5 mm/yr for 250 years.
Cap infiltration rate at 250 years	mm/yr	5	NRS (2024c) Section 5.3. The cap will be designed to reduce the infiltration rate to less than 5 mm/yr for 250 years.
Cap infiltration rate at 1,000 years	mm/yr	43	NRS (2024c) Section 5.3. The infiltration rate through the engineered cap is assumed to increase linearly to a maximum value of 43 mm/yr after 1,000 years.
Cap infiltration rate at 100,000 years	mm/yr	43	NRS (2024c) Section 5.3. Increases in the cap infiltration rate are assumed not to happen after 1,000 years.
Catchment length – SGHWR	m	350	Approximate distance to the upgradient catchment boundary as measured from NRS (2024a) Figure 604/1.
Catchment length - Dragon	m	1,000	Approximate distance to the upgradient catchment boundary as measured from NRS (2024a) Figure 604/1.
Moisture content – Poole Formation unsaturated pathway	m³/m³	0.1	Based on reasonable value for sand field capacity (e.g. USGS, 1966)

Parameter	Unit	Value	Justification/Reference
Porosity – Poole Formation	m³/m³	0.2	Effective porosity from NRS (2024a) Section 6.4.
Density – Poole Formation	kg/m³	2,000	Dry bulk density for Poole Formation from NRS (2024a) Section 6.4.
Hydraulic conductivity – Poole Formation	m/s	2.7E-4	NRS (2024a) Section 6.4 and Table 604/6. Mean value of range of values (7E-5 m/s to 4.7E-4 m/s) interpreted from cross hole tests.
Base elevation – Poole Formation (for use in the SGHWR model)	mAOD	29.26	It is assumed for modelling purposes that the base of the pathway is coincident with the top of the London Clay surface in the vicinity of Regions 1 and 2 (NRS, 2024a).
Recharge rate – Poole	mm/yr	279	NRS (2024a) Section 3.3.
Formation (t = 0 years)			BGS modelled 30-year average recharge for the Lower Frome and Piddle Catchment in 2020 using an 11- member ensemble of simulations of future UK climate under a medium emissions scenario underpinned by UKCP09.
Recharge rate – Poole Formation (t = 53 years)	mm/yr	326	NRS (2024a) Section 3.3. BGS modelled 30-year average recharge for the Lower Frome and Piddle Catchment in 2085 using an 11- member ensemble of simulations of future UK climate under a medium emissions scenario underpinned by UKCP09.
Top of floor slab elevation of the North Annexe	mAOD	37.8	Top of floor slab elevation taken from NRS (2024c) Table 606/1. Parameter used to calculate the unsaturated pathway thickness beneath the North Annexe.
Floor slab thickness of the North Annexe	m	0.33	Typical floor slab thickness taken from NRS (2024c) Table 606/1. Parameter used to calculate the unsaturated pathway thickness beneath the North Annexe.
Mixing zone thickness – Dragon	m	5	NRS (2024c) Section 6.2.3.

4.5.1 SGHWR SOUTH ANNEXE AND DRAGON GROUNDWATER LEVELS UNDER 'CAUTIOUS CENTRAL ESTIMATE' CONDITIONS OF CLIMATE CHANGE

The values of parameters required to model the water outflow from the South Annexe and Dragon reactor following groundwater inundation are presented in Table 611/A8.

Table 611/A8: Values of South Annexe and Dragon Reactor Water Level Parameters

Parameter	Unit	Value	Justification/Reference
Water level above South Annexe base level at t = 0 years	m	0	Current conditions are assumed to occur at the time of restoration of the SGHWR.
Number of years within which groundwater level exceeds South Annexe basal level at t = 0 years	yr	0	Current conditions are assumed to occur at the time of restoration of the SGHWR.
Water level above South Annexe base level during exceedance years at t = 18 years	m	0.75	WSP (2023). 50% of 2050s CCE ³ value.
Number of years in climate change modelling simulation time period ⁴ within which groundwater level exceeds South Annexe basal level at t = 18 years	yr	3	WSP (2023). 2050s CCE value.
Water level above South Annexe base level during exceedance years at t = 48 years	m	0.55	WSP (2023). 50% of 2080s CCE value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds South Annexe basal level at t = 48 years	yr	3	WSP (2023). 2080s CCE value.
Water level above South Annexe base level during exceedance years at t = 100,000 years	m	0.55	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.

³ Cautious Central Estimate

⁴ This time period, required to convert into a probability the number of years during which groundwater levels rise higher than the base of the South Annexe is a separate input and is listed at the end of this table.

Parameter	Unit	Value	Justification/Reference
Number of years in climate change modelling simulation time period within which groundwater level exceeds South Annexe basal level at t = 100,000 years	yr	3	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
Water level above Dragon base level at t = 0 years	m	0	Current conditions are assumed to occur at the time the cap is completed.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon basal level at t = 0 years	yr	0	Current conditions are assumed to occur at the time the cap is completed.
Water level above Dragon base level during exceedance years at t = 18 years	m	0.8	WSP (2023). 50% of 2050s CCE value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon reactor basal level at t = 18 years	yr	4	WSP (2023). 2050s CCE value.
Water level above Dragon reactor base level during exceedance years at t = 48 years	m	0.65	WSP (2023). 50% of 2080s CCE value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon reactor basal level at t = 48 years	yr	3	WSP (2023). 2080s CCE value.
Water level above Dragon reactor base level during exceedance years at t = 100,000 years	m	0.65	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
Number of years in climate change modelling simulation time period within which groundwater level exceeds	yr	3	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.

Parameter	Unit	Value	Justification/Reference
Dragon reactor basal level at t = 100,000 years			
Climate change modelling simulation time period	yr	21	WSP (2023). Used to convert the number of years within which groundwater entry occurs to a probability.

4.5.2 CONTAMINANT DATA

Valus of concentration of, and fate and transport parameters relating to, the modelled contaminants are presented in Table 611/A9.

Parameter		Unit	Value	Justification/Reference
Mass – aliphatic and aromatic hydrocarbon fractions in	>C10-C12 Aliphatic	kg	0.06	NRS (2024c). UCL95 ⁵ of mean value calculated for each hydrocarbon
	>C12-C16 Aliphatic	kg	0.14	fraction using the laboratory results.
SGHWR oil- stained	>C16-C21 Aliphatic	kg	0.78	
Concrete	>C10-C12 Aromatic	kg	0.60	
	>C12-C16 Aromatic	kg	0.19	
	>C16-C21 Aromatic	kg	0.55	
	>C21-C35 Aromatic	kg	118.82	
Solubility – all species	PCB28	mg/l	0.166	MacKay (2006) Section 7.1.1.28. Average of all values presented in the literature review.
	PCB52	mg/l	0.078	MacKay (2006) Section 7.1.1.52. Average of all values presented in the literature review.
	PCB101	mg/l	0.0155	MacKay (2006) Section 7.1.1.101. Average of all values presented in the literature review.

Tabla 611/AQ. (Contominant (Concentrations	and Values of	Eata and	Transport	Daramatara
Table OTT/A9. C			anu values oi	Fale anu	mansport	arameters

⁵ Upper 95th Percent Confidence Limit

Parameter		Unit	Value	Justification/Reference
	PCB118	mg/l	0.0134	WHO (2003).
	PCB138	mg/l	0.0159	
	PCB153	mg/l	0.00091	
	PCB180	mg/l	0.00023	WHO (2003) provides a calculated solubility range of 0.00031 to 0.00656 mg/l. It also provides a solubility of 0.00023 mg/l that is a measured value and is therefore judged preferable. The measured value maintains the solubility trend with congener number.
	>C10-12 Aliphatic	mg/l	3.4E-2	CL:AIRE (2017).
	>C12-16 Aliphatic	mg/l	7.6E-4	
	>C10-12 Aromatic	mg/l	2.5E1	
	>C12-16 Aromatic	mg/l	5.8	
	>C16-21 Aliphatic	mg/l	3E-6	
	>C16-21 Aromatic	mg/l	6.5E-1	
	>C21-35 Aromatic	mg/l	6.6E-3	
	Chromium (III)	mol/m ³	-1	GoldSim default value for unlimited solubility. This is a cautious
	Chromium (VI)	mol/m ³	-1	approach.
	Copper	mol/m ³	-1	
	Lead	mol/m ³	-1	
	Zinc	mol/m ³	-1	
PCB source	PCB28	ug/kg	21	NRS (2024c).
– SGHWR	PCB52	ug/kg	25	UCL95 of mean value for the SGHWR as reported in Table 606/24
and Dragon	PCB101	ug/kg	99	
arisings	PCB118	ug/kg	67	
	PCB138	ug/kg	120	

Parameter		Unit	Value	Justification/Reference
	PCB153	ug/kg	89	
	PCB180	ug/kg	63	
Metals water available	Chromium (III) ⁶	mg/kg	0.19	NRS (2024c). UCL95 of mean for the SGHWR as
concentration – SGHWR demolition	Chromium (VI) ⁶	mg/kg	0.19	reported in Table 606/25.
arisings	Copper	mg/kg	0.05	
	Lead	mg/kg	0.010	
	Zinc	mg/kg	0.16	
Metals water available	Chromium (III) ⁶	mg/kg	0.22	NRS (2024c). UCL95 of mean for Dragon reactor as
concentration – Dragon demolition	Chromium (VI) ⁶	mg/kg	0.22	reported in Table 606/25.
arisings	Copper	mg/kg	0.06	-
	Lead	mg/kg	0.011	-
	Zinc	mg/kg	0.18	
Koc – aliphatics and	>C10-12 Aliphatic	l/kg	2.5E5	CL:AIRE (2017).
aromatics	>C12-16 Aliphatic	l/kg	5.0E6	
	>C10-12 Aromatic	l/kg	2.5E3	
	>C12-16 Aromatic	l/kg	5.0E3	
	>C16-21 Aliphatic	l/kg	6.3E8	
	>C16-21 Aromatic	l/kg	1.6E4	
	>C21-35 Aromatic	l/kg	1.3E5	
Log Koc –	PCB28	l/kg	5.33	Panagopoulos et al. (2017).
PCBs	PCB52	l/kg	5.32	
	PCB101	l/kg	5.47]

⁶ All the leachable chromium inventory has been assumed to be both chromium (III) and chromium (VI).

Parameter		Unit	Value	Justification/Reference
	PCB118	l/kg	5.78	
	PCB138	l/kg	5.79	
	PCB153	l/kg	5.94	
	PCB180	l/kg	6.24	Calculated as an average of all values presented in Mackay (2006) Section 7.1.1.180.
Kd demolition a chromium (III)	arisings –	ml/g	1	Table 14, US DoE^7 (2021). US DoE (2021) directs the user to this table
Kd demolition a chromium (VI)	arisings –	ml/g	1	in concrete components. Cautiously, the value for Stage 3 Oxidising
Kd demolition a	arisings – zinc	ml/g	400	Cement is used as this is the lowest
Kd demolition arisings – copper		ml/g	400	stages.
Kd demolition arisings – lead		ml/g	100	
foc demolition arisings		-	0.0035	Magnox (2019). Mean value of total organic carbon analysis of samples of demolition arisings.
Kd Poole Form chromium (III)	ation –	ml/g	400	Table 16, US DoE (2021). Values for sandy sediment.
Kd Poole Form chromium (VI)	ation –	ml/g	400	
Kd Poole Form	ation – zinc	ml/g	20	
Kd Poole Formation – copper		ml/g	50	
Kd Poole Form	Kd Poole Formation – lead		2,000	
foc Poole Form	ation	-	0.002575	Certificates of soil samples analyses from Atkins (2024). Average value from all soil samples taken from a depth of 0.5 m or greater.
Biodegradation PCB congeners saturated and u Poole Formatio	half life of s in the unsaturated on	yr	50	NRS (2024c).

⁷ United States Department of Energy

5 CHANGES REQUIRED TO MODEL ALTERNATIVE AND VARIANT SCENARIOS

5.1 RECAP OF ALTERNATIVE AND VARIANT SCENARIOS TO BE MODELLED

The approach to assessing sensitivity of the reference scenario to conceptual and model uncertainty is described in Section 5 of the main text of the hydrogeological risk assessment. The alternative scenario defined to assess sensitivity to conceptual uncertainty is reproduced in Table 611/A10 and the variant scenarios defined to assess model uncertainty are reproduced in Table 611/A11.

Table 611/A10: Alter	rnative Scenario Select	ted to Assess Sens	itivity to Conceptua	al Uncertainty
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Uncertainty	Reference Scenario	Alternative Scenario to Support Sensitivity Analysis			
Frequency and extent of groundwater inundation to the SGHWR South Annexe and to the Dragon reactor basement under the worst modelled conditions of climate change.	Groundwater rises above the SGHWR South Annexe and Dragon reactor base to a level and with a frequency consistent with that of a cautious central estimate of future recharge calculated assuming a scenario of medium future global atmospheric emissions.	Assume an alternative scenario in which groundwater rises every year above (and subsequently falls below) the SGHWR South Annexe and Dragon reactor base to the maximum water level modelled assuming a 'reasonable worst case' of future recharge calculated assuming a scenario of medium future global atmospheric emissions.			

Table 611/A11: Variant Scenarios Selected to Assess Sensitivity to Model Uncertainty

Uncertainty	Reference Scenario	Variant Scenario to Support Sensitivity Analysis
Evolution of the effective hydraulic conductivity of the concrete structures.	A cautious estimate of the rate of concrete degradation of the SGHWR Regions 1 and 2 as described in NRS (2024c).	Two variant scenarios: Model with higher initial effective hydraulic conductivity and faster rate of concrete degradation of the SGHWR Regions 1 and 2 structure compared to the reference scenario as described in NRS (2024c).
		Model with lower initial effective hydraulic conductivity for the SGHWR Regions 1 and 2 structure compared to the reference scenario as described in NRS (2024c).

Uncertainty	Reference Scenario	Variant Scenario to Support Sensitivity Analysis
Evolution of the rate of infiltration to the cap.	Model with a cautious estimate of the rate of degradation of the caps over the SGHWR and Dragon reactor End States as described in NRS (2024c).	Model with faster rate of cap degradation compared to the reference scenario as described in NRS (2024c).
Frequency and extent of groundwater inundation to the SGHWR South Annexe and to the Dragon reactor basement.	Groundwater rises above the SGHWR South Annexe and Dragon reactor base to a level and with a frequency consistent with that of a cautious central estimate of future recharge calculated assuming a scenario of medium future global atmospheric emissions.	Groundwater rises above the SGHWR South Annexe and Dragon reactor base to a level and with a frequency consistent with that of a 'reasonable worst case' of future recharge calculated assuming a scenario of medium future global atmospheric emissions.
Demolition arisings porosity	Model with a porosity of 30% v/v.	Model with a porosity of 22% v/v.

Assessment of parameter value uncertainty has focussed on those parameters assessed to be most important to risk mitigation. Variant scenarios to assess sensitivity to parameter value uncertainty have been selected following consideration of the results of the reference scenario. This is described in Section 6.4.

5.2 ALTERNATIVE SCENARIO TO ADDRESS CONCEPTUAL UNCERTAINTY WITH THE EFFECTS OF CLIMATE CHANGE

The alternative scenario requires updated values for model parameters describing the frequency and level of groundwater level rise into the basement of the SGHWR South Annexe and Dragon reactor as shown in Table 611/A12.

Parameter	Unit	Value	Justification/Reference
Water Level above South Annexe base level at t = 0 years	m	0	Current conditions are assumed to occur at the time the cap is completed.
Number of years in climate change modelling simulation time period within which	-	0	Current conditions are assumed to occur at the time the cap is completed.

Table 611/A12: Values of Water Level Parameters used in the Alternative Scenario

Parameter	Unit	Value	Justification/Reference
groundwater level exceeds South Annexe basal level at t = 0 years			
Water Level above South Annexe base level at t = 18 years	m	0.8	WSP (2023). 50% of 2080s RWC ⁸ value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds South Annexe basal level at t = 18 years	-	21	Groundwater is assumed to inundate the South Annexe every year.
Water Level above South Annexe base level at t = 48 years	m	0.8	WSP (2023). 50% of 2080s RWC value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds South Annexe basal level at t = 48 years	-	21	Groundwater is assumed to inundate the South Annexe every year.
Water Level above South Annexe base level at t = 100,000 years	m	0.8	WSP (2023). Worst case conditions are assumed to persist to 2100 and beyond.
Number of years in climate change modelling simulation time period within which groundwater level exceeds South Annexe basal level at t = 100,000 years	-	21	WSP (2023). Worst case conditions are assumed to persist to 2100 and beyond.
Water level above Dragon base level at t = 0 years	m	0	Current conditions are assumed to occur at the time the cap is completed.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon basal level at t = 0 years	-	0	Current conditions are assumed to occur at the time the cap is completed.

⁸ Reasonable Worst Case

Parameter	Unit	Value	Justification/Reference
Water Level above Dragon base level at t = 18 years	m	0.95	WSP (2023). 50% of 2080s RWC value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon basal level at t = 18 years	-	21	Groundwater is assumed to inundate the South Annexe every year.
Water Level above Dragon base level at t = 48 years	m	0.95	WSP (2023). 50% of 2080s RWC value.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon basal level at t = 48 years	-	21	Groundwater is assumed to inundate the South Annexe every year in this alternative scenario.
Water Level above South Annexe base level at t = 100,000 years	m	0.95	WSP (2023). Worst case conditions are assumed to persist to 2100 and beyond.
Number of years in climate change modelling simulation time period within which groundwater level exceeds Dragon basal level at t = 100,000 years	-	21	WSP (2023). Worst case conditions are assumed to persist to 2100 and beyond.

5.3 VARIANT SCENARIOS TO ADDRESS MODEL UNCERTAINTY

Three variant scenarios, addressing model uncertainty, described in this sub-section, require water flows calculated in the reference scenario to be remodelled. A fourth variant scenario, addressing uncertainty in the volumetric porosity of the demolition arisings is concerned with parameter value uncertainty but is included in this sub-section because it, too, potentially affects the modelled water flows.

5.3.1 EVOLUTION OF THE EFFECTIVE HYDRAULIC CONDUCTIVITY OF THE CONCRETE STRUCTURES

The variant scenario models assume, (i) faster degradation from a more degraded starting condition; and (ii) a less degraded (lower effective hydraulic conductivity) starting condition, for the concrete of the SGHWR Regions 1 and 2 structure compared to the reference scenario. Amended values of model parameters are shown in Table 611/A13.

Table 611/A13: Hydraulic Conductivity of the Regions 1 and 2 Structure used in the Variant Scenarios

Parameter	Unit	Value	Justification/Reference
K (early degradation – high K variant) for Regions 1 and 2 structural concrete at 0 years	- (m/s)	-9 (1E-9)	
K (early degradation - high K variant) for Regions 1 and 2 structural concrete at 300 years	- (m/s)	-3.568 (2.7E-4)	
K (early degradation - high K variant) for Regions 1 and 2 structural concrete at 100,000 years	- (m/s)	-3.568 (2.7E-4)	NRS (2024c) Section 5. Uppermost value in cell to left: exponent of base 10.
K (low K variant) for Regions 1 and 2 structural concrete at 0 years	- (m/s)	-12 (1E-12)	brackets): value of hydraulic conductivity.
K (low K variant) for Regions 1 and 2 structural concrete at 1,000 years	- (m/s)	-3.568 (2.7E-4)	
K (low K variant) for Regions 1 and 2 structural concrete at 100,000 years	- (m/s)	-3.568 (2.7E-4)	

5.3.2 EVOLUTION OF THE RATE OF INFILTRATION TO THE CAP

The variant scenario model assumes a faster rate of cap degradation than the reference scenario.

Changes are required to cap infiltration rates to the SGHWR and the Dragon reactor (Table 611/A14) to model this variant scenario.

Table 611/A14: Cap Infiltration Rates used in the Variant Scenario

Parameter	Unit	Value	Justification/Reference
Cap infiltration rate at 0 years	mm/yr	5	NRS (2024c). The variant scenario cap is assumed to be designed to reduce the infiltration rate to less than 5 mm/yr for 125 years.
Cap infiltration rate at 125 years	mm/yr	5	NRS (2024c). The variant scenario cap is assumed to be designed to reduce the infiltration rate to less than 5 mm/yr for 125 years.

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Parameter	Unit	Value	Justification/Reference
Cap infiltration rate at 500 years	mm/yr	43	NRS (2024c). The infiltration rate through the engineered cap is assumed to increase linearly to a maximum value of 43 mm/yr after 500 years.
Cap infiltration rate at 100,000 years	mm/yr	43	NRS (2024c). Increases in the cap infiltration rate are assumed not to happen after 500 years.

5.3.3 FREQUENCY AND EXTENT OF GROUNDWATER INUNDATION TO THE SGHWR SOUTH ANNEXE AND TO THE DRAGON REACTOR BASEMENT

The variant scenario assumes groundwater rises above the base of the SGHWR South Annexe and Dragon reactor base to a level and with a frequency consistent with that of a 'reasonable worst case' of future recharge calculated assuming a scenario of medium future global emissions.

Changes are required to the reference scenario water levels and flooding frequency as described in (Table 611/A15) to model this variant scenario.

Table 611/A15: Values of Water	Level Parameters for the	Variant Scenario of	'Reasonable Worst Case	э'
Recharge				

Parameter	Unit	Value	Justification/Reference
Water Level above South Annexe base level at t = 0 years	m	0	Current conditions are assumed to occur at the time the cap is completed.
Number of years within which groundwater level exceeds South Annexe basal level at t = 0 years	-	0	Current conditions are assumed to occur at the time the cap is completed.
Water level above South Annexe base level at t = 18 years	m	0.8	WSP (2023). 50% of 2080s RWC value.
Number of years within which groundwater level exceeds South Annexe basal level at t = 18 years	-	6	WSP (2023). 2080s RWC value.
Water level above South Annexe base level at t = 48 years	m	0.8	WSP (2023). 50% of 2080s RWC value.

Parameter	Unit	Value	Justification/Reference
Number of years within which Groundwater level exceeds South Annexe basal level at t = 48 years	-	6	WSP (2023). 2080s RWC value.
Water level above South Annexe base level at t = 100,000 years	m	0.8	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
Number of years within which Groundwater level exceeds South Annexe basal level at t = 100,000 years	-	6	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
Water level above Dragon base level at t = 0 years	m	0	Current conditions are assumed to occur at the time the cap is completed.
Number of years within which groundwater level exceeds Dragon basal level at t = 0 years	-	0	Current conditions are assumed to occur at the time the cap is completed.
Water level above Dragon base level at t = 18 years	m	0.95	WSP (2023). 50% of 2080s RWC value.
Number of years within which groundwater level exceeds Dragon basal level at t = 18 years	-	6	WSP (2023). 2080s RWC value.
Water level above Dragon base level at t = 48 years	m	0.95	WSP (2023). 50% of 2080s RWC value.
Number of years within which groundwater level exceeds Dragon basal level at t = 48 years	-	6	WSP (2023). 2080s RWC value.
Water level above South Annexe base level at t = 100,000 years	m	0.95	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
Number of years within which groundwater level exceeds Dragon basal level at t = 100,000 years	-	6	WSP (2023). 2080s conditions are assumed to persist to 2100 and beyond.
5.3.4 POROSITY OF DEMOLITION ARISINGS

This variant scenario is used to assess uncertainty in the volumetric porosity of the demolition arisings and assumes a porosity of 22% v/v for the demolition arisings based on an assumed bulking factor for the demolition arisings of 1.22. This is a lower porosity than that assumed for the reference scenario (30% v/v) that is based on the minimum void space between spherical particles being 26% v/v and random packing of equal spheres having a porosity of around 36% v/v.

6 RESULTS OF THE REFERENCE SCENARIO

6.1 MODELLED HYDRAULICS

Accumulation of water is modelled to occur in Regions 1 and 2 of the SGHWR. The change in water level with time calculated by the GoldSim model for Regions 1 and 2 is shown in Figure 611/A6. As summarised in Table 611/A7 external water levels in the Poole Formation surrounding Regions 1 and 2 have been modelled to rise over the first 48 years of the simulation and be maintained at 34 m AOD thereafter. This corresponds to a modelled external water level elevation of 5.2 metres above the top of the base of the SGHWR Regions 1 and 2 after 48 years. Whilst the water level in Regions 1 and 2 rises above external groundwater levels, it is modelled to not exceed the wall height of 11.8 m and therefore does not overtop the structure.

Figure 611/A6: Annotated Graph of the Modelled Change in Water Level in the SGHWR Regions 1 and 2 for the Reference Scenario [only the first 5,000 years is shown for clarity]



A graph of the modelled volume of water accumulated within the SGHWR Regions 1 and 2 for the reference scenario is shown in Figure 611/A7. The water volume within the void when the internal water level stabilises (and is close to the external groundwater level) is greater than 2,000 m³, satisfying the assumption of the dilution calculations in the GQRA.





Water outflow rates from the SGHWR and Dragon reactor and are shown in Figure 611/A8 and Figure 611/A9, respectively. Of the modelled regions of the SGHWR, the outflow rate is greatest from the SGHWR South Annexe due to the contribution to outflow of episodic groundwater inundation.

Figure 611/A8: Graph of Modelled Water Outflow Rates from the Regions of the SGHWR for the Reference Scenario [only the first 5,000 years is shown for clarity]



Figure 611/A9: Graph of Modelled Water Outflow Rate from the Dragon Reactor for the Reference Scenario [only the first 5,000 years is shown for clarity]



6.2 CONTAMINANT CONCENTRATIONS

The modelled peak concentrations of contaminants in groundwater at the compliance point (the downgradient boundary of the disposals) for the reference scenario are presented in Table 611/A16 and Table 611/A17 for the SGHWR and Dragon reactor End States, respectively. The last column in each table shows the ratio of the compliance limit for each parameter to its modelled peak concentration and is therefore a measure of the factor of safety.

Table 611/A16: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point
of the SGHWR for the Reference Scenario

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
PCB-28	2.9E-08	1435	1.0E-06	34.8
PCB-52	4.2E-08	1429	1.0E-06	23.6
PCB-101	3.4E-08	1527	1.0E-06	29.2
PCB-118	1.7E-09	1934	1.0E-06	602
PCB-138	2.6E-09	1961	1.0E-06	391
PCB-153	4.1E-10	2499	1.0E-06	2445
PCB-180	6.5E-12	4607	1.0E-06	154335
Chromium (III)	5.1E-04	996	4.7E-03	9.3
Chromium (VI)	5.1E-04	996	1.0E-03	2.0
Copper	3.0E-06	11778	1.2E-02	4045
Lead	1.5E-06	8598	2.0E-04	135
Zinc	1.0E-05	6453	3.3E-02	3177
>C10-C12 Aromatic	6.1E-05	761	1.0E-02	163
>C12-C16 Aromatic	1.4E-05	1003	1.0E-02	717
>C16-C21 Aromatic	1.8E-05	1029	1.0E-02	557

 Table 611/A17: Modelled Peak Concentration of Contaminants in Groundwater at the Dragon Reactor

 Compliance Point for the Reference Scenario

Parameter	Peak Concentration	Time of Peak Concentration	Compliance Limit	Compliance Limit / Peak
	(mg/l)	(yr)	(mg/l)	Concentration
PCB-28	4.8E-08	1204	1.0E-06	20.9
PCB-52	6.9E-08	1201	1.0E-06	14.5
PCB-101	8.9E-08	1251	1.0E-06	11.3
PCB-118	1.7E-08	1355	1.0E-06	60.4
PCB-138	2.7E-08	1358	1.0E-06	37.2
PCB-153	1.1E-08	1409	1.0E-06	92.3
PCB-180	2.2E-09	1608	1.0E-06	448
Chromium (III)	2.2E-04	589	4.7E-03	21
Chromium (VI)	2.2E-04	589	1.0E-03	4.5
Copper	6.5E-07	1092	1.2E-02	18501
Lead	4.2E-07	3569	2.0E-04	471
Zinc	1.9E-06	1037	3.3E-02	16951

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants are less than compliance criteria.

PCB-52 and chromium (VI) have the highest calculated peak concentrations of modelled PCBs and metals, respectively, in groundwater downgradient of the SGHWR compared to compliance criteria. The >C10-C12 aromatic hydrocarbon fraction derived from oil staining of Regions 1 and 2 of the SGHWR has the highest modelled peak concentrations of hydrocarbon fractions. Time histories of concentration in groundwater at the downgradient boundary of the SGHWR deposits/disposals for PCB-52, chromium (VI) and the >C10-C12 aromatic hydrocarbon fraction are shown in Figure 611/A10, Figure 611/A11 and Figure 611/A12, respectively. The difference in the shape of the time histories in each of the three figures principally reflects the mobility of each modelled contaminant. PCB-52 is modelled to sorb more strongly to the demolition arisings and Poole Formation than chromium (VI) and the >C10-C12 aromatic hydrocarbon fraction. Resultantly, the modelled time to peak concentration at the compliance point is the longest and the concentration does not return to zero within 20,000 years due to the slower rate of 'flushing' of the contaminant from the demolition arisings. Conversely, the >C10-12 aromatic hydrocarbon fraction is the least strongly sorbing of the three contaminants, resulting in the shortest modelled time to peak concentration at the compliance point and the shortest time for its concentration in groundwater at the compliance point to return to zero.

Figure 611/A10: Modelled PCB-52 Concentration in Groundwater at the Compliance Point for the SGHWR for the Reference Scenario



Figure 611/A11: Modelled Chromium (VI) Concentration in Groundwater at the Compliance Point for the SGHWR for the Reference Scenario



Figure 611/A12: Modelled >C10-C12 Aromatic Hydrocarbon Fraction Concentration in Groundwater at the Compliance Point for the SGHWR for the Reference Scenario



PCB-180 takes the longest time to reach peak concentration in groundwater downgradient of the SGHWR of the modelled PCBs. Copper has the longest modelled time to peak concentration in groundwater downgradient of the SGHWR of the modelled metals.

Graphs of the concentration in groundwater at the downgradient boundary of the SGHWR deposits/disposals for PCB-180 and copper are shown in Figure 611/A13 and Figure 611/A14, respectively. The graph for copper has a maximum concentration and a later, higher, peak concentration. This is because retardation causes a difference in arrival times at the compliance point of dissolved copper released from the SGHWR Regions 1 and 2, North Annexe and South Annexe. The same effect is visible on the graph of the >C10-C12 aromatic hydrocarbon fraction (Figure 611/A12) although it is much less pronounced. This effect is not observed for PCB-180 due to its biodegradation in the Poole Formation saturated and unsaturated pathways.

Figure 611/A13: Modelled PCB-180 Concentration Time History in Groundwater at the Compliance Point for the SGHWR for the Reference Scenario



Figure 611/A14: Modelled Copper Concentration Time History in Groundwater at the Compliance Point for the SGHWR for the Reference Scenario



6.3 ASSESSMENT OF CUMULATIVE EFFECTS

The modelled concentrations of contaminants in groundwater immediately downgradient of the SGHWR are so far below the compliance criteria for the reference scenario that it is evident that an additive effect of the contaminants from the Dragon reactor deposits/disposals will not lead to concentrations downgradient of the Dragon reactor exceeding compliance criteria. No modelling of cumulative effects has therefore been undertaken.

6.4 PARAMETERS SELECTED FOR SENSITIVITY ANALYSIS BASED ON THE RESULTS OF THE REFERENCE SCENARIO

NRS (2024c) lists parameter value uncertainties. These uncertainties have been in part addressed by adopting reasonably cautious values for the reference scenario model. The purpose of sensitivity analysis for parameter value uncertainty is to provide further confidence in the robustness of the assessment. To select parameters for sensitivity analysis the approach has been to:

- Assess the results of the reference scenario model run to identify the most important factors mitigating the risk to groundwater; and
- Assess the level of confidence in the values of the parameters that describe the identified mitigating factors. For those parameters where it is judged the level of confidence in the assessment can be improved by sensitivity analysis, runs varying the values of those parameters have been undertaken.

The risk mitigating factors judged most important are described by component in Table 611/A18.

Component in the SGHWR and Dragon reactor	Most Important Risk Mitigation Factors
Demolition arisings: PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, PCB-153 and PCB-180	 Inventory mass. Partition with the demolition arisings. Dilution. Partition with the unsaturated and saturated Poole Formation. Biodegradation in the unsaturated and saturated Poole Formation.
Demolition arisings: Chromium (as Cr (III) and Cr (VI)), copper, lead and zinc	 Inventory mass. Partition with the demolition arisings. Dilution. Partition with the unsaturated and saturated Poole Formation.
Oil stains (SGHWR only): >C10-C12, >C12-C16 and >C16-C21 aromatic hydrocarbon fractions	 Inventory mass. Dilution. Partition with the unsaturated and saturated Poole Formation.

Table 611/A18: Most Important Mitigation Factors Identified from the GoldSim Model of the Reference Scenario

The level of confidence in each of the factors identified in Table 611/A18 has been assessed as follows:

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- Dilution: The groundwater flow rate is based on catchment area and recharge rate. The catchment area is measured from site plans and there is negligible uncertainty. The recharge rate based on BGS modelling is considered suitably robust for the assessment. There is sufficient confidence in the values of underpinning parameters that no further sensitivity analysis is required.
- **Partition with demolition arisings and Poole Formation**: There is confidence that the selected values are sufficiently cautious that no further modelling is required because:
 - The reference scenario uses conservative metal partition coefficients. Values ten times higher could have reasonably been selected. The results of model runs with variant values would therefore show the risk is even lower.
 - Partition of organic compounds (PCBs and hydrocarbon fractions) depends on the assumed fraction of organic carbon. The reference scenario uses the lower 95% confidence on the mean of the measured values of the fraction of organic carbon in the demolition arisings and in the Poole Formation.
- Inventory mass: The inventory mass of hydrocarbon compounds is based on characterisation data of oil staining in the SGHWR. The reference scenario uses the upper 95% confidence on the mean of the analytical dataset of hydrocarbon concentrations from samples that directly targeted the oil staining. Furthermore, the calculated mass of hydrocarbon compounds was based on a 10mm depth of oil penetration of concrete, approximately three times higher than that encountered during the NRS (2024b) investigation. There is confidence the selected values are sufficiently cautious such that no further modelling is required. A variant scenario has been developed to assess whether the results are sensitive to small differences in the mass of metals and PCBs in the demolition arisings from that derived from the stockpile laboratory analysis results. Such differences could arise if the demolition arisings were less bulked (have a lower volumetric porosity) than assumed in the reference scenario. The variant scenario assumes the PCB and metals inventory is double that of the reference scenario.
- Sensitivity to biodegradation of PCBs in the Poole Formation: Pessimistic degradation rates for PCBs in the Poole Formation have been derived from literature. Whilst the values used in the reference scenario are highly cautious it is judged that, since there is no site-specific data, confidence in the selected values could be improved by sensitivity analysis. Sensitivity to the PCB degradation values used in the model will be assessed by assuming no degradation of PCBs in the Poole Formation.

In summary, variant runs assessing the sensitivity of the model to the rates of PCB and metals inventory and PCB degradation have been carried out.

7 RESULTS OF SENSITIVITY ANALYSIS

7.1 RESULTS OF MODELLING OF THE ALTERNATIVE SCENARIO TO ADDRESS CONCEPTUAL UNCERTAINTY WITH THE EFFECTS OF CLIMATE CHANGE

An alternative scenario has been modelled with GoldSim to assess the risk to groundwater quality with an assumed frequency and level groundwater inundation to the SGHWR South Annexe and to the Dragon reactor basement under 'worst case' conditions of climate change (as described in Table 611/A10). The modelled peak concentrations in groundwater at the downgradient compliance points of the SGHWR and Dragon reactor are presented in Table 611/A19 and Table 611/A20, respectively.

 Table 611/A19: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point

 for the SGHWR for the Reference Scenario and Alternative Scenario

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	Scenario		Altern	ative Scenario	
PCB-28	2.9E-08	1435	4.5E-08	1297	1.0E-06	22.4
PCB-52	4.2E-08	1429	6.6E-08	1293	1.0E-06	15.1
PCB-101	3.4E-08	1527	5.1E-08	1367	1.0E-06	19.5
PCB-118	1.7E-09	1934	2.3E-09	1565	1.0E-06	430
PCB-138	2.6E-09	1961	3.6E-09	1573	1.0E-06	280
PCB-153	4.1E-10	2499	5.6E-10	1718	1.0E-06	1797
PCB-180	6.5E-12	4607	8.5E-12	2508	1.0E-06	117035
Chromium (III)	5.1E-04	996	5.2E-04	879	4.7E-03	9.0
Chromium (VI)	5.1E-04	996	5.2E-04	879	1.0E-03	1.9
Copper	3.0E-06	11778	5.2E-06	1226	1.2E-02	2289
Lead	1.5E-06	8598	2.2E-06	6660	2.0E-04	92
Zinc	1.0E-05	6453	1.7E-05	1091	3.3E-02	1959
>C10-C12 Aromatic	6.1E-05	761	6.0E-05	761	1.0E-02	167
>C12-C16 Aromatic	1.4E-05	1003	1.4E-05	1002	1.0E-02	734
>C16-C21 Aromatic	1.8E-05	1029	1.8E-05	1028	1.0E-02	570

 Table 611/A20: Modelled Peak Concentrations of Contaminants in Groundwater at the Dragon Reactor

 Compliance Point for the Reference Scenario

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	Scenario		Alterna	ative Scenario	
PCB-28	4.8E-08	1204	1.5E-07	1111	1.0E-06	6.8
PCB-52	6.9E-08	1201	2.1E-07	1108	1.0E-06	4.7
PCB-101	8.9E-08	1251	2.8E-07	1141	1.0E-06	3.6
PCB-118	1.7E-08	1355	5.2E-08	1207	1.0E-06	19.3
PCB-138	2.7E-08	1358	8.4E-08	1209	1.0E-06	11.9
PCB-153	1.1E-08	1409	3.4E-08	1237	1.0E-06	29.4
PCB-180	2.2E-09	1608	7.0E-09	1305	1.0E-06	142
Chromium (III)	2.2E-04	589	5.1E-04	214	4.7E-03	9
Chromium (VI)	2.2E-04	589	5.1E-04	214	1.0E-03	2.0
Copper	6.5E-07	1092	2.0E-06	1050	1.2E-02	6033
Lead	4.2E-07	3569	1.1E-06	2526	2.0E-04	176
Zinc	1.9E-06	1037	6.0E-06	1021	3.3E-02	5526

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants are less than compliance criteria.

Increased 'flushing' of PCBs and metals from the SGHWR South Annexe and Dragon reactor demolition arisings is caused by the modelled increase in flooding frequency and level of groundwater inundating the SGHWR South Annexe and Dragon reactor basement.

Increased flushing of the demolition arisings in the SGHWR South Annexe and Dragon reactor basement results in higher mass fluxes of PCBs and metals into Poole Formation groundwater, resulting in higher concentrations in groundwater and earlier arrival of the peak concentrations at the compliance points compared to the reference scenario.

The modelled differences in peak concentrations of contaminants between the alternative scenario and the reference scenario are greatest for the Dragon reactor because a greater proportion of the Dragon reactor demolition arisings is subject to increased flushing compared to the demolition arisings in the SGHWR (only the demolition arisings in the South Annexe are subject to modelled increased flushing at the SGHWR).

The modelled concentrations of the hydrocarbon fractions downgradient of the SGHWR are invariant from the reference scenario as these contaminants are modelled to be only present within SGHWR Regions 1 and 2 and are therefore unaffected by the modelled changes in inundation.

Even under the worst envisaged conditions in which climate change causes groundwater to rise into the South Annexe each year and then fall, thereby flushing contaminants from the deposits/disposals, the risk to groundwater is modelled to be acceptable.

7.2 RESULTS OF MODELLING VARIANT SCENARIOS TO ADDRESS MODEL UNCERTAINTY

7.2.1 EVOLUTION OF THE EFFECTIVE HYDRAULIC CONDUCTIVITY OF THE CONCRETE STRUCTURES

The modelled peak concentrations in groundwater at the SGHWR compliance point for the variant scenarios of slower and faster early time concrete degradation are presented in Table 611/A21 and Table 611/A22, respectively.

Table 611/A21: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point for the SGHWR for the Variant Scenario in which Concrete Degrades more Slowly during Early Time

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	scenario	Variant scenario			
PCB-28	2.9E-08	1435	2.9E-08	1436	1.0E-06	34.9
PCB-52	4.2E-08	1429	4.2E-08	1430	1.0E-06	23.6
PCB-101	3.4E-08	1527	3.4E-08	1527	1.0E-06	29.2
PCB-118	1.7E-09	1934	1.7E-09	1941	1.0E-06	602
PCB-138	2.6E-09	1961	2.6E-09	1968	1.0E-06	391
PCB-153	4.1E-10	2499	4.1E-10	2521	1.0E-06	2448
PCB-180	6.5E-12	4607	6.5E-12	4647	1.0E-06	154517
Chromium (III)	5.1E-04	996	5.1E-04	1008	4.7E-03	9.2
Chromium (VI)	5.1E-04	996	5.1E-04	1008	1.0E-03	2.0
Copper	3.0E-06	11778	3.0E-06	11783	1.2E-02	4046
Lead	1.5E-06	8598	1.5E-06	8602	2.0E-04	135
Zinc	1.0E-05	6453	1.0E-05	6455	3.3E-02	3178

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Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
>C10-C12 Aromatic	6.1E-05	761	6.3E-05	761	1.0E-02	158
>C12-C16 Aromatic	1.4E-05	1003	1.4E-05	1003	1.0E-02	705
>C16-C21 Aromatic	1.8E-05	1029	1.8E-05	1029	1.0E-02	554

 Table 611/A22: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point

 for the SGHWR for the Variant Scenario in which Concrete Degrades more Quickly during Early Time

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference s	scenario		Vari	ant scenario	
PCB-28	2.9E-08	1435	2.9E-08	1432	1.0E-06	34.7
PCB-52	4.2E-08	1429	4.3E-08	1427	1.0E-06	23.5
PCB-101	3.4E-08	1527	3.4E-08	1522	1.0E-06	29.1
PCB-118	1.7E-09	1934	1.7E-09	1909	1.0E-06	599
PCB-138	2.6E-09	1961	2.6E-09	1934	1.0E-06	389
PCB-153	4.1E-10	2499	4.1E-10	2454	1.0E-06	2434
PCB-180	6.5E-12	4607	6.5E-12	4439	1.0E-06	153589
Chromium (III)	5.1E-04	996	5.0E-04	993	4.7E-03	9.4
Chromium (VI)	5.1E-04	996	5.0E-04	993	1.0E-03	2.0
Copper	3.0E-06	11778	3.0E-06	11761	1.2E-02	4041
Lead	1.5E-06	8598	1.5E-06	8585	2.0E-04	135
Zinc	1.0E-05	6453	1.0E-05	6445	3.3E-02	3172
>C10-C12 Aromatic	6.1E-05	761	6.0E-05	761	1.0E-02	166
>C12-C16 Aromatic	1.4E-05	1003	1.4E-05	1003	1.0E-02	724
>C16-C21 Aromatic	1.8E-05	1029	1.8E-05	1029	1.0E-02	559

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants are less than compliance criteria.

The modelled peak concentrations of contaminants at the compliance point in the variant scenarios show little difference from those of the modelled reference scenario. This is because, regardless of the potential for a change in leakage rate under the variant conditions of concrete degradation, it is the cap infiltration rate that largely controls the rate of outflow from the deposits/disposals when the peak concentration is realised. This is illustrated in Figure 611/A15 which shows that the cap infiltration rate and outflow rate for SGHWR Regions 1 and 2 are indistinct after 50 years (the lines of the graph overlie each other).

Figure 611/A15: Comparison of Outflow Rate and Cap Infiltration Rate for the Variant Scenario of Faster Early Time Degradation of the Regions 1 and 2 Structure [only the first 5,000 years is shown for clarity]



With a lower rate of concrete degradation, there is a greater accumulation of water in Regions 1 and 2. However, as demonstrated by Figure 611/A16, the water does not exceed the Regions 1 and 2 wall top elevation of 40.6 mAOD in the modelled variant scenario.

Figure 611/A16: Modelled Water Level for SGHWR Regions 1 and 2 of the Variant Scenario of Slower Early Time Concrete Degradation [only the first 5,000 years is shown for clarity]



7.2.2 EVOLUTION OF THE RATE OF INFILTRATION TO THE CAP

The modelled peak concentrations in groundwater at the downgradient boundary of the deposits/disposals for the variant scenario of cap infiltration are presented in Table 611/A23 and Table 611/A24 for the SGHWR and Dragon reactor, respectively.

 Table 611/A23: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point

 for the SGHWR for the Variant Scenario in which the Cap Degrades Faster

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit /Peak Concentration
	Reference	ce scenario		Vari	ant scenario	·
PCB-28	2.9E-08	1435	2.9E-08	983	1.0E-06	34.8
PCB-52	4.2E-08	1429	4.2E-08	977	1.0E-06	23.5
PCB-101	3.4E-08	1527	3.4E-08	1086	1.0E-06	29.2
PCB-118	1.7E-09	1934	1.7E-09	1583	1.0E-06	601
PCB-138	2.6E-09	1961	2.6E-09	1612	1.0E-06	391
PCB-153	4.1E-10	2499	4.1E-10	2188	1.0E-06	2445
PCB-180	6.5E-12	4607	6.5E-12	4301	1.0E-06	154325
Chromium (III)	5.1E-04	996	5.6E-04	789	4.7E-03	8.4
Chromium (VI)	5.1E-04	996	5.6E-04	789	1.0E-03	1.8
Copper	3.0E-06	11778	3.0E-06	11399	1.2E-02	4044
Lead	1.5E-06	8598	1.5E-06	8351	2.0E-04	135
Zinc	1.0E-05	6453	1.0E-05	6131	3.3E-02	3181
>C10-C12 Aromatic	6.1E-05	761	9.0E-05	502	1.0E-02	112
>C12-C16 Aromatic	1.4E-05	1003	1.8E-05	508	1.0E-02	553
>C16-C21 Aromatic	1.8E-05	1029	1.9E-05	546	1.0E-02	516

 Table 611/A24: Modelled Peak Concentrations of Contaminants in Groundwater at the Dragon Reactor

 Compliance Point for the Variant Scenario in which the Cap Degrades Faster

Parameter	Peak Concentration (mg/l)	Time of Peak (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference s	cenario		Varia	nt scenario	
PCB-28	4.8E-08	1204	4.8E-08	731	1.0E-06	20.8
PCB-52	6.9E-08	1201	6.9E-08	727	1.0E-06	14.5
PCB-101	8.9E-08	1251	8.9E-08	782	1.0E-06	11.3
PCB-118	1.7E-08	1355	1.7E-08	899	1.0E-06	60.4
PCB-138	2.7E-08	1358	2.7E-08	903	1.0E-06	37.1
PCB-153	1.1E-08	1409	1.1E-08	964	1.0E-06	92.2
PCB-180	2.2E-09	1608	2.2E-09	1232	1.0E-06	448
Chromium (III)	2.2E-04	589	3.0E-04	506	4.7E-03	16
Chromium (VI)	2.2E-04	589	3.0E-04	506	1.0E-03	3.3
Copper	6.5E-07	1092	6.5E-07	604	1.2E-02	18448
Lead	4.2E-07	3569	4.3E-07	3299	2.0E-04	470
Zinc	1.9E-06	1037	2.0E-06	542	3.3E-02	16901

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants are less than compliance criteria.

Peak concentrations vary little from those of the reference scenario except for >C10-C12 aromatic compounds. >C10-C12 aromatic compounds are the most mobile hydrocarbon fraction modelled. Earlier and more rapid release of the inventory to the Poole Formation groundwater is observed in the results, as shown in Figure 611/A17.

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Figure 611/A17: Modelled Concentrations of >C10-C12 Aromatic Hydrocarbon Compounds in Groundwater at the SGHWR Compliance Point for the High Infiltration Variant Scenario and the Reference Scenario



7.2.3 THE FREQUENCY AND EXTENT OF GROUNDWATER INUNDATION TO THE SGHWR SOUTH ANNEXE AND TO THE DRAGON REACTOR BASEMENT

The modelled peak concentrations in groundwater at the downgradient boundary of the deposits/disposals for the variant scenario of reasonable worst case conditions of climate change is presented in Table 611/A25 and Table 611/A26 for the SGHWR and Dragon reactor, respectively.

 Table 611/A25: Modelled Peak Concentrations of Contaminants in Groundwater at the Compliance Point for the SGHWR for the Variant Scenario of Reasonable Worst Case Conditions of Climate Change

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference s	scenario	Varian	nt scenario of conditions of	reasonable we climate chan	orst case ge
PCB-28	2.9E-08	1435	3.2E-08	1392	1.0E-06	31.2
PCB-52	4.2E-08	1429	4.7E-08	1386	1.0E-06	21.1
PCB-101	3.4E-08	1527	3.8E-08	1473	1.0E-06	26.5
PCB-118	1.7E-09	1934	1.8E-09	1761	1.0E-06	557
PCB-138	2.6E-09	1961	2.8E-09	1776	1.0E-06	362
PCB-153	4.1E-10	2499	4.4E-10	2161	1.0E-06	2282
PCB-180	6.5E-12	4607	6.9E-12	3857	1.0E-06	145301
Chromium (III)	5.1E-04	996	5.3E-04	935	4.7E-03	8.9
Chromium (VI)	5.1E-04	996	5.3E-04	935	1.0E-03	1.9
Copper	3.0E-06	11778	3.3E-06	10377	1.2E-02	3596
Lead	1.5E-06	8598	1.7E-06	8075	2.0E-04	119
Zinc	1.0E-05	6453	1.2E-05	5931	3.3E-02	2781
>C10-C12 Aromatic	6.1E-05	761	6.1E-05	761	1.0E-02	164
>C12-C16 Aromatic	1.4E-05	1003	1.4E-05	1003	1.0E-02	720
>C16-C21 Aromatic	1.8E-05	1029	1.8E-05	1029	1.0E-02	560

 Table 611/A26: Modelled Peak Concentrations of Contaminants in Groundwater at the Dragon Reactor

 Compliance Point for the Variant Scenario of Reasonable Worst Case Conditions of Climate Change

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	scenario	Variant	scenario o conditions	of reasonable v of climate cha	vorst case nge
PCB-28	4.8E-08	1204	6.9E-08	1175	1.0E-06	14.4
PCB-52	6.9E-08	1201	9.9E-08	1172	1.0E-06	10.1
PCB-101	8.9E-08	1251	1.3E-07	1216	1.0E-06	7.8
PCB-118	1.7E-08	1355	2.4E-08	1307	1.0E-06	41.7
PCB-138	2.7E-08	1358	3.9E-08	1310	1.0E-06	25.7
PCB-153	1.1E-08	1409	1.6E-08	1351	1.0E-06	63.7
PCB-180	2.2E-09	1608	3.2E-09	1476	1.0E-06	309
Chromium (III)	2.2E-04	589	3.3E-04	333	4.7E-03	14
Chromium (VI)	2.2E-04	589	3.3E-04	333	1.0E-03	3.1
Copper	6.5E-07	1092	9.4E-07	1078	1.2E-02	12833
Lead	4.2E-07	3569	5.9E-07	3204	2.0E-04	338
Zinc	1.9E-06	1037	2.8E-06	1032	3.3E-02	11757

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants vary little from the reference scenario.

Like the alternative scenario of worst case conditions of climate change:

- Increased flushing of the South Annexe and Dragon basement results in higher mass fluxes of PCBs and metals into Poole Formation groundwater, resulting in higher concentrations in groundwater and earlier arrival of the peak concentrations at the compliance points compared to the reference scenario;
- The modelled differences in peak concentrations of contaminants between the alternative scenario and the reference scenario are greatest for the Dragon reactor because a greater proportion of the Dragon reactor demolition arisings are subject to increased flushing compared to the SGHWR where only the demolition arisings placed in the South Annexe are subject to increased flushing; and

The concentrations of hydrocarbon compounds downgradient of the SGHWR are invariant from the reference scenario as these are only modelled to be present within SGHWR Regions 1 and 2, and therefore are unaffected by the modelled changes in groundwater inundation.

The effect on peak concentrations and arrival times of metals and PCBs at the downgradient compliance point is less than that of the alternative scenario of worst case conditions of climate change because there is less inundation of the deposits/disposals by groundwater.

7.2.4 POROSITY OF DEMOLITION ARISINGS

The principal effect of lower porosity demolition arisings is on water levels in the SGHWR Regions 1 and 2. Water levels in the variant scenario of lower porosity rise higher than in the reference scenario but do not overtop the structure. However, due to the modelled low hydraulic conductivity of the Regions 1 and 2 structure during the first 100 years of the simulation there is little difference in calculated water outflow rates. This is summarised in Figure 611/A18 and Figure 611/A19.









7.2.5 SUMMARY OF MODELS OF VARIANT SCENARIOS TO ASSESS MODEL UNCERTAINTY

The peak concentrations of contaminants at compliance points for the modelled variant scenarios are little different or invariant from those of the modelled reference scenario. It is therefore concluded that despite the model uncertainty that the risk to groundwater from all modelled contaminants is acceptable.

7.3 VARIANT MODELS TO ASSESS PARAMETER VALUE UNCERTAINTY

7.3.1 SENSITIVITY TO PCB BIODEGRADATION

The modelled peak concentrations in groundwater at the downgradient boundary of the deposits/disposals for the variant scenario of no PCB biodegradation are presented in Table 611/A27 and Table 611/A28 for the SGHWR and Dragon reactor, respectively.

Table 611/A27: Modelled Peak Concentrations of PCBs in Groundwater at the Compliance Point for the SGHWR for the Variant Scenario of no PCB Biodegradation

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration	
	Reference scenario		Variant scenario of no PCB biodegradation				
PCB-28	2.9E-08	1435	6.0E-07	2808	1.0E-06	1.7	
PCB-52	4.2E-08	1429	8.4E-07	2759	1.0E-06	1.2	
PCB-101	3.4E-08	1527	1.4E-06	3623	1.0E-06	0.73	
PCB-118	1.7E-09	1934	4.2E-07	6780	1.0E-06	2.4	
PCB-138	2.6E-09	1961	7.0E-07	6926	1.0E-06	1.4	
PCB-153	4.1E-10	2499	3.6E-07	9564	1.0E-06	2.8	
PCB-180	6.5E-12	4607	1.2E-07	18582	1.0E-06	8	

 Table 611/A28: Modelled Peak Concentrations of PCBs in Groundwater at the Dragon Reactor

 Compliance Point for the Variant Scenario of no PCB Biodegradation

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	scenario	Variant	scenario of	no PCB biode	egradation
PCB-28	4.8E-08	1204	1.2E-07	1398	1.0E-06	8.0
PCB-52	6.9E-08	1201	1.8E-07	1387	1.0E-06	5.6
PCB-101	8.9E-08	1251	2.9E-07	1582	1.0E-06	3.5
PCB-118	1.7E-08	1355	8.9E-08	2334	1.0E-06	11.2
PCB-138	2.7E-08	1358	1.5E-07	2370	1.0E-06	6.8
PCB-153	1.1E-08	1409	7.6E-08	3032	1.0E-06	13.2
PCB-180	2.2E-09	1608	2.5E-08	5382	1.0E-06	40

The concentrations of all contaminants peak within the model run time of 20,000 years and the peak concentrations of all contaminants are less than compliance criteria at the compliance point downgradient of the SGHWR, except for PCB-101.

The peak concentration of PCB-101 should be considered within the context of the cautious modelling assumptions that have been adopted. Besides the pessimistic approach taken to modelling PCB biodegradation in the variant scenario:

- The entire mass of PCBs is assumed to be immediately water available whereas PCB containing materials may take 100s of years to decompose and release PCB to water; and
- No account is made for the volatility of PCBs, which will cause a proportion of the mass of PCB to continuously partition to air.

It is concluded on this basis that the risk from PCBs to groundwater is acceptable even if there is no biodegradation.

7.3.2 SENSITIVITY TO PCB AND METALS INVENTORY

A scenario has been assessed in which the reference scenario mass of PCBs and metals in the demolition arisings placed in both reactor basements is doubled.

The modelled peak concentrations in groundwater at the downgradient boundary of the deposits/disposals are presented in Table 611/A29 and Table 611/A30 for the SGHWR and Dragon reactor, respectively.

Table 611/A29: Modelled Peak Concentrations of PCBs and Metals in Groundwater at the Compliance Point for the SGHWR for the Variant Scenario of Increased PCB and Metals Inventory

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference	ce scenario	Variant scenario of increased mass invent			
PCB-28	2.9E-08	1435	5.7E-08	1435	1.0E-06	17.4
PCB-52	4.2E-08	1429	8.5E-08	1429	1.0E-06	11.8
PCB-101	3.4E-08	1527	6.8E-08	1527	1.0E-06	14.6
PCB-118	1.7E-09	1934	3.3E-09	1934	1.0E-06	301
PCB-138	2.6E-09	1961	5.1E-09	1961	1.0E-06	195
PCB-153	4.1E-10	2499	8.2E-10	2499	1.0E-06	1223
PCB-180	6.5E-12	4607	1.3E-11	4607	1.0E-06	77167
Chromium (III)	5.1E-04	996	1.0E-03	996	4.7E-03	4.6
Chromium (VI)	5.1E-04	996	1.0E-03	996	1.0E-03	1.0
Copper	3.0E-06	11778	5.9E-06	11778	1.2E-02	2023

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Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
Lead	1.5E-06	8598	3.0E-06	8598	2.0E-04	67
Zinc	1.0E-05	6453	2.1E-05	6453	3.3E-02	1588

 Table 611/A30: Modelled Peak Concentrations of PCBs and Metals in Groundwater at the Compliance

 Point for the Dragon Reactor for the Variant Scenario of Increased PCB and Metals Inventory

Parameter	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Peak Concentration (mg/l)	Time of Peak Concentration (yr)	Compliance Limit (mg/l)	Compliance Limit / Peak Concentration
	Reference s	scenario	Variant	scenario of i	increased mas	s inventory
PCB-28	4.8E-08	1204	9.6E-08	1204	1.0E-06	10.4
PCB-52	6.9E-08	1201	1.4E-07	1201	1.0E-06	7.3
PCB-101	8.9E-08	1251	1.8E-07	1251	1.0E-06	5.6
PCB-118	1.7E-08	1355	3.3E-08	1355	1.0E-06	30
PCB-138	2.7E-08	1358	5.4E-08	1358	1.0E-06	19
PCB-153	1.1E-08	1409	2.2E-08	1409	1.0E-06	46
PCB-180	2.2E-09	1608	4.5E-09	1608	1.0E-06	224
Chromium (III)	2.2E-04	589	4.5E-04	589	4.7E-03	11
Chromium (VI)	2.2E-04	589	4.5E-04	589	1.0E-03	2.2
Copper	6.5E-07	1092	1.3E-06	1092	1.2E-02	9251
Lead	4.2E-07	3569	8.5E-07	3569	2.0E-04	235
Zinc	1.9E-06	1037	3.9E-06	1037	3.3E-02	8475

Despite the assumed higher inventory, the modelled peak concentrations of metals and PCBs do not exceed the compliance criteria and the risk to groundwater therefore remains acceptable.

8 SUMMARY

Detailed quantitative risk assessment (DQRA) of substances other than alkalinity has been undertaken using GoldSim for the SGHWR and Dragon reactor End States. This has demonstrated that, for the reference (reasonably cautious estimate) scenario, concentrations in groundwater of all modelled substances are below compliance limits at the compliance point. It is concluded from the results that the risk to groundwater is acceptable.

Sensitivity to conceptual, model and parametric uncertainty has been undertaken in the DQRA through alternative and variant scenario modelling.

The scenarios selected for the SGHWR and Dragon reactor End States to assess conceptual and model uncertainty have been developed to examine the effects of uncertainties identified during CSM development. The modelled concentrations of all substances in groundwater are below compliance criteria at the compliance point for the alternative and variant scenarios. Therefore, despite uncertainty in the rise and fall of the water table under conditions of future climate change, uncertainty in how to model changes to the rate of infiltration through the cap to the deposits/disposals and uncertainty in how to model concrete degradation, the risk to groundwater is acceptable.

Variant scenarios have been assessed in which it is assumed there is no biodegradation of PCBs instead of the cautious degradation rates used in the reference scenario and it is assumed that metals and PCB inventory is double that of the reference scenario.

When it is assumed there is no PCB biodegradation, the concentrations in groundwater of all modelled PCBs are below compliance criteria at the compliance point downgradient of the SGHWR except for PCB-101. The peak concentration of PCB-101 should be considered within the context of the cautious modelling assumptions that have been adopted. Besides the pessimistic approach taken to modelling PCB biodegradation:

- The entire mass of PCBs is assumed to be immediately water available whereas PCB containing materials may take 100s of years to decompose and release PCB to water; and
- No account is made for the volatility of PCBs, which will cause a proportion of the mass of PCB to continuously partition to air.

It is concluded on this basis that the risk from PCBs to groundwater is acceptable even if there is no biodegradation.

When a higher inventory is assumed, the modelled peak concentrations of metals and PCBs remain below compliance criteria and the risk to groundwater is therefore acceptable.

Overall, the results of the analysis of sensitivity to parameter values provide confidence that conclusions from modelling the reference scenario are robust.

On the basis that the modelled concentrations of contaminants in groundwater immediately downgradient of the SGHWR are so far below the compliance criteria in the reference scenario, no modelling has been undertaken of cumulative effects in groundwater downgradient of Dragon reactor from PCBs, metals or hydrocarbon compounds. The risk to groundwater from the cumulative release of contaminants from both the SGHWR and Dragon reactor is judged acceptable.

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Appendix B

DETAILED DESCRIPTION OF MODELLING OF ALKALINITY MIGRATION USING PHAST



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Appendix B: Detailed Description of Modelling of Alkalinity Migration Using PHAST

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this appendix is to describe the implementation of a numerical model in PHAST that calculates attenuation in groundwater of alkalinity released from the SGHWR and Dragon reactor End States.

1.2 OVERVIEW AND STRUCTURE

As described in NRS (2024), the alkalinity attenuation processes required to be modelled by PHAST are illustrated in Figure 611/B1 and summarised as follows:

- Mixing and equilibration of alkalinity with groundwater in the Poole Formation;
- Mechanical dispersion in Poole Formation groundwater;
- Adsorption (surface complexation), cation exchange and mineral precipitation in the downgradient Poole Formation; and
- Mixing and equilibration of alkalinity with rainfall recharge.

Figure 611/B1: Illustration of modelled alkalinity attenuation processes using the SGHWR as an example



This appendix describes the numerical implementation of the SGHWR and Dragon reactor End States concept. To model the processes identified in Figure 611/B1 PHAST requires:

- Construction of a three-dimensional model domain that sufficiently encompasses and represents the (i) the sources of contamination (the End States), (ii) the pathways in the Poole Formation and (iii) the chosen receptors;
- A numerical representation of water flows (groundwater flow, leachate leakage and rainfall recharge); and
- The source (leachate) chemistry, groundwater quality, rainfall recharge quality and the composition of the Poole Formation to be defined.

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This appendix is structured into eight main sections following this introduction:

- Section 2 describes how the model grid and geometry is constructed to represent the concept;
- Section 3 describes how water flows are implemented in the models of the SGHWR and the Dragon reactor End States and how the chemistry of water and the ground is represented;
- Section 4 describes the changes made to reference scenario model to model variant and alternative scenarios;
- Section 5 presents the results of the reference scenario model and assessment of cumulative effects;
- Section 6 presents the results of modelling alternative and variant scenarios;
- Section 7 provides a summary of the modelling; and
- Section 8 lists documents referenced by this appendix.

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2 CONSTRUCTING THE MODEL GRID AND GEOMETRY

The model grid constructed for the SGHWR and Dragon reactor is illustrated in Figure 611/B2 and Figure 611/B3, respectively.

The grid for modelling the effects of alkalinity release from the SGHWR is 800 m long, comprising an upgradient distance of 100 m, a facility length of 85 m and a downgradient distance of 615 m. The downgradient distance is thereby sufficient to assess the effects of alkalinity on groundwater emerging at the mire which, based on the shortest modelled potential groundwater flow path length, is 500 m downgradient of the SGHWR End State (NRS, 2024). It is also of sufficiently large enough to support assessment of the cumulative effect of alkalinity on groundwater that in some circumstances flows from the SGHWR approximately 450 m to Dragon reactor.

The SGHWR model domain width is 300 m. This is sufficiently wide to accommodate the 80 m wide SGHWR End State and it avoids edge effects which might otherwise disrupt the modelled linear groundwater flow beneath the SGHWR.

The SGHWR domain has been defined as 10 m thick with a horizontal top and base. This encompasses the assumed pathway thickness beneath and around the SGHWR based on the vertical distance from the water table to the base of Regions 1 and 2 (NRS, 2024).

The PHAST model of Dragon is constructed in a separate file to the SGHWR model.

The PHAST Dragon reactor model domain is 1200 m long, comprising an upgradient distance of 135 m, a facility length of 30 m and a downgradient distance of 1035 m. The downgradient distance is thereby sufficient to assess the effects of alkalinity on groundwater discharging into, and close to, the River Frome which, based on the shortest modelled potential groundwater flow path length, is 900 m downgradient of the Dragon reactor End State (NRS, 2024).

The Dragon reactor model domain is 300 m wide, sufficient to accommodate the 32 m wide Dragon reactor End State and avoids edge effects.

The Dragon reactor model domain has been defined as 13 m thick with a horizontal top and base. This encompasses the assumed mixing zone thickness of 5 m (NRS, 2024).

The default grid spacing for both domains is 10 m x 10 m but grids are refined to 5 m x 10 m to accommodate Regions 1 and 2 and the annexes of the SGHWR and to 1 m by 10 m to accommodate the Dragon reactor. The Poole Formation has been assumed to be homogeneous and isotropic in the models and on that basis the grid spacing is adequate to represent the Poole Formation pathway.

The grid is by default saturated. Unsaturated flow and reactions are not modelled in PHAST. The PHAST modelling conservatively disregards alkalinity attenuation in the unsaturated zone.



Figure 611/B2: The SGHWR model domain, grid construction and boundary conditions

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Figure 611/B3: Dragon model domain, grid construction and boundary conditions

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3 IMPLEMENTING HYDRAULICS, DEFINING CHEMISTRY AND MODELLING MINERAL PRECIPITATION

3.1 INTRODUCTION TO THE IMPLEMENTATION OF MODEL HYDRAULICS AND CHEMISTRY

The illustration in Figure 611/B4 sets out the key hydraulic and chemistry inputs used in the model and the sections that describe how these inputs have been derived.





3.2 HYDRAULICS

3.2.1 LEACHATE LEAKAGE RATES

Regions 1 and 2 of the SGHWR are deeper structures than the annexes (NRS, 2024). Regions 1 and 2 fully penetrate the Poole Formation saturated pathway and are founded in underlying clay. The outflow of leachate to groundwater in the Poole Formation is therefore assumed to occur through the walls of Regions 1 and 2 rather than the base. This has been modelled in PHAST by creating an open no flow zone within the model grid representing SGHWR Regions 1 and 2. This is illustrated in green in Figure 611/B2 and further illustrated in Figure 611/B5. As the geometry of SGHWR Regions 1 and 2 is irregular, the zone of no flow has been approximated to a cuboid for the purposes of model implementation.

The area of the faces of the cuboid are equal to the contact area between the Regions 1 and 2 and surrounding groundwater. The contact area was obtained from the hydraulics modelling carried out in GoldSim (Appendix A). The wetted area is in reality time variant as the water level changes both inside and outside the facility. The wetted area used in the PHAST modelling is time invariant and was approximated to the 'long term' wetted area calculated in GoldSim once the internal and external water levels equilibrate. The groundwater levels are those modelled for the period beyond 2100 (NRS, 2024).

The faces of the cuboid are defined as boundary condition cells within the model grid and are assigned a flow velocity. The direction of the defined flow is outwards into the surrounding Poole Formation.



Figure 611/B5: Implementation of flows from Regions 1 and 2 of the SGHWR

As summarised in the CSM (NRS, 2024), outflow of leachate through the SGHWR north and south annexes is assumed to occur through the bases of the structures. To implement this within the model, grid surface cells have been defined as boundary conditions shown in Figure 611/B2 in plan view and further illustrated in Figure 611/B6.

The areas of the surface boundary conditions for the annexes are approximated to the plan areas of the annexes defined in NRS (2024).





Flow of leachate through the base of Dragon reactor is modelled in the same manner as for the SGHWR annexes. The surface grid cells defined for downward flow are a simplified representation of the Dragon reactor basal plan area as shown in Figure 611/B3 and are further illustrated in Figure 611/B7. Due to the thick (2.7m) basal concrete slab of the Dragon reactor, conceptually flow is assumed to occur through the outer walls. Numerically, for the purpose of simplification, the same flow rate has been distributed equally over the modelled area of the base.





Leachate leakage rates used in the PHAST model are calculated in the GoldSim model and exported to Excel. In this way the time variant changes in flow due to, for example, cap degradation, hydraulic conductivity changes in the structure and changes in groundwater level, are accounted for in the same way as in the GoldSim contaminant transport calculations. The exported leakage data in dimensions of L³/T (volume/time) has an annual timestep. The flow rate every 10 years has been extracted from the export time series and used as an input within the PHAST model. This is a simplification intended to reduce simulation times. The flow is divided through by the grid area of the region it is being applied to, to give a velocity. The velocity within the PHAST model is assigned to the grid nodes describing the SGHWR annexe bases, the SGHWR Regions 1 and 2 walls and the Dragon base (as shown in Figure 611/B5 to Figure 611/B7) such that collectively when the flow rates from all the cells are added they match with the total outflow that was calculated by GoldSim for that region.

3.2.2 GROUNDWATER FLOW RATE

Poole Formation groundwater flow rates in the PHAST models have been calculated so that they match with the groundwater flow rates used in the GoldSim model. The groundwater flow rate is calculated by multiplying the catchment area upgradient of each End State by the BGS calculated long term recharge rate, as specified in Appendix A, thereby giving a groundwater flow rate with dimensions of L^3/T (volume/time).

The hydraulic head boundary conditions at each end of the PHAST model domains have been adjusted so that the head gradient across each model domain multiplied by the specified hydraulic conductivity and cross-sectional area gives a groundwater flow rate beneath the End States that matches with that calculated from catchment area and recharge rate. This ensures the correct amount of dilution where leachate enters the saturated pathway. The saturated pathways in both End State models are modelled as unconfined. The model groundwater flow rate therefore increases with increasing distance downgradient of the End States by the rainfall recharge added to the pathway.

3.2.3 RECHARGE RATE

The recharge rate to the Poole Formation assumed within the PHAST models is the same as that used to calculate the rate of groundwater flow: 326 mm/yr. This is the long-term recharge rate calculated by the BGS and is entered to the model as a velocity across each surface cell outside the areas occupied by the End States.

3.2.4 SUMMARY DESCRIPTION OF IMPLEMENTED FLOWS

A summary description of how the hydraulics are implemented within the PHAST model is illustrated in Figure 611/B8.

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3.3 DEFINING THE CHEMISTRY OF WATER AND SOLIDS IN THE MODELS

3.3.1 IDENTIFICATION OF SITE-SPECIFIC GEOCHEMICAL DATA REQUIRED TO MODEL ALKALINITY ATTENUATION

The modelling of alkalinity attenuation requires geochemical data specific to the SGHWR and Dragon reactor End States and the surrounding ground that can be categorised as follows:

- Leachate chemistry;
- Upgradient groundwater chemistry;
- Recharge water chemistry; and
- Poole Formation pathway composition.

The approach to including this data in the model is described in Sections 3.3.2 to 3.3.6.

3.3.2 SOURCE (LEACHATE) CHEMISTRY

The grid nodes describing the leachate flow rate to the Poole Formation (Figure 611/B5 to Figure 611/B7) have been assigned a leachate chemistry boundary condition. The leachate chemistry used by the model is from USDoE (2021) and is summarised in Table 611/B1. The 'Cementitious Leachate - Stage II' chemistry (highlighted in red) has been selected as the input boundary condition throughout the duration of the simulation rather than using PHAST to calculate an equilibrated leachate chemistry based on the interaction of infiltrating water with aged, broken demolition arisings. Due to only a small amount of water being needed to completely leach the



relatively small quantity of alkali metal hydroxides associated with Stage I leaching this stage has been disregarded. This is consistent with USDoE (2021) which describes Stage I leaching as corresponding to young cement and excludes this stage on the basis it is extremely short lived. Stages III and IV - stages that will occur over centuries or millennia as the source depletes - have been cautiously disregarded. This approach conservatively assumes the source does not deplete.

An additional cautious simplification is that this leachate chemistry is applied to all basal leakage cells of the Dragon reactor and all the wall leakage cells of the SGHWR Regions 1 and 2, even in areas where low leachability concrete blocks will be placed.

	Cementitious	Cementitious	Cementitious
	Leachate – Stage	Leachate – Stage	Leachate – Stage
	$\mathrm{II}^{(\mathrm{a})}$	III ^(b)	IV ^(c)
pН	12.37	11.14	9.56
Eh (V)	0.49	0.56	0.66
Ionic Strength	4.6E-2	8.2E-3	7.0E-4
Al^{3+} (mol/L)	2.19E-5	1.05E-7	1.32E-5
Ca^{2+} (mol/L)	1.83E -2	2.92E-3	1.43E-4
Cl^{-} (mol/L)	2.64E-4	2.65E-4	2.65E-4
Fe^{3} (mol/L)	6.87E-10	3.63E-11	1.70E-12
HCO_3^{-} (mol/L)	4.59E-6	6.90E-6	1.81E-4
Mg^{2+} (mol/L)	1.04E-8	2.16E-5	4.99E-5
Na^+ (mol/L)	1.33E-4	1.33E-4	1.33E-4
SO_4^{2+} (mol/L)	5.16E-5	2.08E-6	2.08E-6
$SiO_2^{-}(mol/L)$	1.29E-3	2.95E-3	~0

 Table 611/B1: Leachate Quality Defined for the SGHWR and Dragon Reactor End States (from USDoE, 2021)

3.3.3 UPGRADIENT GROUNDWATER CHEMISTRY

The upgradient groundwater chemistry is applied as a boundary condition at the upgradient edge of the model domain. The upgradient groundwater chemistry is derived from analysis of samples of groundwater collected from boreholes upgradient of the two reactors. The borehole upgradient of the SGHWR is OW18, and the borehole upgradient of the Dragon reactor is OW135. A high pH groundwater sample from each borehole from the last five monitoring rounds was used. For borehole OW18 this was a sample taken on 17 May 2023 and for borehole OW135 this was a sample taken on 15 September 2022. The pe [the negative base 10 logarithm of the electron activity of the aqueous solution or Eh (mV)/59.2 (based on a generalised temperature of 25°C)] has been estimated for both locations using PHREEQC based on equilibration of the water with atmospheric partial pressure of carbon dioxide and oxygen. PHREEQC was also used to fully charge balance the anions and cations prior to input to the model. The input data is summarised in Table 611/B2.

 Table 611/B2: Upgradient Groundwater Quality defined for the SGHWR and Dragon Reactor End States

 models (Reference Scenario)

Parameter	Upgradient groundwater quality for the SGHWR model (mg/l unless stated)	Upgradient groundwater quality for the Dragon reactor model (mg/l unless stated)	Inputs for the SGHWR PHAST model (following processing in PHREEQC) mg/kgw ¹ unless stated)	Inputs for the Dragon PHAST model (following processing in PHREEQC) (mg/kgw unless stated)
Calcium	5	6	5	6
Chloride	10	21	10	21
Magnesium	<1	1	1	1
Nitrate (as N)	1.6	0.7	1.6	0.2
Potassium	<1	<1	1	1
Sulphate (as SO ₄)	5	15	1.665	4.95
Alkalinity as CaCO ₃	12.5	9.3	3.15	9.3
Sodium	6	11	6	11
pH (S.U. ²)	5.75	5.6	5.75	5.6
pe (S.U.)			6.23	6.23

3.3.4 RECHARGE CHEMISTRY

Like in most shallow unconfined groundwater systems, the water that mixes with groundwater of the Poole Formation saturated pathway is meteoric water that has equilibrated with the overlying unsaturated zone.

PHAST does not calculate unsaturated zone reactions. For the purposes of the model, a recharge water chemistry is therefore required where these reactions have already taken place. The reactors are close to the groundwater catchment boundary and therefore upgradient groundwater has travelled little distance in the saturated zone and is, essentially, water that has passed through the unsaturated zone. Upgradient groundwater quality is therefore expected to be of similar quality of water that has passed through the unsaturated zone. The upgradient groundwater quality (Table 611/B2) has therefore been used for the quality of infiltrating rainwater recharging the water table downgradient of the two End States. The recharge chemistry has been specified as a boundary condition applied to each surface cell of the model, except in the areas occupied by the End States, so that the chemical species are added to the saturated pathway at the specified concentration and recharge rate.

¹ The concentrations are input as milligrams per kilogram of water to keep the volume of water constant.

² Standard Unit.

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3.3.5 ADSORPTION ON IRON AND ALUMINIUM HYDROXIDES (SURFACE COMPLEXATION) WITHIN THE POOLE FORMATION PATHWAY

Results of analysis of samples of Poole Formation for both aluminium and iron are used in the models to calculate sorption onto solids within the aquifer. Samples were collected at the Winfrith site during a 2020 hydro-ecological investigation (Atkins, 2024) from shallow, intermediate, and deep horizons of the near surface. The median concentrations from samples of the deep horizon were selected for use in the model because the deep samples are considered to be most representative of the Poole Formation saturated pathway, minimising the possibility of samples being influenced by surface inputs. The aluminium and iron concentrations used for modelling are summarised in Table 611/B3.

Table 611/B3: Poole Formation Composition Data from Atkins (2024) (values in red used as inputs to the PHAST model)

Determinant	Unit	Min value	Max value	Range in topsoil	Range in upper subsoil	Range in lower subsoil	Modelled Value (Median)
Aluminium	mg/kg	134	7,100	134 - 3,720	245 - 7,100	662 - 4,970	2,816
Iron	mg/kg	1,640	12,900	1,780 - 8,730	1,640 - 12,900	2,840 - 12,400	7,620

Surface complexation can be described using a mechanistic model to account for adsorption onto metal oxide surfaces. The theory is based on Dzombak and Morel (1990) and Karamalidis and Dzombak (2010) utilizing iron (hydrous ferric oxide [Hfo]) as ferrihydrite FeO(OH) and aluminium (hydrous aluminium oxide [Hao]) as gibbsite $AI(OH)_{3(am)}$ as adsorbing surfaces based on their concentrations measured in representative solids. Surface complexation site densities are then calculated from these values using formulas for Hfo and Hao, based on Dzombak and Morel (1990) and Karamalidis and Dzombak (2010), respectively. Surface complexation sites are allowed, and assumed, to obtain equilibrium with ambient groundwater to establish a pre-loaded background condition. The surface complexation model included in the Thermochimie thermodynamic database for ferrihydrite includes both strong sites (Hfo_strong) and weak sites (Hfo_weak), which are treated as different surface complexation sites in PHAST based on the Dzombak and Morel (1990) model.

To determine adsorption sites for surface complexation, the mass of iron and aluminium in sediment/soil samples can be converted using methods described by Dzombak and Morel (1990) and Karamalidis and Dzombak (2010). This is used in combination with the calculation methodology of Appelo and Postma (2005) to determine the specific quantity of complexation sites on each mineral surface type as well as the amount of each mineral available to participate in the reactions.

Briefly, the methodology calculates:

- The number of surface sites (sites) as the product of the moles of iron ([Fe]) and moles of surface sites per moles of iron ([sites]/[Fe]) (i.e., sites = [Fe] x [sites]/[Fe] or 5.5x10⁻⁴ mol = 2.75x10⁻³ mol iron x 0.2 mol sites/mol iron); and
- The amount of ferrihydrite available for sorption using Appelo and Postma (2005) that assumes the available mass of ferrihydrite (MHFO) in grams (g) equals the product of [Fe] and the molecular mass of ferrihydrite (MWHFO) (i.e., MHFO = [Fe] x MWHFO; or 0.24 g = 2.75x10⁻³ mol x 88.85 g/mol).

The same approach is used for aluminium. Aluminium, based on Karamalidis and Dzombak (2010), only has a single adsorption site type, with a concentration of 0.41 mol sites/mol aluminium, and a molecular mass of $AI(OH)_3$ of 78 g/mol.

3.3.6 CATION EXCHANGE CAPACITY WITHIN THE POOLE FORMATION PATHWAY

To quantify the cation exchange capacity (CEC), a generalised CEC model has been used in PHAST. Cation exchange can be quantified from laboratory measurements of soil samples or estimated based on the type of clay present. Based on information derived from a BGS study of the mineralogy of the Wessex Basin, smectite (montmorillonite) clay is interpreted to be present in the Poole Formation beneath the Winfrith site by AMEC Foster Wheeler (2017). A cautious value for CEC of 40 meq/100g soil is used in the model based on the range of 80-120 meq/100g soil for montmorillonite clays in Appelo and Postma (2005) (i.e. half the minimum value cited in the literature).

3.4 MODELLING OF MINERAL PRECIPITATION WITHIN THE POOLE FORMATION PATHWAY

There are multiple minerals allowed by PHAST to precipitate within the Poole Formation based on the existing Poole Formation geochemistry and the addition of the concrete leachate. Due to the poorly constrained kinetics of the dissolution and precipitation of minerals in the Poole Formation and given the timeframe modelled, equilibrium between the mineral phases and solutes has been assumed. This is a cautious simplification of reality.

Numerous concrete degradation products are allowed to precipitate including several Calcium Silicate Hydrate (CSH) minerals. Three different ratios of silica to calcium CSH compositions are allowed to precipitate: 1.6, 1.2, and 0.8 (Chen et al., 2004). Additionally, other potential hydrated cement products or secondary associated minerals (alkaline) are allowed to precipitate if they become saturated in groundwater. This includes portlandite³, monosulfoaluminate, ettringite, tricalcium aluminate hydrate (C_3AH_6), hydrotalcite, SiO₂(am)⁴, and brucite. These concrete associated minerals are hydration products that can dissolve in groundwater and that promote high pH.

³ The list is of credible hydration products and includes, for completeness, minerals that are not expected to precipitate (e.g. portlandite will not precipitate in near neutral or acidic groundwater)

⁴ Assumed amorphous (am), rather than crystalline (e.g. chalcedony or opal), because it is the most likely to first form.

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In addition to concrete specific minerals, commonly occurring geological minerals (for example, calcite, gypsum, magnesite, and dolomite) are allowed to precipitate from modelled groundwater only if they become saturated (i.e. if the minerals are calculated to be at a concentration in groundwater above the solubility limit). These minerals were chosen because their precipitation or dissolution is known to influence groundwater pH (i.e. these reactions involve the production or consumption of H⁺ ions; Nordstrom and Alpers 1999; Van Breemen and Wielemaker 1974).

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4 CHANGES REQUIRED TO MODEL VARIANT AND ALTERNATIVE SCENARIOS

4.1 ALTERNATIVE SCENARIO TO ADDRESS CONCEPTUAL UNCERTAINTY WITH THE EFFECTS OF CLIMATE CHANGE

An alternative scenario has been assessed in which groundwater rises above the SGHWR south annexe and Dragon reactor bases to a level and with a frequency derived under the worst modelled conditions of climate change.

To model this alternative scenario, revised time-variant water outflow rates from the SGHWR south annexe and Dragon reactor are required. Like the reference scenario, the flow rates of this alternative scenario are taken from the GoldSim model (with an annual timestep) and converted to a ten-year timestep, before being divided by the area of the applicable region so that they are imported to PHAST and used as velocity boundary conditions.

No other changes to the reference scenario model are necessary to model this alternative scenario.

4.2 VARIANT SCENARIOS TO ADDRESS MODEL UNCERTAINTY

The three variant scenarios described in this Section 4.2, require the water flows of the reference scenario to be amended. Like the reference scenario, the flow rates are taken from the GoldSim model of each variant scenario (with an annual timestep) and converted to a ten-year timestep, before being divided by the area of the applicable region so that they are imported to PHAST and used as velocity boundary conditions.

4.2.1 EVOLUTION OF THE EFFECTIVE HYDRAULIC CONDUCTIVITY OF THE CONCRETE STRUCTURES

Variant models assume, (i) faster; and (ii) slower, early time rates of concrete degradation of the SGHWR Regions 1 and 2 structure compared to the reference scenario.

The changes required to run these variant scenarios are updated time-variant outflow rates from the SGHWR Regions 1 and 2. No other changes to the reference scenario model are required.

4.2.2 EVOLUTION OF THE RATE OF INFILTRATION TO THE CAP

A variant scenario model assumes a faster rate of cap degradation than the reference scenario.

The caps are installed over the entire End States, and therefore changes required to model this variant scenario are updated time-variant outflow rates from the SGHWR (all regions) and the Dragon reactor. No other changes to the reference scenario model are required.

4.2.3 FREQUENCY AND EXTENT OF GROUNDWATER INUNDATION TO THE SGHWR SOUTH ANNEXE AND TO THE DRAGON REACTOR BASEMENT

A variant scenario assumes groundwater rises above the base of the SGHWR south annexe and Dragon reactor bases to a level and with a frequency consistent with that of a 'reasonable worst-case' of future recharge calculated assuming a scenario of medium future emissions.

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The changes required to run this variant scenario are updated time variant outflow rates from the SGHWR south annexe and Dragon reactor base. No other changes to the reference scenario model are required.

4.3 VARIANT SCENARIOS TO ADDRESS PARAMETER UNCERTAINTY

In the numerical implementation of the end states, PHAST models the following alkalinity attenuation processes:

- Mixing of leachate with upgradient groundwater;
- Mixing of groundwater with rainfall recharge in the downgradient saturated pathway;
- Adsorption and desorption (surface complexation) of alkalinity to minerals in the downgradient saturated pathway;
- Mineral precipitation; and
- Cation exchange.

Of the processes identified above, assuming instantaneous equilibrium between solutes and mineral phases is cautious and there is therefore no need to test the model sensitivity to mineral precipitation. It is therefore not considered as a parameter uncertainty. The sensitivity of the model results to the remaining attenuation processes has been carried out. This has been undertaken by:

- (i) varying the input recharge chemistry and upgradient groundwater chemistry,
- (ii) varying the concentration of solid phase minerals in the Poole Formation that control adsorption and desorption; and
- (iii) assuming there is no CEC in the downgradient groundwater pathway.

4.3.1 UPGRADIENT GROUNDWATER AND RECHARGE CHEMISTRY

The sensitivity to mixing of leachate with upgradient groundwater; and to the mixing of downgradient groundwater with rainfall recharge, have been assessed by varying the groundwater and recharge water quality in the PHAST model. The groundwater and recharge water quality is based on laboratory analysis of samples of groundwater taken from boreholes upgradient of each End State. The chemistry of a groundwater sample with a high pH from a borehole upgradient of each End State has been chosen from the Winfrith site monitoring dataset for use in reference case model. The variant scenario has assumed the groundwater and recharge water quality is represented by a lower pH groundwater sample from the same borehole as shown in Table 611/B4. The pe has been estimated using PHREEQC for both locations based on equilibration of the water with atmospheric partial pressure of carbon dioxide and oxygen. PHREEQC was also used to fully charge balance the anions and cations prior to input to the model.

Table 611/B4: Upgradient Groundwater Quality defined for the SGHWR End State model (Variant Scenario)

Parameter	Variant upgradient groundwater quality for the SGHWR model (mg/l unless stated)	Inputs for the PHAST Model (following processing in PHREEQC) (mg/kgw unless stated)
Calcium as Ca	9	9
Chloride as Cl	16	16
Magnesium as Mg	1	1
Nitrate as N	1.6	1.42
Potassium as K	<1	1
Sulphate as SO4	9	3
Alkalinity as CaCO3	2.6	2.6
Sodium as Na	16	8
pH (S.U.)	5.05	5.05
pe (S.U)	-	7.26

4.3.2 MINERAL ADSORPTION AND DESORPTION

The sensitivity of modelled downgradient groundwater pH to mineral adsorption and desorption (surface complexation) was assessed by varying the Poole Formation mineralogy in the PHAST model. The reference case model uses median results of analysis of soils from the Winfrith site. A variant scenario has been modelled that uses minimum values from the soil analysis dataset (Table 611/B5).

Table 611/B5: Poole Formation Composition Data from Atkins (2024) (values in red used in the variant model)

Determinant	Unit	Min value	Max value	Range in topsoil	Range in upper subsoil	Range in Iower subsoil	Modelled Value (Min)
Aluminium	mg/kg	134	7,100	134-3,720	245- 7,100	662-4,970	134
Iron	mg/kg	1,640	12,900	1,780- 8,730	1,640- 12,900	2,840- 12,400	1,640

4.3.3 CATION EXCHANGE CAPACITY

The sensitivity of modelled downgradient groundwater pH to changes in CEC has been assessed by a variant scenario that assumes there is no CEC in the downgradient groundwater pathway.

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5 RESULTS OF THE REFERENCE SCENARIO MODEL

5.1 RESULTS OF THE REFERENCE SCENARIO MODELS OF THE SGHWR AND DRAGON REACTOR END STATES

The modelled groundwater pH downgradient of the SGHWR and Dragon reactor End States for the reference scenario are shown as pH contours in Figure 611/B9 and Figure 611/B10, respectively, with concentrations reported at 50 m, 100 m and 500 m downgradient. The point 50 m downgradient is the non-hazardous pollutants' compliance point. The point 500 m downgradient is protective of the receptor. The point 100 m downgradient has been selected to assist illustration of alkalinity attenuation.

Since the modelled source of alkalinity remains constant with time (it does not leach or become carbonated), modelled pH in groundwater steadily rises to a constant value. The contour plans in Figure 611/B9 and Figure 611/B10 represent the pH at steady conditions.



Figure 611/B9: Modelled groundwater pH downgradient of the SGHWR for the reference scenario

The scale limit for pH in groundwater in each plot has been set to a maximum pH of 11 for presentational purposes. The red legend colour therefore corresponds to pH 11 or higher.

The calculated stable pH 500 m downgradient of the SGHWR is 6.35. Compared to the upgradient groundwater pH used in the reference case model of 5.75, this is an increase in pH of 0.6 pH units.

The selected compliance point for pH is 50 m downgradient of the disposals. The compliance limit is 7 pH units. The compliance limit is applicable at the nearest downgradient groundwater receptor, which need not coincide with the compliance point. The acceptable pH may therefore be higher at the compliance point, taking account of attenuation between the compliance point and the receptor. The closest groundwater receptor to the SGHWR is the wet heath/acid mire habitat established in emergent groundwater approximately 500 m down gradient of the End State. The modelled pH is well below 7 at 500 m and therefore, by extension, the modelled pH at the 50 m compliance point is acceptable.

Figure 611/B10: Modelled groundwater pH downgradient of the Dragon reactor for the reference scenario

	6.00 5.90 5.80 5.70 5.60
 50m Downgradient pH: 5.70 100m Downgradient pH: 5.68 500m Downgradient pH: 5.65 	

The calculated stable pH 500 m downgradient of the Dragon reactor is 5.65. This is an increase of 0.05 pH units above the upgradient groundwater pH used in the reference case model (5.6).

The nearest receptor downgradient of the Dragon reactor is the River Frome, 900 m down gradient of the End State. The modelled pH is well below 7 at the 500 m model output point and therefore, by extension, the modelled pH at the 50 m compliance point is acceptable.

Figure 611/B11 and Figure 611/B12 show the modelled pH of groundwater 500 m downgradient of the SGHWR and Dragon reactor, respectively. Both plots show a gradual rise to a stable pH with increasing simulation time. For SGHWR, the pH is interpreted to become stable⁵ at 500 m downgradient after 3,180 years. For the Dragon reactor, the pH is interpreted to become stable after 1,520 years. In models of both the SGHWR and Dragon reactor calcite supersaturation and thereby precipitation occurs in downgradient groundwater. The extent of supersaturation and precipitation increases with model time but eventually stabilises as evidenced by the pH (Figure 611/B11 and Figure 611/B12).

⁵ The time when pH becomes stable has been interpreted for each model (including the models that assess sensitivity) as the time when the calculated pH in groundwater 500 m downgradient of the disposals/deposits rises to within 0.001 pH unit of the pH at the end of the 5,000 year simulation.





Figure 611/B11: Modelled Groundwater pH 500 metres Downgradient of the SGHWR





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5.2 ASSESSMENT OF CUMULATIVE EFFECTS

Groundwater flow modelling suggests that in some circumstances groundwater flows from the SGHWR to beneath the Dragon reactor. The distance of the groundwater flowpath between the SGHWR and the Dragon reactor is 500 m.

There is the possibility under such a scenario that the groundwater passing beneath the Dragon rector is affected by alkalinity from the SGHWR and therefore the added effect of alkalinity release from Dragon reactor could increase the pH in groundwater further.

The possible cumulative effect has been modelled using a variant scenario.

The variant scenario is a highly cautious 'bounding case' of the possible effect of the additive input from both End States, and assumes the modelled groundwater upgradient of the Dragon reactor has the chemistry of the modelled groundwater 500 m downgradient of the SGHWR (reference scenario) when the pH reaches its peak value.

This is highly cautious because the source (leachate) in the SGHWR will deplete over time and will not obey the bounding assumption of a constant source used in the modelling. The dispersed peak pH in groundwater 500 m downgradient of the SGHWR can be expected, in reality, to manifest earlier but to be much lower than that modelled in the reference scenario. Furthermore, the cumulative effect model assumes that all the groundwater downgradient of the SGHWR flows beneath the Dragon reactor throughout the entire duration of the simulation, whereas only some groundwater flows in this direction from the SGHWR some of the time.

To model the cumulative effect, the upgradient groundwater quality boundary condition of the Dragon reactor reference case model has been changed from that representative of natural upgradient groundwater quality at Winfrith to the groundwater chemistry of the SGHWR reference scenario 500 m downgradient of the SGHWR when groundwater pH stabilises. No other changes are required to implement the model of cumulative effects. The results are shown in Figure 611/B13.



Figure 611/B13: Modelled groundwater pH downgradient of the Dragon reactor for the cumulative effects scenario

The calculated stable pH 500 m downgradient of the Dragon reactor is 6.46. Despite the highly cautious bounding approach to the assessment of cumulative effects, the modelled pH in groundwater is less than the compliance limit.

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6 **RESULTS OF SENSITIVITY ANALYSES**

6.1 RESULTS OF MODELLING OF THE ALTERNATIVE SCENARIO TO ADDRESS CONCEPTUAL UNCERTAINTY WITH THE EFFECTS OF CLIMATE CHANGE

The modelled results, with comparison to the reference scenario results, for the SGHWR and Dragon reactor End States are shown in Table 611/B6 and Table 611/B7, respectively.

Table 611/B6: Modelled pH in groundwater downgradient of the SGHWR in the alternative scenario compared to the reference scenario

Distance Downgradient of SGHWR (m)	рН (-)	Approximate time to Steady State (yr)	Ph (-)	Approximate time to Steady State (yr)	
	Referenc	e scenario	Alternative scenario		
50	9.33		10.10		
100	8.73	3,180	9.67	2,540	
500	6.35		6.55		

Table 611/B7: Modelled pH in groundwater downgradient of the Dragon reactor in the alternative scenario compared to the reference scenario

Distance downgradient of Dragon reactor (m)	рН (-)	Approximate time to Steady State (yr)	рН (-)	Approximate time to Steady State (yr)	
'	Referenc	e scenario	Alternative scenario		
50	5.70		5.88		
100	5.68	1,520	5.84	1,380	
500	5.65		5.74		

The modelled pH for both End States is well below 7 in groundwater 500 m downgradient of both End States and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The increase in pH with distance downgradient compared to the reference scenario is consistent with the increased rate of flushing of alkalinity from the SGHWR south annexe and Dragon reactor basement. The difference between the results of modelling reference and alternative scenarios is greater for the SGHWR model than for the Dragon model. Whilst this may appear counterintuitive, because there is a greater proportion of demolition arisings affected by inundation in the Dragon model, there is a higher degree of calcite supersaturation in the groundwater downgradient of the SGHWR End State. Consequently, the modelled alkalinity increase in groundwater downgradient of the SGHWR is limited by additional calcite precipitation.



Figure 611/B14: Modelled groundwater pH downgradient of the SGHWR for the alternative scenario

- 50m Downgradient pH: 10.10
 100m Downgradient pH: 9.67
- 500m Downgradient pH: 6.55

Figure 611/B15: Modelled groundwater pH downgradient of the Dragon reactor for the alternative scenario



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6.2 RESULTS OF MODELLING VARIANT SCENARIOS TO ADDRESS MODEL UNCERTAINTY

6.2.1 EVOLUTION OF THE EFFECTIVE HYDRAULIC CONDUCTIVITY OF THE CONCRETE STRUCTURES

The updated water outflow rates calculated using the GoldSim model of the variant scenarios of concrete degradation of Regions 1 and 2 have been used in the PHAST model.

The modelled results, with comparison to the reference scenario, for the SGHWR are shown in Table 611/B8.

Table 611/B8: Modelled steady state pH in groundwater downgradient of the SGHWR in the variant scenarios of concrete degradation

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario		Variant scenario of faster early time concrete degradation		Variant scenario of slower early time concrete degradation	
50	9.33		9.30		9.30	
100	8.73	3,180	8.68	4,080	8.68	4,080
500	6.35		6.35		6.35	

The modelled pH in groundwater 500 m downgradient of the SGHWR is well below 7 in both variant scenarios and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The modelled results of the sensitivity scenarios are almost invariant to those of the reference scenario. Like for the results of the GoldSim modelling, this is consistent with the maximum rate of aqueous release from the disposals/deposits being dominated by cap infiltration and not by the timing of concrete degradation.

6.2.2 EVOLUTION OF THE RATE OF INFILTRATION TO THE CAP

The modelled results of the effect of an increased rate of cap degradation, with comparison to the reference scenario, for the SGHWR and Dragon reactor are shown in Table 611/B9 and Table 611/B10, respectively.

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Table 611/B9: Modelled steady state pH in groundwater downgradient of the SGHWR in the variant scenario of high cap infiltration compared to the reference scenario

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)	
	Referenc	e scenario	Variant scenario of high cap infiltration		
50	9.33		9.30		
100	8.73	3,180	8.68	3,820	
500	6.35		6.35		

Table 611/B10: Modelled steady state pH in groundwater downgradient of the Dragon reactor in the variant scenario of high cap infiltration compared to the reference scenario

Distance downgradient of Dragon (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
1	Reference scenario		Variant scenario of high cap infiltration	
50	5.70		5.70	
100	5.68	1,520	5.68	1,160
500	5.65		5.65	

The modelled pH in groundwater 500 m downgradient of both End States is well below 7 for the variant scenario and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The model results of the sensitivity scenario are almost invariant from the reference scenario and show the peak pH is determined by the leakage when the cap has fully degraded and not by the rate of cap degradation.

6.2.3 RESULTS OF THE FREQUENCY AND EXTENT OF GROUNDWATER INUNDATION TO THE SGHWR SOUTH ANNEXE AND TO THE DRAGON REACTOR BASEMENT

The modelled results, with comparison to the reference scenario, for the SGHWR and Dragon reactor are shown in Table 611/B11 and Table 611/B12, respectively.

Table 611/B11: Modelled pH in groundwater downgradient of the SGHWR in the variant scenario of reasonable worst-case conditions of climate change under a medium emissions scenario compared to the reference scenario

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario		Variant scenario of reasonable worst- case conditions of climate change	
50	9.33		9.44	
100	8.73	3, 180	9.14	4,060
500	6.35		6.39	

Table 611/B12: Modelled pH in groundwater downgradient of the Dragon reactor in the variant scenario of reasonable worst-case conditions of climate change under a medium emissions scenario compared to the reference scenario

Distance downgradient of Dragon (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario		Variant scenario of reasonable worst- case conditions of climate change	
50	5.70		5.74	
100	5.68	1,520	5.72	1,500
500	5.65		5.67	

The modelled pH in groundwater 500 m downgradient of both End States is well below 7 and therefore, by extension, the pH at the 50 m compliance point is acceptable.

Despite the increased extent of inundation, little increase in modelled pH in groundwater is evident compared to the reference scenario. The model results are insensitive to this aspect of model uncertainty.

6.3 VARIANT MODELS TO ASSESS PARAMETER VALUE UNCERTAINTY

6.3.1 SENSITIVITY TO UPGRADIENT GROUNDWATER CHEMISTRY AND RECHARGE WATER QUALITY

The modelled results, with comparison to the reference scenario, for the SGHWR are shown in Table 611/B13.

Table 611/B13: Modelled pH in groundwater downgradient of the SGHWR in the variant scenario of lower pH upgradient groundwater and recharge compared to the reference scenario

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario (upgradient groundwater and recharge pH = 5.75)		Variant scenario of lower pH upgradient groundwater and recharge (pH = 5.05)	
50	9.33		6.13	
100	8.73	3,180	6.02	4,120
500	6.35		5.58	

The modelled pH in groundwater 500 m downgradient of the SGHWR is well below 7 in the variant scenario and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The results from the variant scenario model show the greatest difference in pH compared to the reference scenario 50 m downgradient, due to the effect of mixing of leachate with a lower pH groundwater. This is because calcite supersaturation in groundwater extends less distance downgradient of the SGHWR when the modelled upgradient groundwater and recharge water chemistry has a lower pH. As a result of continuous mixing with lower pH recharge along the downgradient pathway the pH is lower than that observed in the reference scenario, albeit the 0.5 increase in the pH value above background 500 m downgradient of the SGHWR is little different to the pH value increase of 0.6 when the reference scenario is modelled. The results indicate, as expected, that alkalinity would be attenuated over a shorter distance than in the reference scenario were the upgradient groundwater chemistry and recharge that of groundwater with the lowest monitored pH.



Figure 611/B16: Modelled groundwater pH downgradient of the SGHWR for the variant scenario

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6.3.2 SENSITIVITY TO MINERAL ADSORPTION AND DESORPTION

The modelled results, with comparison to the reference scenario, for the SGHWR are shown in Table 611/B14.

Table 611/B14: Modelled pH in groundwater downgradient of the SGHWR in the variant scenario of minimum sorption/desorption compared to the reference scenario

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario		Variant scenario of minimum sorption/desorption	
50	9.33		9.34	
100	8.73	3,180	8.73	1,240
500	6.35		6.35	

The modelled pH in groundwater 500 m downgradient of the SGHWR is well below 7 in the variant scenario and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The maximum (stable) pH is almost invariant from the reference case although, as expected due to the effect of reduced sorption, the time taken for the pH to become stable in the downgradient pathway has reduced. The model results show that the modelled groundwater pH downgradient of the SGHWR is not sensitive to the assumed mineralogy of the Poole Formation.

6.3.3 SENSITIVITY TO CATION EXCHANGE CAPACITY

The modelled results, with comparison to the reference scenario, for the SGHWR are shown in Table 611/B15.

Table 611/B15: Modelled pH in groundwater downgradient of the SGHWR in the variant scenario in which it is assumed there is no CEC compared to the reference scenario (40 meq/100g CEC)

Distance downgradient of SGHWR (m)	рН (-)	Approximate time to steady state (yr)	рН (-)	Approximate time to steady state (yr)
	Reference scenario		Variant scenario of no CEC included in the model	
50	9.33		9.30	
100	8.73	3,180	8.68	3,500
500	6.35		6.35	

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The modelled pH in groundwater 500 m downgradient of the SGHWR is well below 7 in the variant scenario and therefore, by extension, the pH at the 50 m compliance point is acceptable.

The maximum (stable) pH is invariant from the reference case although it takes longer for the modelled pH to become stable in the downgradient pathway. Unlike for the reference case model, charge balancing of chloride was allowed in order to minimise overall charge balance errors introduced by running the model with no CEC and this may have increased the time for the modelled pH to stabilise. The model results show that the modelled groundwater pH downgradient of the SGHWR is not sensitive to CEC in the Poole Formation.

SUMMARY

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Modelling of the release of alkalinity from the SGHWR and Dragon reactor End States has been undertaken using PHAST. This appendix has described how the concept of alkalinity release from the End States to groundwater has been implemented and lists the values of geochemical parameters used in the modelling.

The modelling has demonstrated that, for the reference scenario, the stable groundwater pH is below the compliance limit downgradient of the reactors. The risk is therefore concluded to be acceptable.

The same scenarios have been selected to assess conceptual and model uncertainty in the SGHWR and Dragon reactor End States as have been selected for the GoldSim modelling. The modelled pH in groundwater downgradient of the reactors is below the compliance criterion for the variant scenarios.

Interpretation of the model shows that mixing and dilution of high pH leachate with groundwater that has flowed from upgradient of the disposals/deposits and with recharge of rainfall downgradient of the disposals/deposits results in calcite supersaturation. The consequent calcite precipitation is the principal process that attenuates alkalinity in the leachate close to the disposals/deposits. Dilution by recharge of rainfall downgradient of the disposals/deposits is important for progressive reduction in groundwater pH with distance downgradient. The modelled stable pH in groundwater downgradient of the SGHWR for a scenario with variant upgradient groundwater and recharge water quality is discernibly different to that modelled in the reference scenario but remains below the compliance criterion. This and the well understood rates of groundwater flow and recharge of rainfall provide confidence that the modelled process of calcite precipitation is robust.

Two further scenarios have been defined to assess sensitivity of modelled pH to the processes of mineral adsorption and desorption and cation exchange. These comprised scenarios with variant Poole Formation mineralogy, as well as a scenario in which the Poole Formation was assumed to have no CEC. The modelled stable pH in groundwater downgradient of the SGHWR in both scenarios remains below the compliance criterion. The results of the sensitivity analyses demonstrate that the modelled groundwater pH is not sensitive to the processes of mineral adsorption and cation exchange.

A bounding case variant scenario has been modelled to assess whether the attenuation of pH downgradient of Dragon reactor would be sufficient to render the cumulative risk from both the SGHWR and Dragon reactor acceptable. The modelled groundwater pH is below the selected compliance criterion and the risk is therefore concluded to be acceptable.

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