

Risk Assessments

Chandler Facility Risk Assessment

Operational Phase Risk Assessment



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Summary

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF). The project will involve the excavation of rooms in a deep underground salt formation and the subsequent storage and isolation of wastes in the rooms produced. The project is located approximately 120 km south of Alice Springs in the Northern Territory of Australia.

This document is an initial Operational Phase Risk Assessment (OPRA), which assesses risks to the environment around the CF and to the facility's operability that arise prior to closure of the facility, based on information available at the end of August 2016. The operational period covered by the risk assessment is nominally 25 years. Risks to the health and safety of workers are outside the scope of this assessment and are covered by separate assessments undertaken by Tellus. The present OPRA is complemented by an initial Post-Closure Risk assessment (PCRA), which is reported separately.

The overall approach to the OPRA followed best international practice¹, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia. In practice the assessment was carried out in a "top-down" fashion, such that the starting point was identifying the main threats to operability and the main threats to the environment posed by the CF during the operational phase. Phenomena that could cause these threats to be realized were then identified iteratively, to a level of detail commensurate with the goal of achieving a robust assessment while not introducing undue complexity. The likelihood of each threat was then estimated and the possible effects assessed. When doing this, the approach was plausibly conservative, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern. Risks were considered as a product of the probability of a threat and its impact, both being represented on qualitative, linguistic scales on the basis of

¹ Here "best practice" refers to the well-established approaches and methodologies that are widely applied throughout the world for assessing the performance and safety of various kinds of underground waste disposal and storage facilities. These approaches and methodologies have been developed over several decades during many projects, including ones concerned with radioactive waste disposal, CO₂ storage, natural gas storage, and hazardous waste disposal. No single document describes this best practice, but rather the approaches and methodologies are documented in numerous reports by international agencies such as the International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), International Energy Agency (IEA), International Standards Organisation (ISO), national regulators, and project implementers.

qualitative information. To ensure that no key issues had been missed, the assessment was audited against experience in other, similar projects and, where appropriate, lists of Features Events and Processes (FEPs) that had been developed in these other projects.

The OPRA involved specifying 7 different scenarios for the behaviour of the CF:

- ▲ An Expected Evolution Scenario (EES), which is a statement of how the CF and its surroundings are expected to behave if development and operational plans are implemented properly.
- ▲ Six Alternative Evolution Scenarios (AES), which are statements of how the system would behave under alternative sets of circumstances, different to those of the EES.

It is important to note that an AES is *not a prediction* of the future behaviour of the system, but rather a representation of the status of the system under a specified set of conditions.

Six AES were analysed:

1. AES 1: Rockfall (in an unfilled or partially-filled room, tunnels);
2. AES 2: Vehicle fire;
3. AES 3: Fixed infrastructure fire;
4. AES 4: Waste package (ISO container or bulka-bag) failure;
5. AES 5: Hydraulic backfill emplacement system failure; and
6. AES 6: Impaired shaft lining performance.

The results of the assessment are presented as risk matrices, which show the highest plausible probability of threat versus plausibly conservative impact if realized; along with “bow-ties”, which illustrate graphically relationships between threats, hazards and potential consequence (if a threat is realized); and qualitative safety arguments.

The OPRA provides confidence that, for the proposed categories of wastes and with appropriate facility design and operation, there will be no significant unmanageable risks in terms of the operability and environmental safety of the CF during the operational phase.

The most probable scenario for the operation of the CF is that it follows the operational plan and that if there are accidents, the consequences can be managed so that there are no lasting unacceptable impacts. Other risks are assessed to be either of sufficiently low probability, or of insufficient impact, to cause concern.

The risks to the environment beyond the CF that could be caused by plausible deviations from facility development and operation plans are assessed to be less than the risks to the operability of the facility.

The OPRA of the CF presented in this report has been deliberately cautious, taking into account uncertainties due to:

- ▲ the detailed designs and operational plans for the CF not yet being finalized;
and
- ▲ the final characteristics and quantities of the wastes not having been defined.

It is expected that, as the designs and operational plans mature further, and as the waste characteristics and waste streams become more precisely defined, risks will be reduced even further, below those assessed in this report.

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1 Introduction

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF), at a site located approximately 120 km south of Alice Springs in the Northern Territory of Australia. The project will involve the excavation of rooms at a depth of approximately 850 m below the ground surface in a halite stratum within the Cambrian age Chandler Formation².

The following risk assessments are required in support of operator and regulatory requirements for this project:

- ▲ an Operational Phase Risk Assessment (OPRA), covering the period between the first emplacement of wastes in the facility and the closure of the facility, nominally 25 years ;
- ▲ a Long-term³, Post-closure Risk Assessment (PCRA), covering the period after facility closure, for sufficiently long to ensure that maximum risks have been considered (i.e. considering longer periods would not cause greater maximum risks to be estimated at a point in the future); and
- ▲ an Integrated Risk Assessment (IRA), taking into account the OPRA and the PCRA.

These risk assessments will be inputs to the outline safety case for the CF, which in turn will underpin the Environmental Impact Assessment (EIA) that forms a basis for the license application.

The present report aims to deliver an initial qualitative OPRA, covering environmental risks and risks to the operability of the CF, based on information available at the end of August 2016. The considered risks are those arising from the wastes, other risks being outside the scope of the assessment. Health and safety risks to workers are outside the scope of this assessment, but will be covered by a separate assessment that has been undertaken by Tellus.

²The Chandler Formation is a halite mineral formation that is approximately 520 million years old which corresponds to the Cambrian Period.

³The overall timescale to be considered by the post-closure assessment is sufficiently long to ensure that maximum risks have been considered. A period of 1 million years is considered quantitatively, consistent with common practice internationally in safety assessments concerned with the underground disposal of radioactive wastes (e.g. NEA, 2007). Beyond this time qualitative arguments are presented, again consistent with common international practice, which recognizes that quantitative assessments become increasingly uncertain over increasingly long time intervals in the future.

The OPRA reported here will inform the development of a quantitative long-term, PCRA.

This report is structured as follows.

- ▲ Section 2 describes the overall approach to the assessment.
- ▲ The context for the assessment is summarized in Section 3.
- ▲ A description of the CF is provided in Section 4.
- ▲ Section 6 presents the scenarios considered in the assessment.
- ▲ A qualitative assessment of the scenarios is presented in Section 7.
- ▲ Section 7.3 contains details of the “BowTie” approach used to present risks and key preventative and mitigation measures.
- ▲ Section 8 provides a summary of the assessment outcomes.
- ▲ Key conclusions are presented in Section 9.
- ▲ Appendix A provides details of potential facility waste classes.
- ▲ A structured list of features, events and processes (FEPs) underpinning the systematic elements of the assessment including the scenarios is presented in Appendix B.

2 Overall Approach

The overall approach followed best international practice, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia.

The approach is consistent with the Northern Territory's WorkSafe Regulations for major hazard facilities (Safe Work Australia, 2012a,b), and covers the following topics that are required under these regulations⁴:

- ▲ establishment of the context (covered by Section 3 of the present report); and
- ▲ safety assessment:
 - hazard identification (covered by Section 4.2.2 of the present report);
 - identification of existing risk controls (covered in part by Section 4.1 and in part by Section 6.3 of the present report);
 - risk assessment, including consequence estimation, likelihood estimation and risk analysis (covered by Section 7 of the present report);
 - risk evaluation against the adopted criteria (covered by Section 7 and Section 8 of the present report); and
 - identification of additional risk controls (covered by Section 7.3 and Section 8 of the present report).

The assessment is also designed to meet the requirements of the European Union's regulations governing underground storage and disposal of hazardous materials (specifically Appendix A of Council Decision (EC) 2003/33/EC) and accordingly explicitly:

- ▲ identifies the hazard (in this case the deposited wastes; Section 4.2.2),
- ▲ identifies the receptors (in this case the biosphere⁵ and possibly groundwater; Section 4.2.4),
- ▲ identifies the pathways by which substances from the wastes may reach the biosphere (Section 4.2.3);
- ▲ assesses the impact of substances that may reach the biosphere (Section 7)

The approach follows closely that which has been adopted in a number of other relevant assessments outside Australia:

⁴ These topics are a subset of all those that need to be considered by a Safety Case developed in accordance with the WorkSafe regulations, consistent with this Operational Phase Risk assessment being only one of the inputs to the Safety Case.

⁵ The term "biosphere" covers that part of the environment normally inhabited by living organisms at sufficiently shallow depths that might typically be affected by basic human actions such as farming (e.g. see IAEA, 2007).

- ▲ the assessment by Minosus Limited of an underground waste management facility at the Winsford Rock Salt Mine in Cheshire, UK, in support of a successful license application under the UK's Integrated Pollution Prevention and Control (IPPC) regulations (Hooker et al., 2002);
- ▲ an assessment by Quintessa Limited, on behalf of AkzoNobel Industrial Chemical's B.V. to determine the feasibility of using residual materials from a waste-to-energy plant operated by Twence B.V. to stabilise caverns developed in halite deposits in the eastern Netherlands (Metcalf et al., 2013);
- ▲ assessments for a number of underground radioactive waste disposal facilities, following a general methodology described by the International Atomic Energy Agency (IAEA, 2004).

More specifically, important principles followed during the assessment are:

- ▲ **The approach adopted for the OPRA was consistent with that adopted for the PCRA**, so that the former can provide suitable input to the latter.
- ▲ **The overall approach was “top-down”**, such that the starting point was identifying the main threats to the environment posed by the CF during the operational phase. The factors that influence the likelihood of each threat and their impacts were then identified to a level of detail appropriate for assessing risks in a plausibly conservative manner.
- ▲ **The overall approach was plausibly conservative**, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern.
- ▲ **The assessment was structured by carrying out a functional analysis of the CF system during the operational phase**, which was audited against experience in other, similar projects (e.g. Metcalf et al., 2013; Hooker et al., 2002) and, where appropriate, FEPs⁶. Consistent with the first point, the emphasis is on identifying threats to the safe functioning of the system, with scenarios⁷ being defined by threats / specific combinations of threats. .

⁶There are many slightly different formal definitions of the term “FEP” (e.g. IAEA, 1997; 2004), but fundamentally the meaning of these terms is as follows: A “Feature” is a physical component of a system, or a physical entity that influences a system. An “Event” is a process that influences the evolution of the system over a time period that is short compared to the time frame being considered. A “Process” is a dynamic interaction between “Features”, which may operate over any particular time interval of interest.

⁷ Following IAEA (2007) a scenario is “A postulated or assumed set of conditions and/or events.”

- ▲ **Risk were treated as a product of the probability of a threat and its impact**, the former being estimated qualitatively and the latter being estimated qualitatively.
- ▲ **Outputs are presented using commonly-used:**
 - **risk matrices**, which show highest plausible probability of threat versus plausibly conservative impact if realized;
 - **bow-ties**, which illustrate graphically, relationships between threats, hazards and potential consequence (if a threat is realized) and provide a basis for risk mitigation planning; and
 - associated **qualitative safety arguments**.
- ▲ **Recommendations for reducing cautious assumptions** have been made.

3 Assessment Context

3.1 Scope of the Risk Assessment

The aim was to undertake an objective assessment of environmental safety during the operational phase of the facility, covering the following topics:

- ▲ risks arising from the wastes, affecting the overall operation of the facility, including the stability of the storage rooms; and
- ▲ risks of a pathway⁸ developing during the operational period between the wastes and the biosphere during the operational period, such that there is an impact on receptors.

A goal was to undertake the assessment on a systematic and structured basis, reported in qualitative terms and supported by a range of different information types.

Impacts to workers (as opposed to human receptors not part of the facility workforce) are explicitly out of scope, and are instead considered in separate safety case / HAZOP documents.

3.2 Key Regulatory Requirements

The principle regulatory submissions that will be underpinned by this work are listed below but it is stressed this is not a complete list and other submissions will draw on the Integrated Risk Assessment and the PSC.

- ▲ Environmental Impact Assessment Guidelines for the Chandler facility project, (<http://www.ntepa.nt.gov.au/environmental-assessments/assessment/register/chandler-salt-mine>);
- ▲ Northern Territory of Australia *Waste Management and Pollution Control Act*, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/waste%20management%20and%20pollution%20control%20act>);
- ▲ Northern Territory of Australia *Mining Management Act*, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/MINING%20MANAGEMENT%20ACT>);
- ▲ Mining Management Plan requirements for the mining of minerals, http://www.nt.gov.au/d/Minerals_Energy/index.cfm?header=Mining;

⁸ A “pathway” is a physical route via which contaminants could potentially move, should they be released from the waste. For example, the possibility that the shafts could form such pathways is considered by the assessment.

- ▲ Northern Territories Worksafe Major Hazard Facilities guidance on the form and structure of the required risk assessment,
(<http://www.worksafe.nt.gov.au/IndustrySectors/Pages/Major-Hazard-Facilities.aspx>)

3.3 Information and Data Sources

Information and data from a wide range of sources have been reviewed and assessed in preparing this OPRA. References to relevant documents are provided in context in subsequent sections, and listed in Section 10. Additional information supplied directly to the authors is summarized in the Appendices. The assessment is primarily based upon information made available by early February 2016. Types of information and data sources reviewed include the following.

- ▲ regulatory guidance documents (Australian and international regulatory sources; including those given in Section 3.2 above);
- ▲ information on potential/projected wastes streams;
- ▲ geological and geotechnical reports;
- ▲ a number of documents concerning the proposed facility design;
- ▲ documents concerning the proposed approach to facility operation; and
- ▲ information about risk assessments undertaken for analogous international facilities.

4 Description of the Chandler Facility

4.1 Facility Description⁹

The current underground CF design (illustrated in Figure 4-1), which was developed during the pre-feasibility study, consists of a uniform room and pillar system with long rectangular pillars. Systematic roof bolting is assumed to be required in the access roads and storage rooms. This provisional underground layout is currently being reviewed as part of a geotechnical work programme.

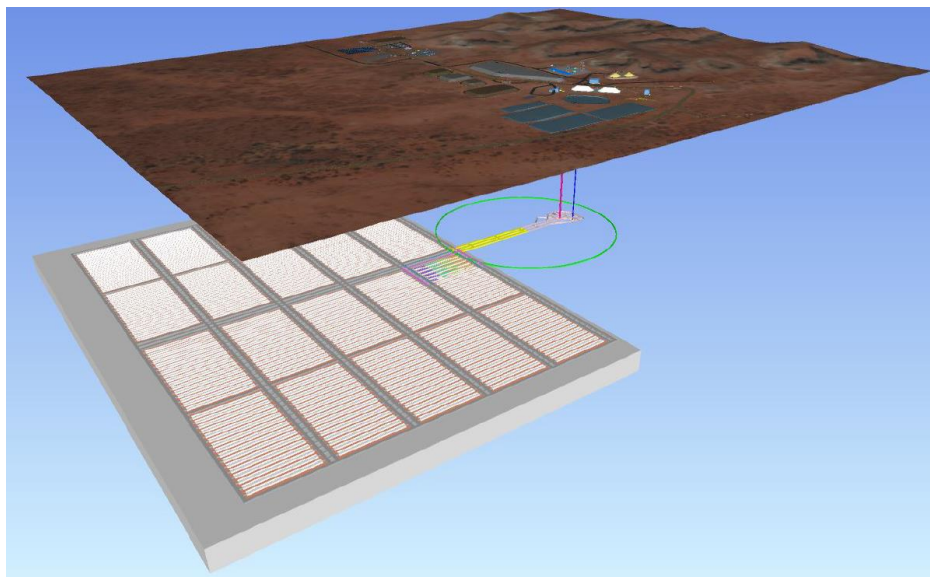


Figure 4-1: Illustration of CF layout.

The salt deposit will be accessed by two vertical shafts, each nominally 800 m deep¹⁰. The shaft used to transport wastes will have an internal diameter of 8.5 m, which is sufficient to accommodate International Standards Organisation (ISO) containers that will be used to transport containerised waste into the facility. The shaft to be used to transport mined salt will have an internal diameter of 6.0 m. Dimensions of storage and disposal rooms are yet to be confirmed. However, provisional dimensions for the storage rooms are 250 m x 10 m x 6 m and provisional dimensions for the disposal

⁹ The facility description set out in the following pages is based upon discussions with Tellus and references including: K-UTEC, 2015; RPS, 2013; TELLUS, 2015; Douglas Partners, 2013, 2016; URS, 2012; and underpinning and related references.

¹⁰ Consideration is also being given to the possibility of accessing the facility via a decline. The implications of this option for the assessment presented in the present report are given in a separate Technical Note (Quintessa Report to Tellus QRS-1809A-DC1).

rooms are 250 m x 15 m x 6 m. Pillars between the rooms are nominally sized at 15 m width currently within each panel, but the widths of the rooms at the margins of the panels may be reduced to give an additional margin of safety with respect to creep. Overall the facility has provisional underground dimensions of 2 km x 2 km x 6 m (high), with a 32% overall extraction volume taken in plan view. Main development roads are to be driven in the same salt horizon and are currently assumed to be 10 m wide by 6 m high. There will be 300 m³/s of cooled air ventilation. The cooling function of the air circulation is as important as the ventilation. The temperature of the mining horizon is expected to be c. 45 °C.

Shaft seal designs have yet to be finalised, but are likely to be based on experience at the WIPP in New Mexico, USA, and at various facilities excavated in salt in Germany.

It is planned that some waste storage and disposal will be performed using hydraulic backfill techniques (K-UTEC, 2015) with the remaining operations using placement of packaged materials which will be transported underground in transport containers. A visual summary of the two waste placement techniques planned for the CF is shown in Figure 4-2. Dry packaged waste packages will have crushed salt emplaced around them, except in cases where there is a requirement for possible waste retrieval (“storage”). Rooms in which wastes are emplaced hydraulically will be fully filled.

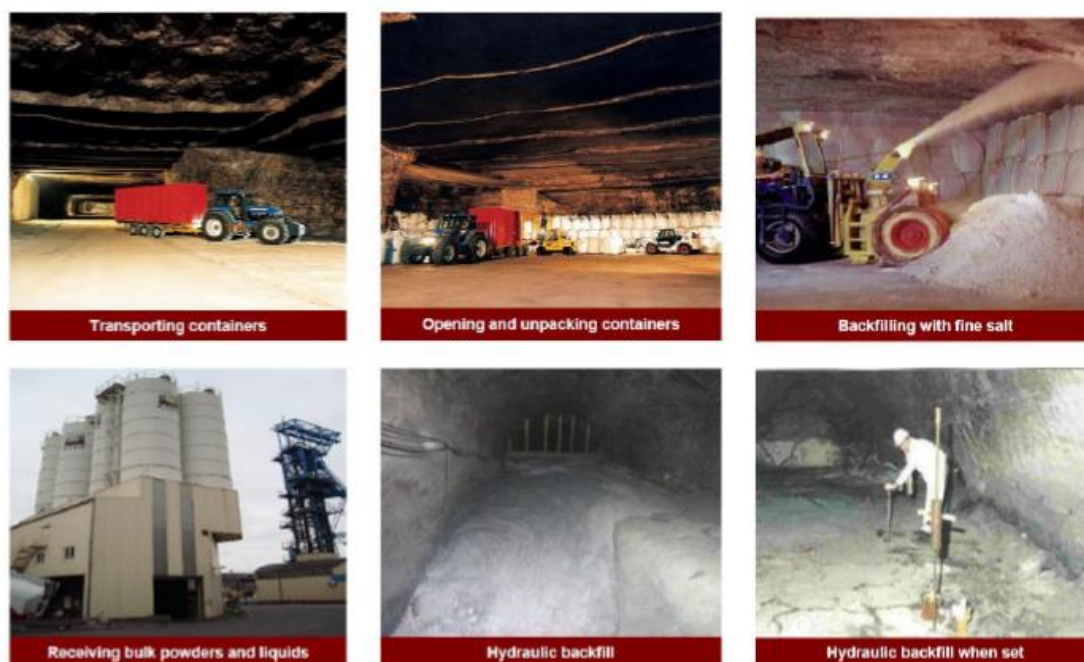


Figure 4-2: Visual representation of waste handling and storage techniques (courtesy of Tellus Holdings).

The hydraulic backfill method of waste emplacement can be employed for certain liquid and solid wastes (K-UTEC, 2015). In this method, a suspension is produced by

mixing fine solids with liquid. The low-viscosity suspension is then transported in via a pipeline to excavated rooms that are being backfilled. In order for gravity to assist in the transport of the backfill, the pipeline will run vertically through one of the shafts. The backfill will acquire sufficient velocity within the shaft that it can be transported to emplacement rooms through an approximately horizontal pipeline. The backfill will be formulated to minimize the quantity of free water remaining after curing. Any fluid that does remain can be collected in sumps to be constructed at locations that at a lower level than the backfill rooms and separated from the dry waste. This liquid can then be managed so as not to cause an adverse impacts, by being re-cycled into new backfill, or returned to the surface for reuse in subsequent backfill batches.

4.2 Location and Surface Environment

The site is located approximately 120 km south of Alice Springs in the Northern Territory of Australia and lies at the transition between erosion-resistant low hills to the northwest and a sandy plain to the south. The closest community to the facility, Titjikala (c. 180 people) is located about 18 km to the northeast.

The region has low rainfall (max c. 300 mm annually), but there can be high “flashy” rainfall events with short duration. Precautions will be taken (e.g. siting on relatively high ground, drainage channels to divert water) to prevent flooding of the facility.

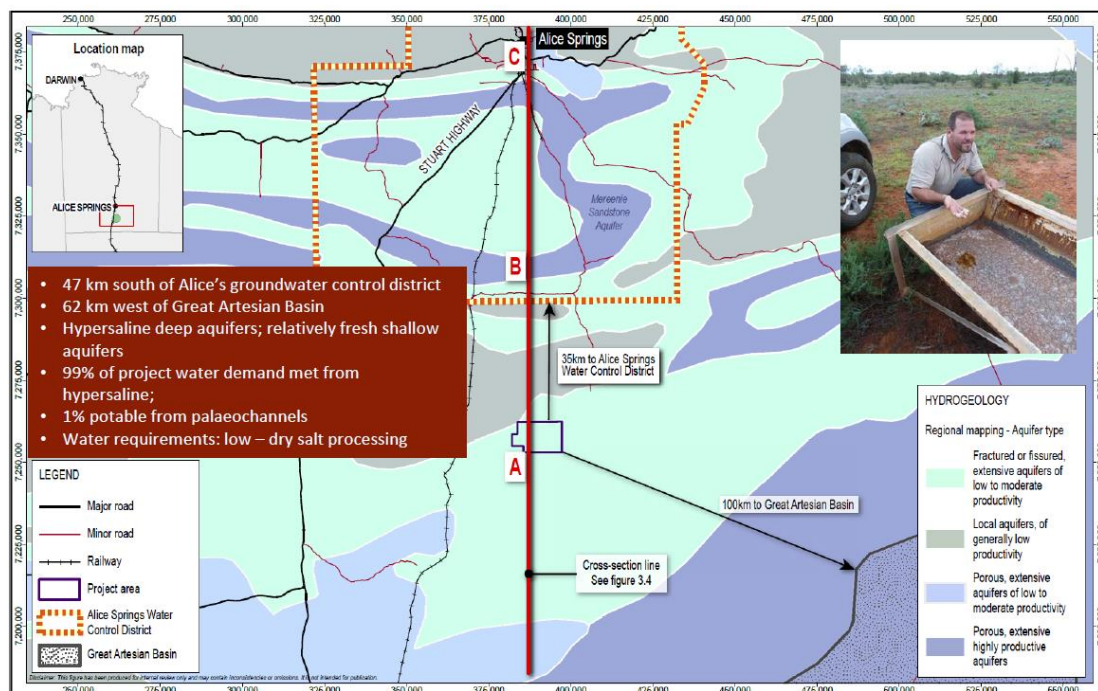


Figure 4-3: Map showing location of CF, local infrastructure and regional hydrogeology.

4.2.1 Geological and Hydrogeological Setting

The Chandler salt deposit is a 300 m thick horizontally bedded deposit. The target mining horizon is at around 800 m depth below the surface and will be located such that there is at least 20 m of intact salt between the roof of the facility and the overlying formation. The salt bed is overlain by a sedimentary sequence of shales, sandstones and limestone which contain a number of aquifers and aquicludes/aquitards at varying depths. The site is approximately 35km south of the Alice Springs Water Control District and 120 km from the main groundwater aquifers that are exploited for drinking water supplies in the Alice Springs area to the north. There is a distance of approximately 70 km between the site and the Great Artesian Basin in the east. There is not thought to be any direct connection with the aquifers that overlie the facility (URS, 2012). However, there are local boreholes that penetrate a shallow aquifer (approximately 140 m below ground level) in the community of Titjikala, located 18 km to the northeast. The Idracowra Sandstone unit, also known as the Santo Sandstone, is used as a source of drinking water for humans. However, this unit is present near the CF only in the vicinity of a borehole (WT4) located about 2 km to the east of the proposed shaft location. The Horseshoe Bend Shale is also used to supply limited quantities of water for drinking by cattle, albeit not in the footprint of the CF.

4.2.2 Hazard Identification

Waste Emplacement Strategy

Two emplacement methods will be used at the Chandler facility:

- ▲ “dry” solid waste emplacement; and
- ▲ “hydraulic backfill” emplacement.

Details are summarized below:

Dry Emplacement

- ▲ Wastes will be emplaced dry in multiple locations (different rooms) simultaneously.
- ▲ Different categories of waste will be emplaced in different zones.
- ▲ These wastes will be contained in:
 - double-lined Flexible Intermediate Bulk Containers (FIBC), also termed “bulka-bags”, which are constructed of woven fabric; or
 - barrels of granular material; and
 - may have a more robust over pack if necessary.

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- ▲ The waste-containing bulka-bags or barrels will be placed on pallets within 20-foot long ISO-containers. There will be up to 10 pallets on the floor of each container. Each container could contain up to 20 bags weighing about 1 tonne each.
- ▲ Each ISO-container will be transported into the facility via the larger diameter shaft and opened in the room within which the waste is to be emplaced.
- ▲ There will be entrances to both ends of the room in which the waste is emplaced. There will be seals on the rooms only after they have been filled. It is assumed that there are no doors while a room is being filled.
- ▲ Air circulating in the rooms will be filtered using standard dust filters that are commonly used in mines.

Hydraulic backfill Emplacement

- ▲ Wastes emplaced in a hydraulic backfill will be wet at the time of emplacement, but will subsequently cure to form a dry solid.
- ▲ Wastes will be emplaced in this form in only a single location at any one time.
- ▲ The room configuration for hydraulic backfill emplacement is different to that for dry emplacement. Rooms will have a slight incline downwards from a single entrance, so that a tendency for the wastes to flow will be directed away from the entrance.
- ▲ Following waste emplacement there will be almost no voidage apart from a small wedge-shaped void at the end nearest the door.
- ▲ During filling there will be no workers within a room.
- ▲ In order to emplace the hydraulic backfill, pipes will be installed within the facility. Only the last part of the pipe, within the emplacement room, will be flexible.
- ▲ There will be pressure monitors within the pipe network to detect possible blockages.
- ▲ Potential bursts have been considered in the conceptual design of the facility. There will be valves within the pipe network enabling emergency shut-offs to minimise the volume of waste that might be spilt. Depending upon the mix used, the hydraulic backfill could become solidified within the pipe, if for any reason pumping needs to be stopped. For example such solidification may potentially follow a shut-off after a leakage event. In such a case the pipe will need to be replaced and the replaced section of pipe will effectively become solid waste.

Mobile and Static Infrastructure

- ▲ Movement of salt and wastes will be via diesel vehicles.

- ▲ It can be assumed that while rare in normal operation, over the course of the 25 year long operational period there will be some vehicle or machinery fires. However, if these do occur, there will be a mitigation strategy in place to reduce possible impacts.
- ▲ Leaks of any fuel/oil would be recognised and remediated.

Waste Types and Inventory

A list of potential wastes has been provided by Tellus (Table A1, Appendix A), based on:

- ▲ National Environment Protection Measures (NEPM) 75 waste categories;
- ▲ the assumption that an average of 340,000 tonnes per annum (tpa) will be emplaced;
- ▲ the assumption that there will be a total of c. 8.5 million tonnes of waste emplaced over the 25 year operational lifetime of the project; and
- ▲ market research.

A list of the top 20 waste categories along with a description and identification of possible hazardous substances is given in Table 4-1.

It should be noted that Waste Acceptance Criteria (WAC) will be developed and adopted that are consistent with European legislation (specifically Appendix A of Council Decision (EC) 2003/33/EC and Article 5(3) of the Landfill Directive, Council Directive (EC) 1999/31/EC, which deals with underground disposal of wastes in salt mines). Accordingly, a number of waste types / forms will not be permitted:

- ▲ wastes listed in Article 5(3) of the Landfill Directive:
 - liquid waste¹¹;
 - waste which, in the conditions of landfill, is explosive, corrosive, oxidising, highly flammable or flammable (as defined in Annex III to Directive 91/689/EEC);
 - hospital and other clinical wastes arising from medical or veterinary establishments, which are infectious as defined by (property H9 in Annex III) Directive 91/689/EEC);
 - whole used tyres and shredded used tyres.
 - wastes and their containers which might react with water or with the host rock under the storage conditions and lead to:

¹¹ Initially liquid wastes may be accepted if they have undergone a process to incorporate them into a waste form, such as hydraulic backfill, suitable for disposal prior to emplacement in the facility.

- generation of auto-flammable or toxic or explosive substances or gases; or
 - any other reactions which could endanger the operational safety and/or the integrity of the barrier.
- ▲ wastes which might react with each other must be defined and classified in groups of compatibility (the different groups of compatibility must be physically separated in the storage);
 - ▲ wastes that are biodegradable;
 - ▲ wastes that have a particularly pungent smell;
 - ▲ wastes that can generate a gas-air mixture which is toxic or explosive;
 - ▲ wastes with insufficient stability to correspond to the geo-mechanical conditions
 - ▲ wastes that are auto-flammable or liable to spontaneous combustion under the storage conditions, gaseous products, volatile wastes, wastes coming from collections in the form of unidentified mixtures; and
 - ▲ wastes that contain, or could generate, pathogenic germs of communicable diseases.

Table 4-1: Top 20 “75” code waste descriptions, expected mass proportions at the CF and identification of potential hazardous substances.

NEPM “75” code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
N205	25.30%	Residues from industrial waste treatment/disposal operations	Scrubber sludge; Ion-exchange column residues, Ind waste treatment sludges and residues nos, Residues from pollution control operations nos	heavy metals/metalloids, organic compounds, <i>possibly pesticides</i>	Large component of inventory, possibly largely immobilized in hydraulic backfill
D110	19.60%	Inorganic fluorine compounds excluding calcium fluoride (SPL)		fluoride	<i>Largely low solubility material?</i>
N120	16.60%	Soils contaminated with a controlled waste		heavy metals, hydrocarbons (see other entries)	<i>Trace/minor amounts of metals, metalloids, hydrocarbons, possible pesticides(?), assume containerised</i>
N220	10.70%	Asbestos		amosite, chrysotile, crocidolite	<i>Assumed contained in inert matrices, potential for loose fibres / degrading ACM? Potential for Hydraulic backfill</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
J120	5.60%	Waste oil/ water, hydrocarbons/ water mixtures or emulsions	Vehicle washwaters Boiler blowdown sludge Cooling tower washwaters Textile effluent & residues nos Industrial plant washwaters Ethylene glycol-water (antifreeze) Oil/hydrocarbon (<50%) mixed with water Oil/hydrocarbon (>50%) mixed with water Other (cutting oils, soluble oils) Oil/hydrocarbon mixed with water nos	numerous hydrocarbons	<i>Potentially not suitable for hydraulic backfill</i>
D220	4.90%	Lead; lead compounds	Lead acid batteries Gritblast waste Lead & lead compounds nos	lead	<i>Assume battery acid liquid, and other forms are solid, liquids not suitable for hydraulic backfill?</i>
C100	4.90%	Basic solutions or bases in solid form	Alkaline cleaners, potash, caustic soda Ammonium hydroxide Waste lime & cement (no metallic constituents) Caustic neutralised waste (metallic constituents) Other alkaline waste (inorganic) Other alkaline waste (organic)	ammonia (others such as metals)	<i>Assume solid possible sludges? Possible hydraulic backfill candidate?</i>
D230	2.90%	Zinc compounds	Zinc ash/dust, galvaniser's ash Zinc compounds	zinc (and possibly cadmium as an impurity)	Assume solid, including particulates
NORMS	2.20%	NORMs	Mining related resins, oilfield sludges etc, but <i>not</i> NORM derived from the Nuclear Fuel Cycle.	radium, radon, barium, (uranium?) + associated radioactivity	Assume solids, with Rn gas being generated over longer timescale by decay

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics</i> indicate areas of uncertainty in future characteristics)	Assumptions on Form and Disposal Route (NB <i>italics</i> indicate areas of uncertainty in future characteristics)
J100	2.20%	Waste mineral oils unfit for their original intended use	Mineral oils unfit for their original intended use Oil filters Transformer fluids (excluding PCB's) Waste hydrocarbons	numerous hydrocarbons	<i>Unsuitable for hydraulic backfill?</i>
D300	1.20%	Non-toxic salts	Aluminium dross, aluminium smelter waste Salt slag Non-metallic product Non-toxic salts no	aluminium compounds, other metals	Assume solid
B100	0.80%	Acidic solutions or acids in solid form	Sulfuric acid Hydrochloric acid Nitric acid Phosphoric acid Chromic acid, sodium dichromate Hydrofluoric acid Sulfuric/hydrochloric acid mixtures Mixed acids (inorganic) Organic acids Pickle liquor Acids nos	<i>assume acids have largely been neutralised prior to disposal? may have some chromium/fluoride/sulpha te/phosphate/chloride compounds.</i>	<i>Assume insoluble salts?</i>
N160	0.50%	Encapsulated, chemically- fixed, solidified or polymerised wastes referred to in this list	Encapsulated waste Chemically fixed waste Solidified or polymerised waste	see other entries	Solids

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
F100	0.50%	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	Paints, inks, etc (aqueous non-flammable vapours) Paints, inks, etc (aqueous, flammable vapours) Paints, inks, etc (solvent combustible FP<60.5C) Paints, inks, etc (solvent combustible FP>60.5C) Paint residues nos	numerous compounds, including solvents	<i>Unsuitable for hydraulic backfill?</i>
M100	0.30%	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or polybrominated biphenyls	Oil, solvents & materials contaminated with PCB Equipment containing PCBs Polychlorinated biphenyls (PCBs) nos Equipment containing PCNs, PCTs and PBBs PCNs, PCTs and PBBs	PCBs, PCTs, PBBs	<i>Unsuitable for hydraulic backfill?</i>
N100	0.30%	Containers and drums that are contaminated with residues of substances referred to in this list	Drums containing waste which must be tracked Other containers containing waste which must be tracked Aerosol cans	see other entries	Containerised materials, probable low water content
N190	0.20%	Filter cake contaminated with residues of substances referred to in this list	Filter cake	see other entries	<i>Containerised solid?</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics</i> indicate areas of uncertainty in future characteristics)	Assumptions on Form and Disposal Route (NB <i>italics</i> indicate areas of uncertainty in future characteristics)
G110	0.20%	Organic solvents excluding halogenated solvents	Klenasol (non-chlorinated) Non-halogen organic solvents (flammable FP<60.5C) Non-halogen organic solvents (combustible FP>60.5C) Non-halogenated organic solvents nos	organic solvents	<i>Unsuitable for hydraulic backfill?</i>
M250	0.10%	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	Surfactants	surfaces, metals/metalloids	<i>Unsuitable for hydraulic backfill?</i>
A100	0.10%	Waste resulting from surface treatment of metals and plastics	Waste from metals & plastics treatment	metals, plastic degradation compounds	Possibly includes superplasticiser compounds

For both the OPRA and PCRA, all substances of possible concern to the receiving environment present in each waste type have been considered. All the hazardous substances in the wastes that are listed in the relevant NEPM guideline (NEPC, 2013) are considered. These substances also include priority substances and certain other pollutants within the corresponding EU legislation (Environmental Quality Standards, Council Directive (EC) 2008/105/EC).

The first step in considering these substances is to rank them 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Appendix A, Table A2). The product of the three values is then used to derive an “index” value used to identify substances of greater importance, a subset of which is suggested for consideration by the PCRA in particular. This index does not take into account interactions that occur because of the mixing of compounds that might in turn result in a product with higher solubility/mobility and/or toxic potential. However, the index approach is appropriate for the present assessment, taking into account that:

- ▲ the waste will be emplaced within a virtually dry salt formation, such that toxic compounds will not be mobilized significantly by water; and
- ▲ wastes will be emplaced in such a manner as to prevent such interactions.

Once more detailed information becomes available about the nature of the wastes, further assessment will be needed to determine any potential interactions that might be detrimental to safety. This knowledge can be used to ensure that waste handling and emplacement are carried out in a way that appropriately separates different waste types if needed to prevent such interactions

This ranking process identified the following substances of greatest priority:

- ▲ Beryllium (score 12);
- ▲ Chromium (as Cr(VI)) (score 12);
- ▲ Dichloromethane (score 12);
- ▲ Hexachlorobutadiene (score 12);
- ▲ Mercury (score 12);
- ▲ Benzene (score 9);
- ▲ Epichlorohydrin (score 9);
- ▲ Lead (score 9);
- ▲ Molybdenum (score 8); and
- ▲ Nickel (score 8).

A number of different pesticides/herbicides could be associated with wastes from agriculture and soils; a list of representative substances is given in Appendix A (Table A3). For the PCRA in particular, a subset of illustrative substances has been identified based on potential toxicological hazard and aqueous solubility:

- ▲ Dieldrin;

- ▲ Fenamiphos; and
- ▲ Diquat

Naturally-occurring radioactive material (NORM) is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate most likely from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose per year, with about 1 % being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

Releases of the substances underground could take the form of:

- ▲ spills from containers of solids, leading to dusts being introduced to the cavern atmosphere;
- ▲ leakage from pipes carrying hydraulic backfill, leading to waste slurry being released to the roadways or shafts, depending upon the leak location (although this waste would solidify during curing of the backfill);

4.2.3 Pathways

The potential for the following pathways to connect hazardous substances and receptors are assessed:

- ▲ shafts, which could allow any dusts/aerosols released underground to be transported to the surface during operations;
- ▲ pathways linking the caverns to aquifers in the overburden:
 - transmissive fractures or faults (noting that no faults have been identified within the footprint of the facility);
 - collapse columns that would be created should the roof of a cavern fail;
- ▲ aquifers in the overburden (in combination with other kinds of pathway); and
- ▲ pathways associated with boreholes intersecting other transmissive features (it being assumed that no boreholes will penetrate from the surface into the footprint of the facility, so that only shallower monitoring boreholes, which have depths of up to c. 300 m, could potentially form part of a pathway).

4.2.4 Receptors

In general terms a receptor is something that could be adversely affected by a contaminant, such as people, an ecological system, property, or a water body¹². In the assessment, the following receptors are considered:

- ▲ groundwater aquifers;
- ▲ surface water bodies;
- ▲ surface soils;
- ▲ air;
- ▲ humans (members of the wider public, since worker health and safety is not included in this assessment);
- ▲ flora (including crops – although crop production is not part of the current land use within the project area);
- ▲ fauna (including livestock).

¹² e.g. Environment Agency of England and Wales (2004). Contaminated Land Report 11.

5 Functional Analysis of the CF System

5.1 Interactions Among System Components

An interaction matrix was used to identify systematically potential interactions among different components of the Chandler Facility and the surrounding geosphere. The matrix represents system components along the leading diagonal. Processes by which these components could potentially interact are then entered in off-diagonal elements. The approach is illustrated schematically in (Table 5-1). An interaction matrix for the CF is shown in Table 5-2. In this matrix, it is assumed that all engineered and natural systems features present (and many that could be present, such as unknown fractures) are present, and can potentially interact (noting that many can be discounted). The reason for this approach is to provide a way of auditing the systems evolution scenarios (Section 7) developed using a “top-down” approach, to ensure that system evolution scenarios or potential source-pathway-receptor connections have not been missed.

Table 5-1: Schematic illustration of a component interaction matrix.

Component 1	Processes by which Component 1 affects Component 2	No direct interaction between Component 1 and Component 3, so “greyed out” (-)
Processes by which Component 2 affects Component 1	Component 2	Processes by which Component 2 affects Component 3
Processes by which Component 3 affects Component 1	No direct interaction between Components 3 and Component 2 so “greyed out”(-)	Component 3

Table 5-2: Potential Interaction Matrix for Chandler Facility (see text)

Salt extraction shaft and seals	-	-	-	-	-	-	-	-	-	potential pathway	potential pathway	-	-	creep	-	potential pathway	-	-	pathway for contamination of surface air/soil	exposure to contaminants (if pathway intact) - workers and public
-	Waste emplacement shaft and seals	ventilation	ventilation	ventilation	ventilation	-	-	-	-	potential pathway	potential pathway	-	-	creep	-	potential pathway	-	-	pathway for contamination of surface air/soil	exposure to contaminants (if pathway intact) - workers and public
-	-	Rooms	-	-	-	unloading	-	-	-	contamination (loss of containment)	contamination (loss of containment)	unloading (geometry change)	possible destabilisation/roof collapse	creep	-	potential pathway	-	-	cavern collapse	falling material (workers)
-	-	-	Tunnels	-	-	-	-	-	-	potential pathway	potential pathway	unloading (geometry change)	possible destabilisation/roof collapse	creep	potential pathway	potential pathway	-	-	cavern collapse	falling material (workers)
vehicle fire	vehicle fire	vehicle fire	vehicle fire	Moveable/fixed infrastructure	-	impact/destabilisation	-	-	-	-	-	-	-	-	-	-	-	-	-	vehicle accidents (workers)
-	-	-	-	-	Head space	-	-	-	-	-	contamination (loss of containment)	-	possible destabilisation/roof collapse	creep	-	-	-	-	-	-
-	-	structural support	-	-	-	Pillars	structural support	structural support	-	sorption of contaminants	sorption of contaminants	loading	structural support	-	-	-	-	-	-	-
-	-	-	contamination if pipe fails	contamination if emplacement pipe fails	-	loading	HBF Waste	-	-	-	-	loading	exert pressure (overfill/salt creep)	exert pressure (overfill/salt creep)	-	-	-	-	-	worker exposure (leak)
-	-	-	-	-	backfill reduced head space	loading	-	Loose salt backfill	-	sorption substrate	sorption substrate	-	-	-	-	-	-	-	-	worker exposure (dust)/collapse impact
-	-	contamination (loss of containment)	-	-	-	-	-	-	Solid waste+container	-	mixing of waste materials	loading	-	loading	-	-	-	-	-	worker exposure
-	contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	possible damage to vehicles	-	possible dissolution	-	possible dissolution	waste interaction (loss of containment)	Liquid waste+container	-	possible dissolution if released	-	possible dissolution if released	contamination (loss of containment)	contamination (loss of containment)	-	-	contamination if pathway intact	worker/public exposure if pathway intact
contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	possible damage to vehicles	contamination (loss of containment)	salt deliquescence	-	salt deliquescence	mixing of waste materials	possible gas dissolution into liquid	Aerosol/ gas from waste release/accidental mixing	salt deliquescence	salt deliquescence	salt deliquescence	potential pathway	contamination (loss of containment)	-	-	contamination if pathway intact	worker/public exposure if pathway intact
-	-	-	-	-	-	structural support	structural support	-	-	sorption substrate/diffusive transport medium	-	Underlying salt	-	-	potential pathway	potential pathway	-	-	-	-
loading of shaft seal materials	loading of shaft seal materials	-	-	-	-	loading	possible loading (creep)	-	sorption substrate	sorption substrate	-	Overlying salt	-	-	potential pathway	-	-	-	-	-
potential pathway	potential pathway	potential pathway	-	-	-	-	possible emplacement water leakage	-	-	potential pathway	potential pathway	-	-	Confining salt	change in geometry due to creep (closure)	change in geometry due to creep (closure)	-	-	-	-
potential pathway	potential pathway	potential pathway	-	-	-	-	possible emplacement water leakage	-	-	potential pathway	potential pathway	potential pathway	potential pathway	creep	Boreholes	combined potential pathway	possible contamination	possible pathway	No impact if boreholes not in use	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	creep	combined potential pathway	Fractures	possible contamination	possible pathway	possible contamination of surface soil	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Aquifers	-	impact on water quality	drinking water contamination (public)
flooding	flooding	flooding	flooding	flooding	flooding	flooding	flooding	mobilisation	mobilisation	mobilisation	mobilisation	dissolution	dissolution	-	-	-	pathway if breached	Aquicludes	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	flooding	flooding	contamination	-	Biosphere Receptors (incl. surface waters)	contamination of environmental media (soil, water, air, flora and fauna)
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Human Receptors

5.2 Scenario-Defining Events and Processes

In general, any event or process that influences the behaviour of the CF will not operate in isolation, but will be coupled to other events and processes. Consequently, the identification of an event or process as the cause of a loss of control over the hazard and activation of one or more pathways is to some extent one of convenience for the purposes of analysis. Furthermore, a given process could cause such loss of control and pathway activation in some cases, but may in other circumstances be caused by some other process. For example, a roof collapse may potentially damage the electrical and fuel systems of a vehicle leading to a fire. On the other hand the heat generated by a vehicle fire caused by an electrical system failure might cause a roof collapse. The goal here is therefore to identify a set of events and processes that lead naturally to the definition of a set of scenarios that cover all plausible states / evolutions of the system.

Based on the assessment of interactions among components of the system, the phenomena listed in Table 5-3 have been identified as possible causes of loss of control over the hazard during the operational phase.

Table 5-3: Phenomena that could initiate loss of control over the hazard and activation of one or more pathways between the hazard and one or more potential receptors.

Cause of Loss of Control	Description	Treatment
Rockfall in partially-filled room/tunnel	Roof failure in partially filled room or rockfall could also potentially connect the rooms to conductive features within the overburden (considered in the PCRA)	Covered explicitly by a scenario. Qualitative evaluation.
Conductive feature of the rock (fault or aquifer) encountered unexpectedly	During the excavation of the facility a conductive feature (fault or aquifer) is encountered unexpectedly and connects the facility to shallower conductive features in the overburden.	Not explored explicitly by a scenario. Given the self-sealing characteristics of halite and the fact that conductive features are highly likely to be identified based on seismic data and hence avoided, if they occur, this process is highly unlikely. The effects would be similar to those of a rockfall that leads to the facility being connected to conductive features higher in the overburden. This process is therefore considered together with rockfalls in the analysis.
Vehicle fire	Vehicle fire at the surface or in tunnels/disposal rooms/shaft, leading to waste packaging being compromised. Depending upon where the fire occurs there could be release of contaminants to the atmosphere within the facility, from where it can be circulated by the ventilation system, or contamination of the atmosphere at the surface. Also depending upon where the fire occurs, possibly there could be contamination of groundwater.	Covered explicitly by a scenario. Qualitative evaluation.

Cause of Loss of Control	Description	Treatment
Fire in fixed facilities	Fire in fixed facilities underground or in buildings at the surface, leading to waste packaging being compromised. Depending upon where the fire occurs there could be release of contaminants to the atmosphere within the facility, from where it can be circulated by the ventilation system, or contamination of the atmosphere at the surface. Also depending upon where the fire occurs, possibly there could be contamination of groundwater.	Covered explicitly by a scenario. Qualitative evaluation.
Ventilation and other services fail	Inadequate ventilation, leading to a build-up of contaminated air in the facility. It should be noted that this process in itself would not lead to loss of control over the hazard, unless a lack of ventilation resulted in actions being taken that would diminish proper supervision and management of the wastes within the facility.	Not considered explicitly within a scenario. Implications for workers and general excavation/emplacement operations, not considered further in this OPRA. Ventilation failure, would not itself lead to release of contamination from wastes. Similarly, failure of other services, such as electrical failures, would not cause releases of contaminants from wastes directly. Indirect releases of contaminants from wastes that might result from the failure of such services are considered by other scenarios. If it were to occur in combination with a process leading to contaminant release, ventilation failure could result in decreased potential for air-borne contamination to reach surface. On the other hand, ventilation failure could also produce higher peak levels of contamination within

Cause of Loss of Control	Description	Treatment
		underground parts of the facility and / or result in contamination remaining in the underground atmosphere for longer than would be the case should the ventilation function.
Waste degradation and gas generation	Corrosion of metals (H_2) generation and build-up of gases (e.g. methane) due to organic waste degradation, possible pressurisation in vaults	Not considered explicitly within a scenario. Waste degradation and gas generation during the operational phase unlikely to be significant. Most degradation processes that can be envisaged require a source of water, but conditions within the CF will be dry. The only source of water will be any residual moisture within the wastes themselves. Such moisture will be present in limited quantities, with the result that any waste degradation and gas generation in the operational phase will be limited.
Waste package failure	Release of solids (or derived dust) due to: ▲ package drops/breach (vehicle accidents etc.), either at the surface or within the facility; ▲ a container drop in the access shaft; ▲ degradation of canisters within a panel.	Covered explicitly by a scenario. Consider potential for contaminant release (effect on workers not included in this OPRA) and transport via potential pathways to biosphere. Qualitative assessment.
Hydraulic backfill emplacement system failure	Failure of the backfill emplacement system may take three general forms: ▲ emplacement pipe bursts during emplacement, ▲ failure of pumping system; or	Covered explicitly by a scenario. Operational: prevent continued normal operations. There is potential for infrastructure to be contaminated, depending upon where the burst occurs. However, the backfill will

Cause of Loss of Control	Description	Treatment
	▲ failure of hydraulic backfill supply. Any of these circumstances may lead to hydraulic backfill present within the pipe system solidifying, causing a blockage that prevents further use of the system.	solidify and cure once it is has leaked, thereby limiting the potential for receptors to come into contact with it.
Impaired shaft lining performance	Water ingress during operations, leading to potential for flooding of underground facility and mobilization of contaminants (if containers leak/hydraulic backfill can be leached).	Covered explicitly by a scenario. Minor leaks will be identified and can be grouted. Major water ingress potentially more of an issue, both considered.
Sabotage / criminal acts	Conceivably sabotage, or criminal acts could lead to loss of control over the hazard, for example by causing spills. However, the effects of such sabotage or criminal acts would	Not considered in detail. Sabotage or criminal acts are unlikely owing to operating procedures designed to prevent them. Were they to occur, then the environmental effects would be similar to those of other initiating processes that are considered (e.g. vehicle fires, spillages etc.)
Seismic activity	Earthquakes lead to package breaks/hydraulic backfill emplacement failure, leakages of waste, leakage of fuel/oil from vehicles, major infrastructure damage, risk to workforce etc.	Not considered in detail. Qualitative arguments that seismic activity is unlikely to impact upon the facility and, if it occurs during the operational period, such impacts are unlikely to be significant. Significant seismicity is not expected, because the Chandler facility is located in the stable interior of a tectonic plate. It should be noted that, even if it occurs, seismic activity would likely only affect shallower operations, to depths of a few tens of metres owing to the attenuation of ground displacements

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Cause of Loss of Control	Description	Treatment
		with increasing depth; mines are generally unaffected adversely by seismic activities, even in highly seismically active regions such as Japan.

These initiating events can be mapped to events that were identified to potentially cause releases of waste materials to sensitive receptors during the successful OPRA for the Minosus facility in Cheshire, UK (Hooker et al., 2002). This mapping is made in Table 5-4.

Table 5-4: Correspondence between events considered by the Minosus assessment (Hooker et al., 2002) to potentially cause releases of waste materials and initiating events considered in the CF OPRA.

Minosus Assessment (Hooker et al., 2002)		Corresponding Initiating Event From Table 5-3
Event No.	Event Description	
1	HGV accident at surface	Vehicle fire Waste package failure
2	Container damage during unloading at surface	Waste package failure
3	Container damage during handling / storage at surface	Waste package failure
4	Failure of lift resulting in container damage	Waste package failure
5	Container damage at base of shaft	Waste package failure
6	Vehicle accident underground	Vehicle fire Waste package failure Hydraulic backfill emplacement system failure
7	Container damage during handling at panel	Waste package failure
8	Degradation of canisters in panel	Waste package failure
9	HGV fire at surface	Vehicle fire
10	Fire in surface buildings	Fire in fixed facilities
11	Fire in lift	Vehicle fire Fire in fixed facilities
12	Vehicle fire on waste route	Vehicle fire
13	Flooding of mine	Impaired shaft lining performance Rockfall in partially-filled room/tunnel Conductive feature of the rock (fault or aquifer) encountered unexpectedly
14	Earthquake of highest magnitude recorded in last 500 years	Seismic activity
15	Release of methane / hydrogen	Waste degradation and

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Minosus Assessment (Hooker et al., 2002)		Corresponding Initiating Event From Table 5-3
Event No.	Event Description	
		gas generation
16	Failure of extractor fan	Ventilation and other services fail

It should be noted that the initiating process “Hydraulic backfill emplacement system failure” was identified for the CF system, but is not relevant for the Minosus facility where hydraulic backfilling was not employed.

The assessment for the Minosus facility did not explicitly consider “Sabotage / criminal acts”. These are noted in the CF OPRA for completeness, but are not considered in detail, owing to their effects being similar to other initiating processes that are considered.

6 Scenario Development

6.1 Nature of Scenarios

Scenarios are commonly developed and analysed during risk assessments for a wide range of sub-surface storage and waste disposal projects (e.g. NEA, 2001; Robinson and Hooker, 2002; Watson et al., 2008; Capture Power and National Grid, 2016). There are several slightly different definitions, but broadly a “scenario” is *a plausible description of the potential behaviour or evolution of a system according to the nature of the features, events and processes that might act within and upon it*. In the present OPRA, the “system” of concern consists of the wastes, the surrounding engineered structures (e.g. backfill and shaft seals), the surrounding geosphere (rock sequences, including geological structures such as faults and fractures that may occur within them, and the groundwater) and the potential receptors that could be affected.

Here, two types of scenario are distinguished:

- ▲ An Expected Evolution Scenario (EES), which is a statement of how the CF and its surroundings are expected to behave if development and operational plans are implemented properly.
- ▲ Six Alternative Evolution Scenarios (AES), which are statements of how the CF system would behave under alternative sets of circumstances, different to those of the EES.

It is important to note that an AES is *not a prediction* of the future behaviour of the system, but rather a representation of the status of the system under a specified set of conditions.

Any impact arising should the system not behave as planned, would be no greater than the greatest impact arising from the assessed scenarios.

6.2 Approach

A “top-down” approach to developing scenarios was undertaken, involving the following steps:

1. Firstly, the system was described to identify important components of the system and spatial and temporal relationships among them.
2. The hazard of concern to the assessment was described.

3. Potential¹³ pathways for contaminants to come into contact with potential¹⁴ sensitive receptors were identified. These pathways would become relevant should control over the hazard be lost.
4. Potential sensitive receptors were identified. These receptors are entities that could plausibly be harmed should they come into contact with contaminants as a consequence of control being lost over the hazards identified in 1. and one or more pathways identified in 3. becoming active.
5. Possible interactions between the different components of the system were determined systematically to identify possible processes by which:
 - control over the hazard could be lost;
 - pathways between the hazard and potential receptors could become active.
6. Processes that could cause a combination of loss of control over the hazard and one or more pathways to become active were then identified.
7. Scenario descriptions were then developed consisting of:
 - an Expected Evolution Scenario (EES), which describes how the system is expected to behave, according to plans being followed;
 - a set of Alternative Evolution Scenarios (AES), describing how the system might behave in the event that one of the processes identified in 6. occurs, each one comprising:
 - i. a description of the initiating process; and
 - ii. the interactions among the components of the system that could arise as a result of the initiating process.

6.3 Expected Evolution Scenario

The EES is a statement of the evolution of the Chandler Facility during the operational period, assuming that operations are carried out as planned and that the facility behaves as designed.

- ▲ There are no significant changes to the presently planned operational regime (e.g. types of waste accepted, changes in facility concept).
- ▲ Rooms and pillars behave in accord with the design intent.
- ▲ No rockfall/roof collapses occur that are sufficient to threaten the integrity of waste containers.

¹³ These are pathways that are not proven to exist, but which could plausibly exist under appropriate circumstances. Therefore, the likelihood for these pathways occurring and the consequences should they occur, need to be assessed.

¹⁴ These receptors are not necessarily certain to occur at the time of any contaminant release, but could plausibly occur.

- ▲ Vehicles operate as planned, such that there are no collisions or fires that would cause release of contamination.
- ▲ Some minor change in room geometry possible due to creep, but this is not significant during the operational phase and can be managed.
- ▲ Ventilation and other services work as planned.
- ▲ Hydraulic backfill emplacement occurs as planned, without any pipe blockages or leakages of hydraulic backfill.
- ▲ Degradation of wastes in containers and hydraulic backfill is very slow and does not result in any significant changes to the properties of the wastes during the operational phase. For example, large volumes of gas are not expected to be produced by metal corrosion or waste degradation.
- ▲ There are no spills of waste material from package drops / breaches.
- ▲ The salt provides an effective barrier against contaminant transport in the event of minor spills
- ▲ Creep begins, causing a tendency to seal voids associated with rooms and access roads in the salt horizon.
- ▲ Shaft linings prevent water ingress to the facility, so water does not compromise the integrity of waste packages, mobilize contaminants or adversely affect operations. A monitoring system is established, which will be used until the end of institutional control.
- ▲ No significant seismic activity occurs (i.e. seismic activity that would compromise the integrity of any structures or operations).
- ▲ Wastes that include explosive /clinical waste etc. are not permitted and excluded under Waste Acceptance Criteria (WAC), which are consistent with European legislation (specifically Appendix A of Council Decision (EC) 2003/33/EC and Article 5(3) of the Landfill Directive, Council Directive (EC) 1999/31/EC).

6.4 Alternative Evolution Scenarios (AES)

The AES in the operational phase proposed to be taken forward for further risk assessment are:

1. AES 1: Rockfall (in an unfilled or partially-filled room, tunnels);
2. AES 2: Vehicle fire;
3. AES 3: Fixed infrastructure fire;
4. AES 4: Waste package (ISO container or bulka-bag) failure;
5. AES 5: Hydraulic backfill emplacement system failure; and
6. AES 6: Impaired shaft lining performance.

The initiating processes that are outlined in Section 5.2 which are not used to define an AES are discussed as variants of these scenarios.

7 Qualitative Assessment of Alternative Evolution Scenarios

7.1 Approach

A qualitative assessment of AES during the operational phase of the CF has been undertaken. For each scenario (1-6), a description of the scenario and sub-scenarios are presented, along with a consideration of likelihood of “causing event(s) and / or process(es)” to occur, possible mitigating/managing actions and likely impacts.

The combination of likelihood (over the timescale of operation) and impact give the overall risk as shown in the matrix given in Table 7-1. The likelihood of a scenario occurring on a linguistic scale is considered qualitatively to range from “improbable” to “probable”. Similarly, the impact of each scenario is considered qualitatively on a scale “none” to “very high”.

The approach taken is that each scenario has been described given plausible initiating events that are likely to result in the system evolving in a different manner to that assumed in the expected evolution scenario.

Table 7-1: Risk Matrix Approach (red = high risk; yellow = moderate risk; blue = low risk; green = effectively no risk).

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable	Green	Blue	Yellow	Red	Red	Red
Likely	Green	Blue	Yellow	Yellow	Red	Red
Possible	Green	Blue	Blue	Yellow	Yellow	Red
Unlikely	Green	Blue	Blue	Blue	Yellow	Yellow
Highly Improbable	Green	Blue	Blue	Blue	Blue	Yellow

Bowtie representations are also presented to show and communicate risks from the qualitative assessment (Section 7.3).

Risks can be placed into two categories:

- (1) Risks resulting from threats to ongoing operation of the CF; and
- (2) Risks posed by threats to environmental receptors, due to intact source-pathway-receptor linkages (exposure to materials release from wastes or substances released due to accidents, such as products of combustion from vehicle fires).

For each category considered, the terminology used to describe likelihood is given in Table 7-2. The terminology used to describe impacts is given in Table 7-3.

Table 7-2: Description of terms used to describe the likelihood of a scenario occurring.

Highly Improbable	Unlikely	Possible	Likely	Highly Probable
Virtually certain <i>not</i> to occur. The evidence base ¹ is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur and <u>none of the available evidence</u> indicates that the phenomenon / scenario will occur.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u>will not</u> occur than there is that it will occur. It is judged <u>clearly that the phenomenon / scenario will probably not occur</u> .	The evidence base is substantial, but some evidence indicates that the phenomenon / scenario will occur, whereas other evidence indicates that it will not occur. However, the evidence that the phenomenon / scenario will occur has about the same weight as the evidence that the phenomenon / scenario will not occur. In other words there is <u>no clear balance of evidence</u> that the phenomenon / scenario will occur as opposed to it not occurring.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u>will occur</u> than there is that it will not occur. <u>It is judged clearly that the phenomenon / scenario will probably occur</u> .	Virtually certain <i>to</i> occur. The evidence base is sufficient to reach a clear conclusion about whether a phenomenon / scenario will / will not occur and <u>all available evidence</u> points to the phenomenon / scenario occurring.

Notes: 1. Application of this scale is predicated on there being sufficient evidence (in terms of “quantity” and “quality”) to make a judgement of likelihood. That is, aleatory uncertainties (related to the inherent variability of a phenomenon) are encompassed by the scale, but epistemic uncertainties (arising from lacking knowledge) are not.

Table 7-3: Description of terms used to scale impact.

Assessment	None	Very Low	Low	Medium	High	Very High
Operability	None	Trivial disruption and associated costs.	Minor disruption to ongoing operations, short term (<1 day), minor additional cost to Facility for remedial action (if needed)	Significant disruption to ongoing operation (days-weeks), significant additional cost to Facility for remedial action (if needed)	Major disruption to ongoing operation (month-years), high additional cost to Facility for remedial action (if needed), viability of ongoing operations brought into question	Facility permanently unable to function in any capacity. Major socio-economic impact incurred due to loss of operations (very high costs for remedial activity).
Environmental	None	Negligible contamination of environmental receptors Negligible ecological impact Negligible / immeasurable public exposure to contaminants and no significant public health implications Negligible livestock exposure to contaminants	Minor contamination of environmental receptors (measurable) Minor potential for ecological impact (possibly short-term/reversible) Very low level of public exposure, theoretical possibility of health effects (acute/chronic) Possible minor livestock (e.g. cattle) exposure	Low-level contamination of environmental receptors (potential exceedances of environmental quality indicators) Potential for ecological impact (possibly short-term/reversible) Low level public exposure, possibility of increased risks to health, possible observation of related acute health effects in susceptible individuals Livestock exposed to contaminants need to consider potential tainting of animal products Overall impacts result in regulatory observations	Significant contamination of environmental receptors Ecological impact (possibly irreversible) Significant public exposure, expected increased risks to health and/or observation of acute health effects in population Livestock exposed to contaminants, possible detrimental health effects, animal products deemed unfit for human consumption Overall impacts result in regulatory intervention	Catastrophic contamination of environmental receptors (including loss of any local vegetation) Major potentially irreversible ecological damage Major widespread public exposures resulting in significant observable adverse health effects, and/or loss of life) Complete loss of livestock and need for disposal of animal products as unfit for human consumption

7.2 Alternative Evolution Scenario Descriptions and Qualitative Analyses

Brief descriptions of AES, associated-source-pathway-receptor linkages, mitigating measures, likelihood, degree of impact and overall risk with regard to operability and environment are given in Table 7-4 and Table 7-4, summaries of overall risks relating to operability and environment are given in Table 7-6 and Table 7-7, respectively. The risks assume that appropriate plans are in place to prevent these scenarios from arising, and for mitigating their effects should they do so.

The Tables include overall assessments of potential impacts, made on a qualitative basis considering the key information inputs and expert judgements described in previous sections.

To provide context for the assessment, key elements of the AES are listed below.

The **rockfall in partially-filled room / tunnel scenario (AES 1)** assumes that there is a significant mass of material falling from the roofs (more than minor dust, or a few small fragments) in either:

- a. a tunnel; or
- b. a room that is being excavated or into which waste is being emplaced.

This scenario reflects a degree of failure in rockfall mitigation measures that are expected to be in place (e.g. rock bolting and design). Multiple simultaneous rockfalls in different parts of the facility are considered to be implausible.

This scenario could result in three kinds of risk to the environment or operability of the facility:

- i. restricted access to all or part of the facility;
- ii. damage to waste containers; or
- iii. water ingress to the CF.

Were damage to containers to occur, the potential for contaminant release would be similar to that covered by the waste package failure scenario (AES 4).

If a significant volume of water were to ingress into the facility as a result of roof collapse (more than minor seepages that could be easily avoided by waste emplacement activities and readily stopped by grouting), then the potential for contaminant release and risks to operations would be broadly similar to the impaired shaft lining scenario (AES6).

The **vehicle fire scenario (AES 2)** assumes that at least one vehicle fire event could occur during the operation of the facility, even if fire prevention measures and vehicle

maintenance procedures are in place. The fire could occur anywhere between the ground surface and the site of waste emplacement underground. There are two main variants:

- a. a fire underground (likely worst case within or at the base of a shaft); or
- b. a fire at the ground surface.

The chief differences between a vehicle fire at the surface and underground will be:

- ▲ Compared to vehicle fires at the surface, vehicle fires underground may result in higher peak concentrations of any contaminants that are released, owing to the confined space within which release occurs.
- ▲ Compared to vehicle fires underground, vehicle fires at the surface will have a higher probability of contaminating the wider environment owing to atmospheric dispersal.
- ▲ Compared to vehicle fires underground, those at the surface will pose less risk to the operations of the facility since any damage will likely be more readily rectified.

The **Fixed infrastructure fire (AES 3)** considers the potential for a fire in fixed infrastructure, at the ground surface or underground. The effects of such a scenario being realized at any particular locality would largely be similar to those for a vehicle fire at a similar locality, except in so far as an item of fixed infrastructure could be larger than a single vehicle. Scenario AES 2 and AES 3 could be closely related in that a vehicle fire could cause a fixed infrastructure fire, or vice versa.

The **waste package failure scenario (AES 4)** considers the potential for release of containerised waste underground due to:

- a. containment being breached (for example, containers being dropped in rooms/tunnels or damaged by vehicles);
- b. the drop of an iso-container down the disposal shaft resulting in rupture of waste container and ISO container.

The **hydraulic backfill emplacement failure scenario (AES 5)** considers the potential for failure of hydraulic backfill emplacement system, leading to blockage and need to remove the pipe and repair/replace. There are two variants:

- a. failure to maintain a flow of backfill mix, due either to pump failure or failure to introduce backfill mix to the system; or
- b. a pipe burst

In either case, there would be consequences at the ground surface and underground. Were a pipe burst to occur, then slurry would be spilled either in the sub-surface environment or at the ground surface. It is assumed that such a spill would be recognized quickly and the system shut down, so that the spill, whether at the surface

or underground would be restricted in volume. The spilled backfill mix would solidify and could then be broken into pieces if necessary and treated as solid waste. Backfill in the remaining pipe would also solidify, once pumping had stopped. A consequence would be a requirement to replace the pipe before resuming hydraulic backfilling operations.

The **impaired shaft lining scenario (AES 6)** assumes that there has been either a failure in the QA/QC associated with lining materials or their emplacement and that this results in either:

- a. minor water seepage; or
- b. major water ingress via permeable horizons.

The latter situation would occur only if the failure of the shaft lining grout occurred at a location adjacent to an aquifer which could sustain prolonged inflows. Many of the more permeable horizons within the overburden have been found in boreholes to be incapable of supporting such sustained flow.

Table 7-4: Description of alternative evolution scenarios: operability impacts.

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
1	Rockfall	Failure of engineering measures to mitigate against significant rockfall in (a) a tunnel (b) a room In each case, two variants: (ai) Rockfall only (aai) Rockfall accompanied by water influx (bi) Rockfall only (bii) Rockfall accompanied by water influx Multiple simultaneous rockfalls in different parts of facility deemed implausible	(a) (i) vehicles, possible disruption to transport of containers (ii) access to all or part of the facility prevented, possible mobilization of contaminants (b) (i) vehicles, possible loss of a room for disposal (ii) access to all or part of the facility prevented, possible mobilization of contaminants Results in impeding of transport in tunnels or rooms	Standard monitoring and inspection of working Use of mitigating procedures (e.g. rock bolting) and appropriate excavation design geometry Remedial measures if rockfalls occurred may include re-excavation, or disposing to different rooms If water ingress would need to physically isolate the part of the facility affected, which may not be possible	(ai) Likely (aai) Highly improbable (bi) Likely (bii) Highly improbable	(ai) Medium Loss of accessibility, need to clear material/re-excavate resulting in disruption (aai) Medium-High Depending on extent of flooding, possible long-term remediation required/facility ceasing to function. Relatively low permeability of aquifer limits inflow. (bi) Low Possible loss of room for waste emplacement, or shift emplacement to different room until remedial actions complete (bii) Medium-High Depending on extent of flooding, possible long-term remediation required/facility ceasing to function. Relatively low permeability of aquifer limits inflow.

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
2	Vehicle Fire	Fire in underground tunnels/room, or at the ground surface causes disruption to emplacement activities, potential releases of combustion products (gases and particulates)	Damage to underground infrastructure and disruption of operations if occurring underground, contamination of the atmosphere underground and potentially contamination of the atmosphere at the surface, if smoke / fumes vented via the shafts Damage to surface infrastructure and disruption of operations if occurring at the surface, potentially contamination of the atmosphere around the facility	Standard fire prevention practices and vehicle maintenance Emergency response arrangements Remedial measures (e.g. decontamination if required)	Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility	Medium Significant disruption to ongoing operations, need for remedial activities
3	Fixed infrastructure fire	Fire in fixed equipment in underground tunnels/rooms, or in facilities at ground surface causes disruption to emplacement activities, potential releases of productions of combustion (gases and particulates)	Damage to underground infrastructure and disruption of operations if occurring underground, contamination of the atmosphere underground and potentially contamination of the atmosphere at the surface, if smoke / fumes vented via the shafts	Standard fire prevention practices and facility maintenance Emergency response arrangements Remedial measures (e.g. decontamination if required)	Unlikely - Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility. Lower probability corresponds to higher impact.	Medium - High Significant disruption to ongoing operations, need for remedial activities. The maximum plausible impact for a fixed facility is greater than for a single event involving a vehicle (except in so far as the vehicle fire could cause a larger fire in a fixed facility, especially at the surface).

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
			Damage to surface infrastructure and disruption of operations if occurring at the surface, potentially contamination of the atmosphere around the facility			Greater impacts correspond to lower probability events.
4	Waste package failure	Dry emplacement wastes (a) Discrete waste spill due to container drop or failure (e.g. vehicle accident, damage due to fire, rockfalls) (b) Container drop in shaft resulting in rupture of containers at base of shaft	(a) Tunnels/rooms/infrastructure (b) Shaft, tunnels connecting shaft to rooms	General minimisation of likelihood considered during facility design Maintenance of equipment (a) Standard health and safety procedures, worker training for underground operation of vehicles (b) Elevator safety mechanisms to prevent opening of doors when elevator at bottom of shaft and/or elevator drop. Standard health and safety procedures, worker training. Possible waste interaction due to spills resulting in exacerbated gas/aerosol production mitigated	(a) Likely Probability minimised via standard operating procedures, but considered that one event could occur over whole operational lifetime, in contrast to expected scenario (b) Highly Improbable Multiple safety protocols to prevent drop of containers in shaft	(a) Medium Significant disruption to operations, need for remediation of contaminated areas prior to ongoing working (b) High Major disruption, need for extensive remedial activities

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
				against by considering separation of wastes during acceptance and emplacement Emergency response protocols and actions		
5	Hydraulic backfill emplacement system failure	(a) Failure of hydraulic backfill emplacement system at the surface, or underground, leading to blockage (b) Leak of backfill pipe, either underground or at the surface	(a) Hydraulic backfill emplacement pipe must be replaced, the blocked pipe itself becoming solid waste (b) Tunnels/rooms/infrastructure, shaft, tunnels connecting shaft to rooms, if at surface facilities close to the leak	QA/QC procedures for backfill manufacture and emplacement, design of facility. Maintenance of equipment. Standard procedures, worker training If a leak were to occur, emplacement of backfill would cease	(a) Likely (b) Possible Risk minimised by quality control procedures in place for backfilling system	(a),(b) Medium Disruption to operations, need for remediation prior to ongoing waste emplacement
6	Impaired shaft lining performance	Failure of shaft liner during operations and water ingress via permeable horizons/surface possibly exacerbated via high rainfall/recharge	Possible failure of shaft lining grout (possibly exacerbated by high rainfall/surface flooding) leading to water ingress resulting in: (a) minor water ingress into tunnels and disruption to salt excavation/waste	QA/QC procedures for shaft liner manufacture and emplacement Site design to minimise potential for build-up of surface water and run-off in vicinity of shafts Inspection of facility,	(a) Possible Risk minimised by facility design and mitigating procedures (e.g. grouting) (b) Highly Improbable-Unlikely Risk minimised by facility design and mitigating procedures (e.g. grouting)	(a) Very low Minor disruption whilst minor leaks are repaired (b) Medium-Very High Depending on extent of flooding, possible long-term remediation required/facility ceasing to

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
			emplacement operations (b)major water ingress minor water ingress into tunnels and disruption to salt excavation/waste emplacement operations	identification of minor leaks and mitigation via grouting Major ingress of water to rooms reduced by closure of bulkhead doors. Potential to pump out water from shaft to minimize extent of flooding of rooms/tunnels	prior to significant failure Lower probability corresponds to higher impact.	function Greater impacts correspond to lower probability events.

Table 7-5: Description of alternative evolution scenarios: environmental impacts during the Operational Phase.

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
1	Rockfall	Occurring in either: (a) a tunnel (b) a room In each case, two variants: (ai) Rockfall only (aii) Rockfall accompanied by water influx (bi) Rockfall only (bii) Rockfall accompanied by water influx Multiple simultaneous rockfalls in different parts of facility deemed implausible (ai) and (bi) leading to release of contaminants, with similar effects to those considered in Scenario 4 (aii) and (bii) leading to mobilization in a similar way to considered in Scenario 6	(ai) and (bi) Considered in Scenario 3 (aii) and (bii), similar pathways to those in Scenario 6 plus escape through collapsed overburden to the Stairway Formation aquifer.	Standard monitoring and inspection of working Use of mitigating procedures (e.g. rock bolting) Remedial measures if rockfalls occurred may include re-excavation, or disposing to different rooms If flooding occurs may prove impossible to mitigate	(ai) and (bi) Environmental impacts considered in Scenario 3 (aii) Highly Improbable (bii) Highly Improbable	(ai) and (bi) Environmental impacts considered in Scenario 4 (aii) Very low (bii) Very low Potentially the lowest aquifer (the Stairway) formation would be contaminated. However, this aquifer contains dense, saline water and there are probably no natural conduits through which contaminated water could be transported to shallower levels. Within the operational time frame environmental impacts would be very low. The implications of this scenario for longer-term impacts are considered further in the PCRA.

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
2	Vehicle Fire	Vehicle fire in tunnels/room, disruption to operational activities, potential releases of productions of combustion (gases and particulates)	Products of combustion underground– (a)shaft air -members of public at surface (b)shaft air-local livestock/ecosphere Products of combustion at the surface– (c)members of public at surface (d)local livestock/ecosphere	Standard fire prevention practices and vehicle maintenance Emergency response arrangements	(a)-(d)Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility	(a)-(d)Very Low (a),(c) Potential for members of public being exposed very low due to distance of local population to the facility (b), (d) Potential exposure of nearby livestock, depending on atmospheric conditions, livestock could be moved if considered at risk until fire put out
3	Fixed infrastructure fire	Fire in underground tunnels/room, or at the ground surface causes disruption to emplacement activities, potential releases of combustion products (gases and particulates)	Products of combustion underground– (a)shaft air -members of public at surface (b)shaft air-local livestock/ecosphere Products of combustion at the surface– (c)members of public at surface (d)local livestock/ecosphere	Standard fire prevention practices and vehicle maintenance Emergency response arrangements	(a)-(d)Unlikely-Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility. Lower probability corresponds to higher impact.	(a)-(d)Very Low to Low (a),(c) Potential for members of public being exposed very low due to distance of local population to the facility, but if fire occurred in a large waste store at the surface, the potential impact is possibly higher than for a vehicle fire at the surface. (b),(d) Potential exposure of nearby livestock, depending on atmospheric conditions, livestock could be moved if considered at risk until

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
						fire put out, but if fire occurred in a large waste store at the surface, the potential impact is possibly higher than for a vehicle fire at the surface. Greater impacts correspond to lower probability events.
4	Waste package failure	(a) Discrete waste spill due to container drop or breach (e.g. vehicle accident) (b) Container drop in shaft resulting in rupture of containers at base of shaft	(i) Dust –Shaft-Local air+deposition on surface soil/vegetation (including local cattle grazing areas) (ii) Dust –shaft-surface water/biota (iii) Dust –shaft-surface air-members of public	General minimisation of likelihood considered during facility design Maintenance of equipment (a) Standard health and safety procedures, worker training for underground operation of vehicles (b) Elevator safety mechanisms to prevent opening of doors when elevator at bottom of shaft and/or elevator drop. Standard health and safety procedures, worker training Emergency response protocols and actions	(ai-aiii) Likely Probability minimised via standard operating procedures, but considered that one event could occur over whole operational lifetime, in contrast to expected system evolution scenario (bi-biii) Highly Improbable Multiple safety protocols to prevent drop of containers in shaft, “double” containerisation (bags/barrels in ISO containers)	(ai) Very Low Considering length of pathway (aii) Very Low Considering length of pathway distance to receptor (aiii) Very Low Considering length of pathway and distance to nearest population centre (bi) Low Considering length of pathway (bii) Low Considering length of pathway (biii) Low

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
				Possible waste interaction due to spills resulting in exacerbated dust production mitigated against by considering separation of wastes during acceptance and emplacement		Considering length of pathway Note that release at shaft base is more likely to enable movement of contamination to the surface, hence classification of (b) pathways as “low” rather than “very low”.
5	Hydraulic Backfill emplacement system failure	(a)Failure of hydraulic backfill emplacement system at the surface, or pipe underground, leading to blockage (b)Leak of backfill pipe, either underground or at the surface	Hydraulic backfill emplacement pipe	QA/QC procedures for backfill manufacture and emplacement, design of facility. Maintenance of equipment. Standard procedures, worker training	(a),(b)Possible Risk minimised by quality control procedures in place for backfilling system	(a)None It is likely that any failure of the injection system would result in at least some of the pipe needing to be replaced, but there would be no direct environmental impacts; the pipe itself, and the solidified waste that it contains, would need to be treated as solid waste. (b)Very Low It is likely that any leak would be stopped quickly owing to the system being continuously monitored. Whether the leak occurs at the surface or underground, the small

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
						volume of leaking material would solidify before it could migrate significantly.
6	Impaired shaft lining performance	Failure of shaft liner during operations and water ingress via permeable horizons/surface possibly exacerbated via high rainfall/recharge	Possible failure of shaft liner grout (exacerbated by high rainfall/surface flooding) leading to water ingress resulting in: (a)minor water ingress and disruption to salt extraction/waste emplacement operations (b)major water ingress and disruption to salt extraction/waste emplacement operations and mobilization of contaminants via leaching of backfill or disruption of dry emplaced wastes (assume container leakage)	QA/QC procedures for shaft liner manufacture and emplacement Site design to minimise potential for build-up of surface water and run-off in vicinity of shafts Inspection of facility, identification of minor leaks and mitigation via grouting Major ingress of water to rooms reduced by closure of bulkhead doors. Potential to pump out water from shaft to minimize extent of flooding of rooms/tunnels	(a)Possible Risk minimised by facility design and mitigating procedures (e.g. grouting) (b)Highly improbable Risk minimised by facility design and mitigating procedures (e.g. grouting) prior to significant failure	(a)None Minor water ingress unlikely to result in flooding of rooms/tunnels, high capacity for water to be soaked up into salt (deliquescence) (b)Very low Lack of conductive features, therefore lack of pathways for contaminant transport to aquifers

None of the (plausible, yet cautious) alternative scenarios or their subsets poses a “high” overall risk on operability. There are five of the scenarios/subsets that have a “moderate risk” and three that have a “low risk”. Also, it should be noted that numerous mitigating measures can be taken for each of the alternative evolution scenarios. None of the alternative scenarios were considered to be “highly probable”. Only one possible subset (AES 5b) was considered to potentially have a very high associated impact, however that scenario was considered to be “highly improbable”, leading to a “moderate” overall risk.

None of the alternative scenarios pose a “high” overall risk to environmental receptors. Four source-pathway-receptor linkages have a “moderate” overall risk (associated with AES2, AES3 and AES4) and six have source-pathway-receptor linkages that are “low” overall risk (associated with AES1, AES4, AES5 and AES6). Also, it should be noted that numerous mitigating measures can be taken for each of the alternative evolution scenarios. None of the source-pathway-receptor linkages considered in the scenarios were considered to result in a “medium”, “high” or “very high” impact.

Table 7-6: Summary of risks related to operability for each alternative scenario.
Colour coding as in Table 7-1.

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely			1bi	1ai, 2, 3, 4a, 5a		
Possible		6a		5b		
Unlikely				6b	3	
Highly Improbable					1aii, 1bii, 4b	6b

Table 7-7: Summary of risks related to environmental receptors for each alternative scenario. Colour coding as in Table 7-1.

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely	5a	2a, 2b, 2c, 2d 3a, 3b, 3c, 3d, 4ai, 4aii, 4aiii				
Possible	6a	5b				
Unlikely						
Highly Improbable		1aii, 1bii, 6b	4bi, 4bii, 4biii			

It can be seen from comparing Table 7-6 and Table 7-7 that the risks are generally higher with respect to operability of the facility, than they are with respect to the environment. That is, should one of the AES be realized, its implications for operating the facility are likely to be more significant than its implications for environmental safety.

7.3 Bowtie Analysis

For each alternative evolution scenario, a BowTie has been constructed. This approach is a structured methodology for visualising and communicating risks and the steps taken to manage them (e.g. as implemented in BowTieXP™, Governors, 2012). A schematic diagram of showing the components of a BowTie are given in Figure 7-1. Each BowTie illustrates:

- ▲ The hazard – with the potential to cause harm.
- ▲ A top event – that could cause the hazard to be actually harmful (reflecting loss of control).
- ▲ Threats (left hand side) that could realize the top event; and consequences (right hand side) that could be caused by the top event.
- ▲ Barriers on both sides of the BowTie, reflecting measures that could prevent (left hand side) or mitigate (right hand side) the effects of the top event.

Thus each BowTie provides an overview of the key risks and potential measures associated with the system for each of the scenarios. It does not provide an assessment

of those risks and associated overall likelihood / impact associated with them; the BowTies can be seen as complementing, not duplicating, the above risk matrices.

BowTies for each alternative evolution scenario that encompass both operability and environment aspects are presented in Figure 7-2 to Figure 7-6. Outcomes are discussed in context in Section 9.

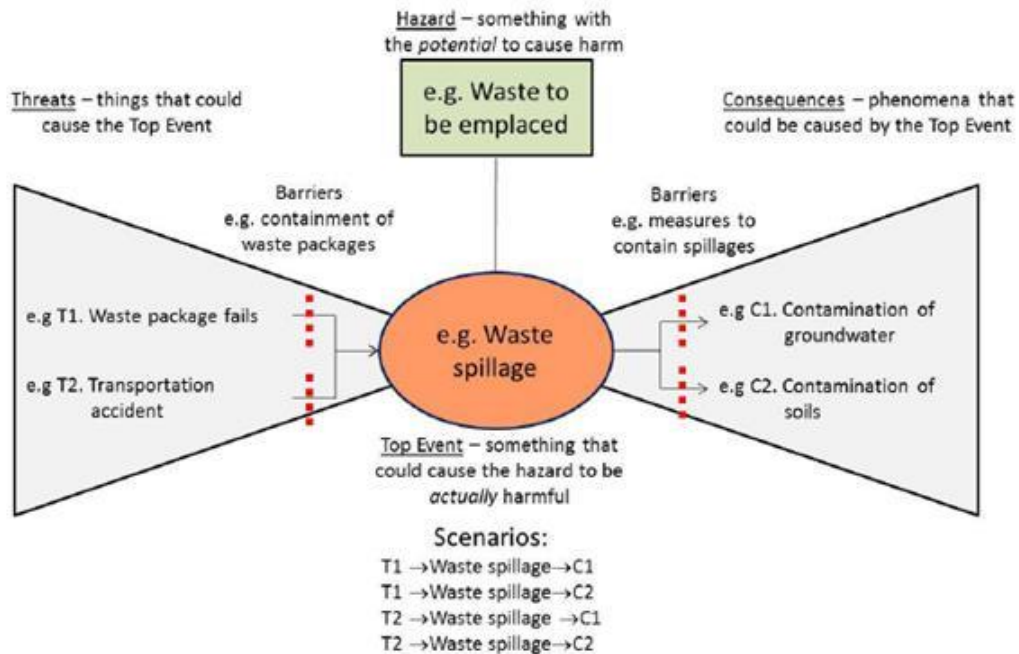


Figure 7-1: Schematic illustration of BowTie analysis.

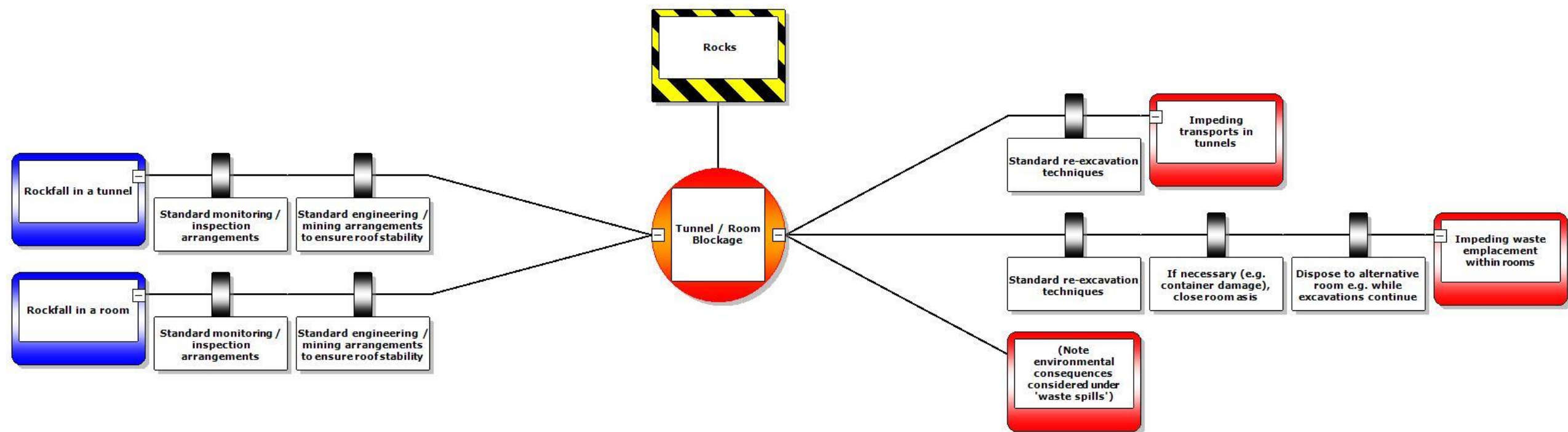


Figure 7-2: BowTie for Rockfall alternative evolution scenario.

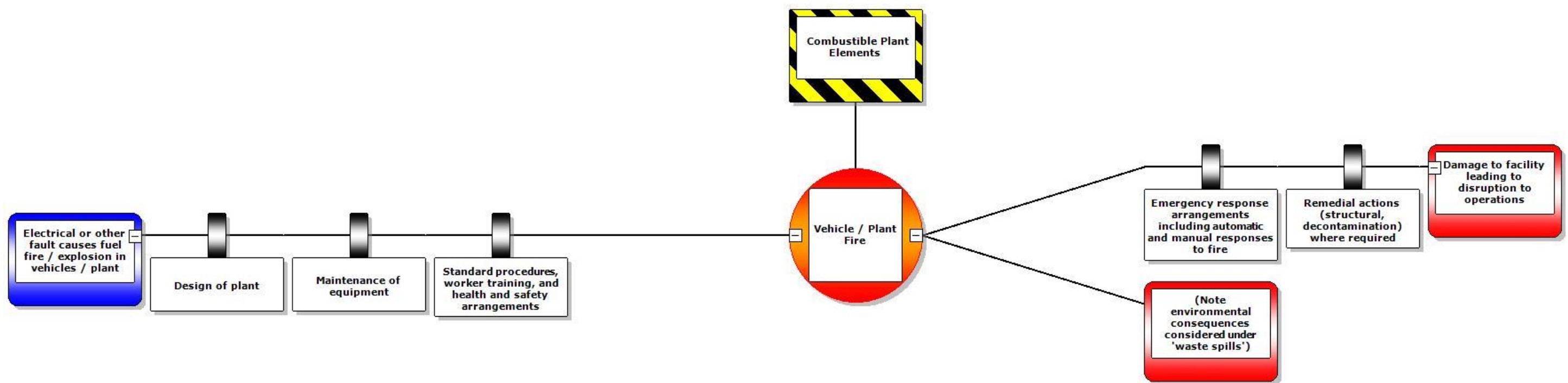


Figure 7-3: BowTie for Vehicle/Plant Fire alternative evolution scenario

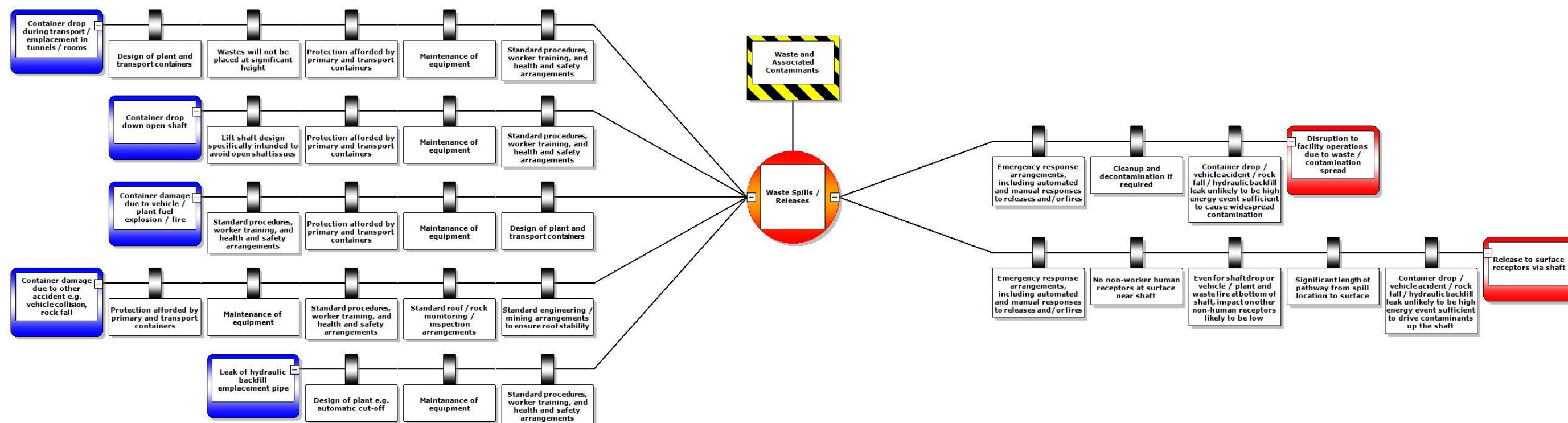


Figure 7-4: BowTie for Waste Spill/Release alternative evolution scenario

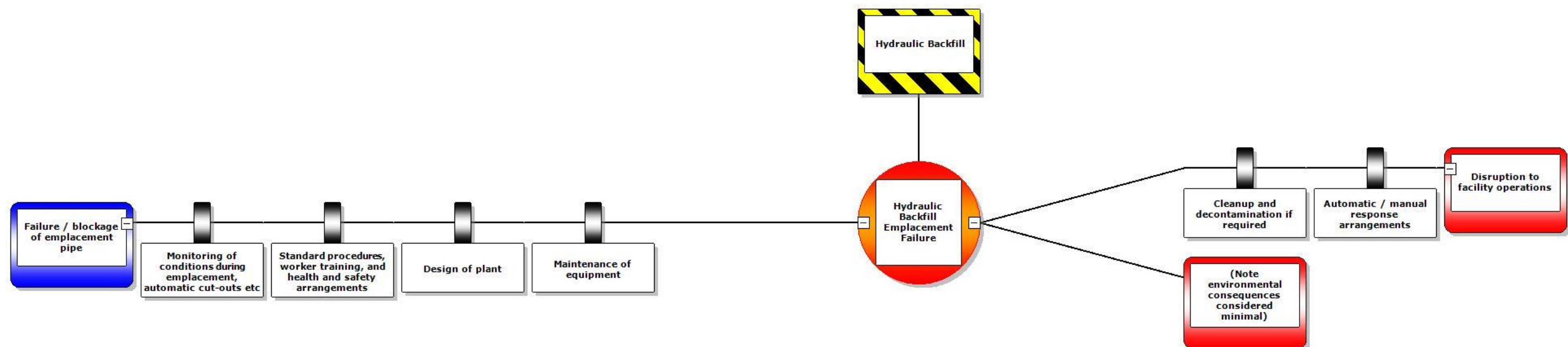


Figure 7-5: BowTie for Hydraulic backfill emplacement failure alternative evolution scenario

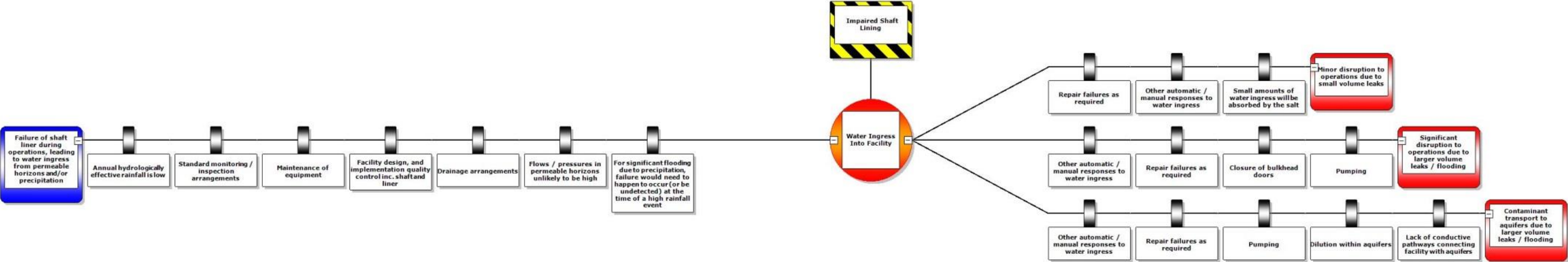


Figure 7-6: BowTie for Impaired shaft lining performance alternative evolution scenario

8 Summary of the OPRA Outcomes

8.1 Overview of Potentials Risks and Mitigation

As would be expected at the outset, the OPRA has concluded that the EES, where operation and environmental performance of the facility is as planned with no significant deviations, is the only “probable” scenario.

The outcomes of the AES assessments can be summarized as follows.

Risks to Operability

- ▲ None of the AES were assessed as representing a “high” risk.
- ▲ Scenarios cautiously assessed as having a potential “moderate” risk, in that they could impair operations for a few days or weeks and require remedial action if they occur, included rockfall, vehicle plant/fire, waste spill/release, hydraulic backfill emplacement failure and impaired shaft lining performance scenarios. However all but a “highly improbable” scenario of shaft lining failure leading to significant flooding could cause significant impacts, but not ones that could not be mitigated or call into question the effective operation of the facility. That is, even the cautious assessment undertaken provides confidence that none of these risks are sufficient to compromise the overall business case for the effective running of the facility.
- ▲ The BowTies indicate various preventative and mitigation measures that may be employed. At present these have been taken into account in the assessment, but cautiously. That is, it has been assumed that no preventative “barrier” can be completely effective. Further analysis of the mitigation methods described in the BowTies could provide additional confidence in performance that could, should a further iteration of assessment be undertaken, help reduce both the assessed likelihoods of the AES occurring and of the plausible impacts that could arise if they were to be realized. “Barriers” that might be employed and / or modified to prevent the AES or mitigate their impact, depending upon the scenario considered, include: plant and facility design and maintenance; waste packaging; operational methods, including emplacement methods; monitoring approaches to identify the potential for incidents to occur and allow preventative actions to be taken; emergency responses; and subsequent remedial actions that could reduce the impacts of an AES that occurs.

Risks to Environmental Receptors

- ▲ None of the AES were assessed as representing a “high” risk.

- ▲ The highest impact scenarios were assessed as having potential “low” impacts, but those scenarios were all considered “improbable” to “unlikely”, the latter corresponding to larger fires involving fixed infrastructure at the surface.
- ▲ Scenarios involving vehicle plant/fires and waste spills/releases could potentially lead to a “very low” impact whilst being considered cautiously as “likely” to occur. However, these impacts would not be sufficient to lead to impacts to receptors above regulatory targets.
- ▲ Essentially, the lack of clear “source-pathway-receptor” linkages between the underground facility and its environs, given the nature of the facility, means there is confidence that the risks involved are manageable. For example, underground accident events would be unlikely to cause a release of a high enough energy to lead to significant impacts at the surface via releases of contaminants being transported through excavated tunnels or shafts. Furthermore contaminant transport through the salt host rock of the facility could not occur on the timescale of the operational phase, given the impermeable nature of the salt and its very low water content, combined with the fact that containerized wastes will be essentially dry, while the hydraulic backfill will be formulated to contain minimal free water following curing. Further consideration of the various barriers involved may serve to further reduce assessed risks should any future iteration of assessment be undertaken.

8.2 Comparison to other Facilities

Assessments for the Minosus facility in Cheshire, northwest England (Robinson and Hooker, 2002), and a proposed salt cavern stabilisation programme at Hengelo in the eastern Netherlands (Metcalfe et al., 2013), were reviewed as part of the assessment development process. Scenarios and key FEPs for these other facilities were reviewed and compared / audited with those adopted for the present assessment. It is notable that the focus of these other assessments was different to the focus of the assessment for the CF, in particular in terms of operational assessments. Nevertheless, the confidence in operability and operational environmental safety provided for the Minosus facility and the Dutch salt cavern stabilisation programme by the relevant assessments helps provide confidence in the OPRA of the proposed CF presented here. In particular it is notable that the current proposed CF facility is much deeper (c. 800 m) than the Minosus one (c. 175 m) and the Dutch salt caverns (c. 500 m). Also, there are fewer present local potential environmental receptors in the vicinity of the CF, which, unlike the Minosus facility and eastern Netherlands’ salt caverns, is located in a desert environment remote from large population centres. Consequently, it could be expected that for similar wastes and care in design and operations, potential risks for the CF should be even lower.

9 Conclusions

The assessment presented provides confidence that, for the proposed categories of wastes and with appropriate facility design and operation, there will be no significant unmanageable risks in terms of the operability and operational environmental safety of the CF.

The most probable scenario for the operation of the CF is that it follows the operational plan and that if there are accidents, the consequences can be managed so that there are no lasting unacceptable impacts. Other risks to the environment are assessed to be very low, because they are either of sufficiently low probability and / or impact.

The risks to operability of the CF that could be caused by plausible deviations from development plans are assessed to be greater than the risks to the environment beyond the CF.

The assessment of the operational phase of the CF presented in this report has been deliberately cautious, taking into account uncertainties due to:

- ▲ the detailed designs and operational plans for the CF not yet being finalized;
and
- ▲ the final characteristics and quantities of the wastes not having been defined.

It is expected that, as the designs and operational plans mature further, and as the waste characteristics and waste streams become more precisely defined, risks will be reduced even further, below those assessed in this report.

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Appendix A: Waste Screening

Waste stream data ("75" code) supplied by Tellus are given in Table A1.

Table A-1: Waste Descriptions and Projected Inventory ([1] Source: TCO-5-05-01_Tellus Sites_NEPM Code Volume & Transport Analysis Model_5May2016)

		Inputs	340,000	8,500,000
			tpa	t LOM
NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%)[1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
	Total Haz chem waste	97.1%	330,160	8,253,992
	Total NORM's	2.9%	9,840	246,008
	Commercial and Industrial (passed onto to 3rd party landfill)			
	Total (Haz. waste & NORM's)	100.00%	340,000	8,500,000

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
N205	Residues from industrial waste treatment/disposal operations	25.3%	85,969	2,149,221
N120	Soils contaminated with a controlled waste	16.6%	56,300	1,407,495
N150	Fly ash, excluding fly ash generated from Australian coal fired power stations	14.5%	49,198	1,229,957
N220	Asbestos	10.7%	36,250	906,250
J120	Waste oil/water, hydrocarbons/water mixtures or emulsions	6.6%	22,291	557,267
D220	Lead; lead compounds	4.9%	16,622	415,553
C100	Basic solutions or bases in solid form	4.9%	16,530	413,253
D110	Inorganic fluorine compounds excluding calcium fluoride (SPL)	4.3%	14,613	365,318
D230	Zinc compounds	2.9%	9,840	246,008
	NORMs	2.2%	7,456	186,399
J100	Waste mineral oils unfit for their original intended use	2.2%	7,439	185,986
D300	Non-toxic salts	1.2%	4,003	100,080
B100	Acidic solutions or acids in solid form	0.8%	2,874	71,855
N160	Encapsulated, chemically-fixed, solidified or polymerised wastes referred to in this list	0.5%	1,742	43,550
F100	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	0.5%	1,649	41,225
M100	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or polybrominated biphenyls	0.3%	1,127	28,185

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
N100	Containers and drums that are contaminated with residues of substances referred to in this list	0.3%	962	24,038
N190	Filter cake contaminated with residues of substances referred to in this list	0.2%	765	19,120
G110	Organic solvents excluding halogenated solvents	0.2%	584	14,606
M250	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	0.1%	422	10,546
A100	Waste resulting from surface treatment of metals and plastics	0.1%	403	10,080
K140	Tannery wastes (including leather dust, ash, sludges and flours)	0.1%	356	8,899
F110	Waste from the production, formulation and use of resins, latex, plasticisers, glues and adhesives	0.1%	310	7,756
J160	Waste tarry residues arising from refining, distillation, and any pyrolytic treatment	0.1%	292	7,311
G160	Waste from the production, formulation and use of organic solvents	0.1%	235	5,885
R120	Waste pharmaceuticals, drugs and medicines	0.1%	234	5,842
M230	Triethylamine catalysts for setting foundry sands	0.1%	192	4,810
H100	Waste from the production, formulation and use of biocides and phytopharmaceuticals	0.1%	186	4,643
T100	Waste chemical substances arising from research and development or teaching activities, including those which are not identified and/or are new and whose effects on human health and/or the environment are not known	0.0%	168	4,197
N230	Ceramic-based fibres with physico-chemical characteristics similar to those of asbestos	0.0%	149	3,729
D120	Mercury; mercury compounds	0.0%	94	2,351
D190	Copper compounds	0.0%	77	1,916
D140	Chromium compounds (hexavalent and trivalent)	0.0%	69	1,720
R140	Waste from the production and preparation of pharmaceutical products	0.0%	57	1,434
K190	Wool scouring wastes	0.0%	51	1,265
M150	Phenols, phenol compounds including chlorophenols	0.0%	50	1,259
G150	Halogenated organic solvents	0.0%	49	1,217
N140	Fire debris and fire wash waters	0.0%	47	1,166
G100	Ethers	0.0%	46	1,152
T200	Waste of an explosive nature not subject to other legislation	0.0%	42	1,060
T120	Waste from the production, formulation and use of photographic chemicals and processing materials	0.0%	38	961

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
D330	Inorganic sulfides	0.0%	35	870
H110	Organic phosphorous compounds	0.0%	30	749
D130	Arsenic; arsenic compounds	0.0%	27	681
M220	Isocyanate compounds	0.0%	19	468
D360	Phosphorus compounds excluding mineral phosphates	0.0%	17	423
E100	Waste containing peroxides other than hydrogen peroxide	0.0%	17	413
D210	Nickel compounds	0.0%	13	314
M260	Highly odorous organic chemicals (including mercaptans and acrylates)	0.0%	12	312
H170	Waste from manufacture, formulation and use of wood-preserving chemicals	0.0%	12	293
D100	Metal carbonyls	0.0%	7	174
A130	Cyanides (inorganic)	0.0%	5	134
M210	Cyanides (organic)	0.0%	5	123
D270	Vanadium compounds	0.0%	5	122
M160	Organo halogen compounds—other than substances referred to in this Table or Table 2	0.0%	4	110
D150	Cadmium; cadmium compounds	0.0%	2	62
A110	Waste from heat treatment and tempering operations containing cyanides	0.0%	2	60
D160	Beryllium; beryllium compounds	0.0%	2	38
D350	Chlorates	0.0%	1	25
D170	Antimony; antimony compounds	0.0%	1	25
D250	Tellurium; tellurium compounds	0.0%	1	13
D340	Perchlorates	0.0%	0	9
D200	Cobalt compounds	0.0%	0	6
D310	Boron compounds	0.0%	0	5
D290	Barium compounds (excluding barium sulphate)	0.0%	0	3
D240	Selenium; selenium compounds	0.0%	0	1
D180	Thallium; thallium compounds	0.0%	0	1
M170	Polychlorinated dibenzo-furan (any congener)	0.0%	0	1
M180	Polychlorinated dibenzo-p-dioxin (any congener)	0.0%	0	1
T140	Tyres	0.0%	-	-
K100	Animal effluent and residues (abattoir effluent, poultry and fish processing wastes)	0.0%	-	-
K110	Grease trap waste	0.0%	-	-
K130	Sewage sludge and residues including nightsoil and septic tank sludge	0.0%	-	-
R100	Clinical and related wastes	0.0%	-	-

The substances in Table A1 have been screened to identify representatives for detailed analysis, using expert knowledge and Australian drinking water guidelines. Substances are identified in Table A2. Pesticides are considered separately. For both operation and post-closure risk assessment, substances of possible concern present in each waste type have been considered. Illustrative substances potentially of concern have been identified based on expert judgement and a consideration of substances typically included in environmental risk assessment (including a consideration of the substances included in Australian drinking water guidelines; Australian Government, 2015). The substances are then ranked 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Table A2). The product of the three values is then used to derive an “index” value used to identify substances of greater importance, a subset of which is suggested for post closure assessment in particular. This approach gives the following top ten ranked contaminants:

1. Beryllium (score 12);
2. Chromium (as Cr(VI)) (score 12);
3. Dichloromethane (score 12);
4. Hexachlorobutadiene (score 12);
5. Mercury (score 12);
6. Benzene (score 9);
7. Epichlorohydrin (score 9);
8. Lead (score 9);
9. Molybdenum (score 8); and
10. Nickel (score 8).

When account is taken of the different chemical properties of these elements and their likely forms in solution, it is suggested that from this list the following elements are considered in more detail in the analysis:

1. Beryllium;
2. Chromium;
3. Mercury;
4. Benzene; and
5. Lead.

Table A-2: Substances potentially present in wastes (excluding pesticides/herbicides/fungicides), Australian drinking water guidelines, rankings (1-3) and index of potential impact (product of values for 1-3).

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Aluminium (acid soluble)	c	0.2	based on post-flocculation problems	3	1	1	3	component of waste metals, possibly high volume, low solubility, low toxicity, not suitable for hydraulic backfill
Ammonia	c	0.5	typically associated with sewage contamination/microbial activity	1	2	1	2	probably only present in small amounts, soluble in water
Antimony	0.003		guidelines note that exposure may rise with increasing use of antimony-tin solder	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils)
Arsenic	0.01		natural sources, mining/industrial/agricultural wastes	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, some degree of sorption to minerals likely, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils, mining wastes)
Barium	2		primarily from natural sources	2	2	1	4	possible associated with mineral scales from oil industry, mobility in environment depends on

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								sulphate availability
Benzene	0.001		human carcinogen	1	3	3	9	associated with petroleum products (one of the "BTEX" compounds), possible present in small amounts (trace level/as breakdown product), highly flammable .
Beryllium	0.06		fossil fuel burning	2	2	3	12	associated with specialist alloys, possibly anionic speciation in water and relatively higher mobility than other metals
Cadmium	0.002		industrial/agricultural contamination, impurities in galvanised (zinc) fittings, solders and brasses	2	1	3	6	heavy metal, numerous sources (including soils, mining wastes), potentially solubility-limited, likely to sorb to minerals, some waste streams may be suitable for hydraulic backfill
Chloride		250		2	3	1	6	from rock salt, drinking water guideline based on aesthetics
Chlorobenzene	0.3	0.01	intermediate, solvent, taste/odour threshold lower than health based concentrations	1	3	2	6	possibly present as waste from chemical industry or solvent, soluble in water to some extent

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Chromium (as Cr(VI))	0.05		associated with industrial/agricultural contamination	2	2	3	12	Cr(VI) from industrial waste of greater concern than Cr(III), which is found in stainless steel, Cr(VI) generally of more concern via inhalation exposure so index value possibly a little unrepresentative
Copper	2	1	associated with metal pipe corrosion	3	1	1	3	could be present in relatively large volume compared to other metals for some waste streams, of less concern than heavy metals in terms of toxicological properties, likely to have low solubility in water
Cyanide	0.08		associated with industrial waste	1	2	3	6	cyanide associated with wastes, not clear as to how likely it is to be present, presumably in relatively smaller amounts
1,2 dichlorobenzene	1.5	0.001	chemical intermediate, may be used as a solvent in some applications; taste/odour threshold lower than health based concentrations	1	1	3	3	possibly from chemical industry, may be used as a solvent
1,3 dichlorobenzene	c	0.02	taste/odour threshold lower than health based concentrations	1	1	3	3	

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
1,4 dichlorobenzene	0.04	0.0003	disinfectant, pesticide odour threshold lower than health based concentrations	1	1	3	3	
1,2-dichloroethane	0.003		vinyl chloride manufacture, intermediate, solvent	1	2	3	6	possibly from chemical industry, may be used as a solvent, limited solubility in water
1,1-dichloroethene	0.03			1	1	3	3	possibly largely immobilized in hydraulic backfill depending on waste streams that are disposed in such a manner, poorly soluble in water
1,2-dichloroethene	0.06			1	1	3	3	
Dichloromethane	0.004		widely used solvent	2	2	3	12	volatile liquid
Epichlorohydrin	0.0005d		used in manufacture of resins for water treatment	1	3	3	9	possibly associated with waste from water treatment, moderately soluble in water
Ethylbenzene	0.3	0.003	component of petrol and petroleum products	1	2	2	4	associated with petroleum products, may be used as solvent, possibly present in trace quantities (flammable), partly soluble in water, can be mobile in sub-surface environment
Ethlenediamine tetraacetic acid (EDTA)	0.25		metal complexing agent commonly used in industry	1	3	1	3	presumably could be present as residue from cleaning metals/other

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								materials, mobile in the environment
Hexachlorobutadiene	0.0007		Industrial solvent	2	2	3	12	relatively greater potential toxicological hazard compared to other materials, could be present as solvent residue
Lead	0.01			3	1	3	9	heavy metal, could be associated with different waste streams, relatively low solubility under most conditions, neurotoxin
Manganese	0.5	0.1		2	2	1	4	possibly present in some metal wastes
Mercury	0.001		Industrial sources	2	2	3	12	possibly present in some waste streams (including as a lower volume mercury waste stream). Forms amalgams with some metals, native form volatile, limited solubility of oxidised species in water. International efforts to reduce use given toxicological hazard

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Molybdenum	0.05		associated with mining, agriculture and fly ash	2	2	2	8	chemical and metallurgical applications, associated with mineral residue in fly ash, can have relatively high solubility in water compared with other metals, possibly associated with waste streams that could be hydraulic backfill (e.g. soil)
Nickel	0.02			2	2	2	8	associated with many metal products, can have relatively high solubility in water compared with other metals
Di(2-ethylhexyl)phthalate	0.01		associated with PVC products, may leach from them over prolonged periods of time	2	2	2	8	possibly associated with plastics (plasticiser) and may leach from them
Benzo(a)pyrene	0.0001		can leach from bituminous materials (linings in water distribution systems)	2	1	3	6	genotoxic carcinogen, polycyclic aromatic hydrocarbon (PAH), very low solubility, sometimes found in drinking water that has been transport through systems containing bituminous materials
Styrene	0.03	0.004	associated with industrial contamination	1	2	2	4	volatile oily liquid, limited solubility in water

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Tetrachloroethene	0.05		solvent (dry cleaning especially), degreaser	2	2	2	8	colourless liquid, possibility that it is present in small quantities in some waste streams, classed as a dense non-aqueous phase liquid (DNAPL)
Toluene	0.8	0.025	petrol, natural gas, industrial contamination	2	1	1	2	industrial solvent and feedstock, low solubility in water
Trichlorobenzenes(total)	0.03	0.005	solvent and precursor chemical	2	1	2	4	possibly associated with some wastes
Uranium	0.017		associated with mill tailings, combustion of coal	1	1	2	2	possibly present in mineral residue from coal combustion, likely to have relatively low solubility, especially under anoxic conditions, possibly in waste streams suitable for hydraulic backfill
Zinc	c	3	associated with corrosion of galvanised pipes/fittings and brasses	3	2	1	6	associated with numerous metals and alloys, possibly in waste streams suitable for hydraulic backfill

Key

(i)c = insufficient data to generate value

(ii)d = issues with detecting concentrations associated with health guideline

Agricultural wastes and soil could potentially include pesticides, herbicides, fungicides and related compounds. A large number of such substances exist with varying compositions and physico-chemical and toxicological properties. A number of representative substances have been selected based on potential for environmental impact (i.e. lower drinking water guideline values) and solubilities in water which is of particular relevant to post closure risk assessment modelling. The following substances have been considered in post closure modelling, given their relatively low drinking water guideline values and ranges of solubility in water:

- ▲ Dieldrin
- ▲ Fenamiphos
- ▲ Diquat

Table A-3: Representative pesticides and herbicides, types, Australian Drinking Water Guidelines and reported aqueous solubilities.

Substance	Australian Drinking Water Guideline mg/L	Type of material	Solubility (mg/L)	Source of solubility data
Aldrin (+dieldrin)	0.0003	organochlorine pesticide	0.011 (aldrin) 0.11 (dieldrin)	ATSDR (2002) Chapter 4 of Toxicological Profile for Aldrin/Dieldrin. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp1-c4.pdf
Heptachlor	0.0003	organochlorine pesticide	0.05	ATSDR (2007) Chapter 4 of Toxicological Profile for Heptachlor. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp12-c4.pdf
Profenofos	0.0003	organophosphorous pesticide	28	PUBCHEM Open Chemistry Database https://pubchem.ncbi.nlm.nih.gov/compound/profenofos#section=Top
Fenamiphos	0.0005	organophosphorous pesticide	700	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/jmpr/jmpmono/v074pr23.htm
Aldicarb	0.004	carbamate insecticide	6000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/0304_72/en/index3.html
Paraquat	0.02	herbicide	620 000	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/icsc/icsc/eics0005.htm
Diquat	0.007	herbicide	718 000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/diquat.pdf
Molinate	0.004	herbicide	880	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/molinate.pdf

The wastes that may be disposed of at the Chandler facility also include NORM (naturally-occurring radioactive material). NORM is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose per year, with about 1% being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

Appendix B: FEP List

A list of FEPs derived for the Chandler design concept is given in Table B-10-1 along with a list of potential EFEPs. The FEPs have been audited against those considered in a risk assessment for storage of municipal incinerator waste in salt caverns in the Netherlands (Metcalf et al., 2013).

A top-down examination of the main components of the process system suggests that the main FEPs of interest can be classified as belonging to the following main FEP groups.

1. Cavern zone (the caverns themselves, and the cavern rock).
2. Host geological environment.
3. Boreholes (including those boreholes used for backfill, and others).
4. Access shafts and ventilation system.
5. Biosphere and surface water bodies.

Table B-10-1: FEPs List

FEPs	Notes
1. Cavern zone 1.1. Room features 1.1.1. Roof 1.1.2. Pillars 1.1.3. Floors 1.1.4. Access tunnels 1.1.5. Rooms for disposal of waste 1.1.5.1. Containerised waste emplacement 1.1.5.2. Hydraulic backfill waste emplacement 1.1.6. Rooms for storage of wastes 1.1.7. Doors/seals/partitions 1.2. Room internal geometry 1.2.1. Change in geometry due to salt creep 1.2.2. Change in geometry due to loss of material from roofs 1.2.3. Change in geometry due to any salt dissolution/precipitation 1.3. Mobile and Fixed Infrastructure 1.3.1. Vehicles for excavation (continuous miner) 1.3.2. Vehicles for salt product 1.3.3. Vehicles for waste boxes 1.3.4. Other machinery for emplacement 1.3.5. Lighting 1.4. Salt product	Data supplied by Chandler Assuming bulkhead doors, potential partitioning of rooms Assuming diesel/petrol vehicles

FEPs	Notes
1.4.1. Halite 1.4.2. Containers 1.5. Wastes 1.5.1. Metal container for bags/barrels 1.5.2. Hydraulic backfill waste (HBW) 1.5.2.1. Backfill physical properties 1.5.2.2. Backfill chemical properties 1.5.2.3. Backfill mechanical properties 1.5.2.4. Contaminants 1.5.2.4.1. Heavy metals 1.5.2.4.2. Organics 1.5.3. Containerised Wastes 1.5.3.1. Containers (drums/bags) 1.5.3.2. Contaminants 1.5.3.2.1. Solid inorganics, includes Heavy metals/metalloids 1.5.3.2.2. Liquid inorganics 1.5.3.2.3. Organics, solid 1.5.3.2.4. Organics, liquid 1.5.4. Gas associated with wastes/waste degradation 1.5.5. Salt extraction processes 1.5.5.1. Excavation of salt 1.5.5.2. Underground transport of salt to access shaft 1.5.5.3. Removal of salt product via access shaft 1.5.6. Waste emplacement processes 1.5.6.1. Hydraulic backfilling 1.5.6.2. Underground transport of metal boxes of waste 1.5.6.3. Containerised waste emplacement 1.5.7. Hydraulic backfill consolidation and related processes 1.5.7.1. Geometry evolution 1.5.7.2. Chemical and physical properties evolution 1.5.7.2.1. Solids 1.5.7.2.2. Pore fluids 1.5.7.2.3. Contaminant release due to chemical or physical evolution during consolidation 1.5.7.2.3.1. Due to initial consolidation 1.5.7.2.3.2. Due to longer-term continued consolidation 1.5.7.2.3.3. Due to salt creep and waste pressurisation 1.5.8. Hydraulic backfill migration (liquid/uncured or solid) inc.	T-B-C Type of barrels? Liquids? Assuming physical separation of hydraulically backfilled waste and containerised wastes For rooms with containerised waste

FEPs	Notes
response to cavern geometry change /pressurisation 1.6. Loose salt backfill 1.7. Void space 1.8. Workers 1.9. Advective flow/transport in hydraulic backfill (inc. contaminant transport) 1.9.1. Waters (inc. brine) 1.9.2. Gas 1.9.3. Other fluids (e.g. hydrocarbons) 1.10. Diffusive transport in backfill (inc. contaminant transport) 1.10.1. Waters (inc. brine) 1.10.2. Gas 1.10.3. Other fluids (e.g. hydrocarbons) 1.11. Contaminant retardation 1.11.1. Sorption/ de-sorption and cation exchange 1.11.2. Contaminant solubility / co-precipitation 1.11.3. Rock-matrix diffusion	
2. Geology 2.1. Salt deposit - halite 2.2. Salt deposit - impurities/ other minerals/interbeds 2.3. Overlying salt 2.4. Underlying salt 2.5. Confining salt 2.6. Overlying lithologies (including aquifers) 2.7. Underlying lithologies (including aquifers) 2.8. Hydrogeological properties 2.9. Chemical properties 2.10. Mechanical properties 2.11. Change in salt geometry due to creep 2.12. Change in salt geometry due to dissolution / precipitation 2.13. Fracturing/ faulting 2.14. Induced seismicity 2.15. Self-healing 2.16. Hydraulic gradients and pressures 2.17. Advective flow/transport (inc. contaminant transport) 2.17.1. Waters (inc. brine) 2.17.2. Gas 2.17.3. Other fluids (e.g. hydrocarbons) 2.18. Diffusive transport (inc. contaminant transport) 2.18.1. Waters (inc. brine)	Descriptions to be added

FEPs	Notes
2.18.2. Gas 2.18.3. Other fluids (e.g. hydrocarbons) 2.19. Contaminant retardation 2.19.1. Sorption/ de-sorption and cation exchange 2.19.2. Contaminant solubility / co-precipitation 2.19.3. Rock-matrix diffusion 2.20. Temperature gradients	
3. Boreholes 3.1. Borehole walls 3.2. Borehole casing 3.3. Borehole backfill 3.4. Borehole seals 3.5. Borehole disturbed zone 3.6. Chemical evolution of borehole seals 3.7. Evolution of borehole seals 3.8. Corrosion of steel casings 3.8.1. Evolution of cement bonding 3.8.2. Evolution of the borehole seal 3.8.3. Physical deformation due to external stresses (e.g. rock creep) 3.8.4. Physical deformation due to chemical processes 3.8.5. Gas pressurisation within bores (due to corrosion, mechanical effects etc.) 3.8.6. Pressure gradients across seals 3.9. Contaminant pathways in borehole/damaged zone 3.10. Contaminant transport within disturbed zone 3.11. Residual contamination from borehole drilling	
4. Access shafts and ventilation system 4.1. Shaft wall rock 4.2. Ventilation system 4.3. Doors/partitions 4.4. Elevator 4.5. Elevator machinery 4.6. Workers 4.7. Shaft sealing materials 4.7.1. Concrete monolith 4.7.2. Seals	T-B-C
5. Biosphere and Surface Water Bodies 5.1. Environmental media (soil, surface water bodies, flora and fauna) 5.2. Workers at surface	

FEPs	Notes
5.3. Members of the public 5.4. Livestock 5.5. Surface run-off/floodwaters	

The “EFEPs” (external FEPs) that were identified are listed below:

1. **Future human actions** (e.g. accidental human intrusion);
2. **Exploitation of resources** (e.g. mining, water management);
3. **Neotectonics** (including seismicity, which may induce cavern instability);
4. **Climate and landscape change** (e.g. influence water table; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall); and
5. **Accidents and unplanned events (e.g. container drop/breach leading to spills)**
6. **Changes to the mine operational regime** (e.g. types of waste accepted, changes in facility concept)

Note that *deliberate* human intrusion, whereby a future human group might intentionally intrude into the wastes, is not considered as (a) such an action is highly unlikely to occur and (b) the risk involved would be the responsibility of the deliberate intruding party to manage. Thus, future human actions here focus on accidental intrusion, for example contact with wastes during borehole exploration for resources. This scenario is also, however, considered unlikely to occur.

Post Closure Risk Assessment

Chandler Facility Risk Assessment

Long-term, Post-closure Risk Assessment



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Summary

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF). The development involves the excavation of rooms in a deep underground salt formation and the subsequent storage and isolation of wastes in the rooms produced. The project is located approximately 120km south of Alice Springs in the Northern Territory of Australia.

This document is an initial Long-term, Post-closure Risk Assessment, which assesses risks to the environment around the CF that arise following closure of the facility. The assessment involved quantitative analysis of potential system behaviour complemented by qualitative arguments concerning the magnitude and likelihood of environmental impacts. The period covered by quantitative calculations undertaken during the risk assessment is sufficiently long to ensure that maximum risks have been considered (i.e. considering longer periods would not cause greater maximum risks to be estimated at a point in the future). Hence, calculations were undertaken for periods of up to 1000,000 years. The present initial long-term, Post-closure Risk Assessment complements an Operational Phase Risk Assessment (Metcalf et al., 2016).

The overall approach to the Long-term Post-closure Risk Assessment followed best international practice¹, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia, such as hazardous waste and gas storage facilities in the UK, and radioactive waste disposal facilities in Canada, Finland and Sweden. In practice the assessment was carried out in a “top-down” fashion, such that the starting point was identifying the main threats to the environment posed by the CF during the post-closure phase. Phenomena that could cause these threats to be realized were then identified iteratively, to a level of detail commensurate with the goal of achieving a robust assessment while not introducing undue complexity. The likelihood of each threat was then estimated and the possible effects assessed. When doing this, the

¹ Here “best practice” refers to the well-established approaches and methodologies that are widely applied throughout the world for assessing the performance and safety of various kinds of underground waste disposal and storage facilities. These approaches and methodologies have been developed over several decades during many projects, including ones concerned with radioactive waste disposal, CO₂ storage, natural gas storage, and hazardous waste disposal. No single document describes this best practice, but rather the approaches and methodologies are documented in numerous reports by international agencies such as the International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), International Energy Agency (IEA), International Standards Organisation (ISO), national regulators, and project implementers.

approach was plausibly conservative, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern. Risks were considered as a product of the probability of a threat and its impact, both being represented on quantitative scales on the basis of qualitative information. To ensure that no key issues had been missed, the assessment was audited against experience in other, similar projects and, where appropriate, lists of Features Events and Processes (FEPs) that had been developed in these other projects.

The results of the assessment are presented as a risk matrix, which show the highest plausible probability of threat versus plausibly conservative impact if realized.

The assessment provides confidence that, for the proposed categories of wastes and with appropriate facility design, there will be no significant risks arising from the CF in terms of environmental safety following closure of the facility.

The most probable scenario for the future evolution of the CF is that the facility behaves as planned and no significant contamination leaves it following closure (the Expected Evolution Scenario, EES).

To assess the risks of the CF unexpectedly not behaving as designed (i.e. the EES not being realized) four Alternative Evolution Scenarios (AES) have been defined:

- ▲ AES1, Connected porosity through the halite roof of the CF;
- ▲ AES2, Collapsed roof of the CF, with the variants:
 - AES2a, Collapsed roof in the Operational Phase;
 - AES2b, Collapsed roof in the Post-closure Phase;
- ▲ AES3, Impaired shaft seal;
- ▲ AES4, Accidental human intrusion.

These scenarios are *not* predictions of future CF behaviour. Instead, they are designed to illustrate alternative ways in which contaminated water might leave the facility and be transported through the surrounding geological system to potential receptors, in the unlikely event that the EES is not realized. AES1, AES2 and AES3 have been analysed by means of numerical models, whereas AES4 has been analysed qualitatively.

Even if containment of the CF were to be lost, contaminated water would not necessarily travel to near-surface receptors. Under these circumstances the contaminated water may travel upwards only as far as the aquifers in the Stairway Sandstone. However, the Stairway Sandstone contains saline water (TDS = 15,000 g/L; Douglas Partners, 2013) and is at substantial depth (>390 m). Therefore it is very unlikely that this formation will be exploited as a water resource in future. Consequently it is highly unlikely that near-surface receptors, including humans, would be exposed to the peak contaminant concentrations calculated for the Stairway Sandstone, even if one of the AES were to be realized.

Any contaminants that enter the aquifers of the Stairway Sandstone would be diluted and transported laterally by groundwater flowing slowly under the natural head gradient. The contaminant concentrations would then decrease downstream owing to dispersion. Calculations show that it would take more than a hundred thousand years for the concentrations of any contaminants in the Stairway Sandstone to exceed groundwater standard/guideline values at a distance 10 km downstream from the facility in AES1 and both variants of AES2. In the case of AES3, it would take 10,000 years or more for these groundwater standard/guideline values to be exceeded in the Stairway Sandstone at a distance of 10 km downstream. However, even in the case of AES3 being realized it is possible that some contaminants would never exceed groundwater standard or guideline concentrations at this location.

Were contaminants to be transported via any conceivable pathway from the Stairway Sandstone to shallower aquifers that are more likely to be exploited as water resources, the contaminants would be diluted and dispersed along the pathway. Thus, these shallower aquifers would tend to have lower contaminant concentrations than those in the Stairway Sandstone at the location where the contaminants left the Stairway Sandstone.

These shallower aquifers are believed to have poor lateral hydraulic connectivity. This characteristic would limit the potential for any contaminants that reach the aquifers to be transported laterally, away from the footprint of the CF. However, during the slow lateral groundwater flow that does occur under the influence of the natural head gradient, any transported contaminants would be diluted and dispersed, in the same way as described above for the Stairway Sandstone. Thus, contaminant concentrations would decrease within an aquifer, with increasing distance from the CF.

There are uncertainties about the release, migration and attenuation of contaminants in the unlikely event of the CF losing containment (an AES being realized), principally reflecting the fact that the following characteristics are not well known at this stage:

- ▲ behaviour of the wastes under the conditions within the CF (notably the chemical forms in which contaminants occur and their solubilities);
- ▲ driving force provided by the creep of the halite in the post-closure period;
- ▲ magnitudes of processes controlling retardation of migrating contaminants (sorption, diffusion into parts of the rock matrix where there is no advection);
- ▲ hydraulic conductivities of the different rock formations;
- ▲ porosities of the different rock formations;
- ▲ groundwater head gradients;
- ▲ groundwater recharge rates;
- ▲ dispersivity of the aquifers; and
- ▲ lateral connectivity of the aquifers.

These uncertainties have been treated in the assessment by making cautious qualitative arguments and using pessimistic values of relevant parameters, consistent with the available data. It is therefore likely that calculated contaminant concentrations in the aquifers for the AES tend to over-estimate the concentrations that would actually occur in the rock formations above the CF at any particular location and time in the future, should the CF lose containment.

Taking into account these uncertainties, it is conceivable that, should containment of the CF be lost in the post-closure phase no contaminant concentrations in the Stairway Sandstone would ever exceed groundwater standard / guideline values beyond a distance of 10 km from the facility. Since the shallower aquifers are likely to contain even lower concentrations of contaminants than the Stairway Sandstone, it follows that it is even less likely that under these circumstances the shallower aquifers could contain concentrations of contaminants in excess of groundwater standards or guideline values.

It is expected that, as the designs and operational plans mature further, and as the waste characteristics and waste streams become more precisely defined, risks will be reduced even further, below those assessed in this report.

Further numerical modelling of the system could reduce the outstanding uncertainties once complete compositions of the wastes have been established and further relevant hydrogeological information becomes available.

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1 Introduction

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF) at a site located approximately 120 km south of Alice Springs in the Northern Territory of Australia. The project will involve the excavation of rooms at a depth of approximately 850 m below the ground surface in a halite stratum within the Cambrian age Chandler Formation.

The following risk assessments are required in support of operator and regulatory requirements for this project:

- ▲ an Operational Phase Risk Assessment (OPRA), covering the period between the first emplacement of wastes in the facility and the closure of the facility, nominally 25 years ;
- ▲ a Long-term, Post-closure Risk Assessment (PCRA), covering the period after facility closure, for sufficiently long to ensure that maximum risks have been considered (i.e. considering longer periods would not cause greater maximum risks to be estimated at a point in the future); and
- ▲ an Integrated Risk Assessment (IRA), taking into account the OPRA, the PCRA.

These risk assessments will be inputs to the overall Environmental Safety Case for the CF, which in turn will underpin the Environmental Impact Assessment (EIA) that forms a basis for the license application.

The present report aims to deliver a quantitative **Long-term, Post-closure Risk Assessment**, covering environmental risks associated with the proposed CF. The considered risks are those arising from the emplacement and permanent isolation of hazardous wastes.

This Long-term, Post-closure Risk Assessment reported is informed by an initial Operational Phase Risk Assessment (Metcalf et al., 2016).

This report is structured as follows.

- ▲ Section 2 describes the overall approach to the assessment.
- ▲ Section 3 gives the context for the assessment.
- ▲ Section 4 describes the CF.
- ▲ Section 5 presents a functional analysis of the system.
- ▲ Section 6 presents the scenarios considered in the assessment.
- ▲ Section 8.4 presents a quantitative assessment of the scenarios, supported by qualitative arguments concerning their probabilities and impacts.
- ▲ Section 9 contains a summary of the assessment outcomes.
- ▲ Conclusions are presented in Section 10.

- ▲ Appendix A provides details of potential facility waste classes.

2 Overall Approach

The overall approach followed best international practice, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia.

The approach is designed to be consistent with the Northern Territory's WorkSafe Regulations for major hazard facilities (Safe Work Australia, 2012a,b), and covers the following topics that are required under these regulations²:

- ▲ establishment of the context (covered by Section 3 of the present report); and
- ▲ safety assessment:
 - hazard identification (covered by Section 4.2.2 of the present report);
 - identification of existing risk controls (covered in part by Section 7 and in part by Section 8.3 and Section 8.4 of the present report);
 - risk assessment, including consequence estimation, likelihood estimation and risk analysis (covered by Section 7.3, Section 8.3, Section 8.4 and Section 9 of the present report);
 - risk evaluation against the adopted criteria (covered by Section 7.3, Section 8.4 and Section 9 of the present report); and
 - identification of additional risk controls (covered by Section 7.3 and 8.4 of the present report).

The assessment is also consistent with the requirements of the European Union's regulations governing underground storage and disposal of hazardous materials (specifically Appendix A of Council Decision (EC) 2003/33/EC) and accordingly explicitly:

- ▲ identifies the hazard (in this case the deposited wastes; Section 4.2.2),
- ▲ identifies the receptors (in this case the biosphere and possibly groundwater; Section 4.2.4),
- ▲ identifies the pathways by which substances from the wastes may reach the biosphere (Section 4.2.3);
- ▲ assesses the impact of substances that may reach the biosphere (Section 8.4)

The approach follows closely that which has been adopted in a number of other relevant assessments outside Australia:

- ▲ the assessment by Minosus Limited of an underground waste management facility at the Winsford Rock Salt Mine in Cheshire, UK, in support of a successful license application under the UK's Integrated Pollution Prevention and Control (IPPC) regulations (Robinson and Hooker, 2002);

² These topics are a subset of all those that need to be considered by a Safety Case.

- ▲ an assessment by Quintessa Limited, on behalf of AkzoNobel Industrial Chemical's B.V. to determine the feasibility of using residual materials from a waste-to-energy plant operated by Twence B.V. to stabilise caverns developed in halite deposits in the eastern Netherlands (Metcalf et al., 2013);
- ▲ although the CF is not to be a radioactive waste repository, assessments for a number of underground radioactive waste disposal facilities, following a general methodology described by the International Atomic Energy Agency (IAEA, 2004).

More specifically, important principles followed during the assessment are:

- ▲ **The approach adopted for the Long-term, Post-closure Risk Assessment was consistent with that adopted for the Operational Phase Risk Assessment**, so that the former can provide suitable input to the latter.
- ▲ **The overall approach was “top-down”**, such that the starting point was identifying the main threats to the environment posed by the CF during the post-closure phase. The factors that influence the likelihood of each threat and their impacts were then identified to a level of detail appropriate for assessing risks in a plausibly conservative manner.
- ▲ **The overall approach was plausibly conservative**, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern.
- ▲ **The assessment was structured by carrying out a functional analysis of the CF system during the Post-closure phase**, which was audited against experience in other, similar projects (e.g. Metcalf et al., 2013; Hooker et al., 2002) and, where appropriate, Features Events and Processes (FEPs³). Consistent with the first point, the emphasis is on identifying threats to the safe functioning of the system, with scenarios⁴ being defined by threats / specific combinations of threats.
- ▲ **Risk were treated as a product of the probability of a threat and its impact**, the former being estimated qualitatively and the latter being estimated qualitatively.

³There are many slightly different formal definitions of the term “FEP” (e.g. IAEA, 2004; 2007), but fundamentally the meaning of these terms is as follows: A “Feature” is a physical component of a system, or a physical entity that influences a system. An “Event” is a process that influences the evolution of the system over a time period that is short compared to the time frame being considered. A “Process” is a dynamic interaction between “Features”, which may operate over any particular time interval of interest.

⁴ Following IAEA (2007) a scenario is “A postulated or assumed set of conditions and/or events.”

- ▲ **Outputs are presented using commonly-used:**
 - **risk matrices**, which show highest plausible probability of threat versus plausibly conservative impact if realized; and
 - associated **qualitative safety arguments**.
- ▲ **Recommendations for reducing cautious assumptions** have been made.

3 Assessment Context

3.1 Scope of the Risk Assessment

The aim was to undertake an objective assessment of environmental safety during the post-closure phase of the facility, covering the following topics:

- ▲ describe the properties of the various barriers that act to prevent contaminants travelling from the CF to the receiving environment (equivalent to biosphere⁵ in many other assessments in other countries) and hence establish what processes might threaten their barrier function, considering in particular:
 - the wasteforms themselves;
 - engineered materials, such waste containers and backfills;
 - shaft seals;
 - the host rock; and
 - the rocks surrounding the host rock, principally the overburden.
- ▲ risks of a pathway developing between the wastes and the receiving environment, such that there is an impact on receptors;

A goal was to undertake the assessment on a systematic and structured basis, reported in qualitative terms and supported by a range of different information types.

The overall timescale to be considered by the assessment is sufficiently long to ensure that maximum risks have been considered. That is, considering longer periods would not cause greater maximum risks to be estimated at a point in the future. While this timescale is not defined precisely, an overall period of 1 million years is deemed sufficient, as is common practice internationally in safety assessments concerned with the underground disposal of radioactive wastes (e.g. NEA, 2007).

In addition, within this overall time frame the assessment discusses in more detail variations in risk over the following time intervals:

- ▲ 300 years (possible institutional control period);
- ▲ 1,000 years (a millennium); and
- ▲ 10,000 years (a defined epoch).

⁵ The term “biosphere” covers that part of the environment normally inhabited by living organisms at sufficiently shallow depths that might typically be affected by basic human actions such as farming (e.g. see IAEA, 2007).

3.2 Key Regulatory Requirements

The principal regulatory Acts, Regulations and guidelines that have underpinned this work are listed below:

- ▲ Environmental Impact Assessment Guidelines for the Chandler facility project, (<http://www.ntepa.nt.gov.au/environmental-assessments/assessment/register/chandler-salt-mine>);
- ▲ Northern Territory of Australia Waste Management and Pollution Control Act, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/waste%20management%20and%20pollution%20control%20act>);
- ▲ Northern Territory of Australia Mining Management Act, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/MINING%20MANAGEMENT%20ACT>);
- ▲ Northern Territory Environmental Protection Authority (NT EPA) Guidelines for the Siting, Design and Management of Solid Waste Disposal Sites, (https://ntepa.nt.gov.au/__data/assets/pdf_file/0006/284685/siting_design_1andfills.pdf);
- ▲ Mining Management Plan requirements for the mining of minerals, http://www.nt.gov.au/d/Minerals_Energy/index.cfm?header=Mining;
- ▲ Northern Territories Worksafe Major Hazard Facilities guidance on the form and structure of the required risk assessment, (<http://www.worksafe.nt.gov.au/IndustrySectors/Pages/Major-Hazard-Facilities.aspx>)

3.3 Information and Data Sources

Information and data from a wide range of sources have been reviewed and assessed in preparing this long-term, post-closure risk assessment. References to relevant documents are provided in context in subsequent sections, and listed in Section 11. Additional information supplied directly to the authors is summarized in the Appendices. The assessment is primarily based upon information made available by early February 2016. Types of information and data sources reviewed include the following.

- ▲ regulatory guidance documents (Australian and international regulatory sources; including those given in Section 3.2 above);
- ▲ information on potential/projected wastes streams;
- ▲ geological and geotechnical reports;
- ▲ groundwater analyses from the Maryvale property and from the wider region;

- ▲ information on the hydrogeology of the Maryvale property and surrounding region, including a number of Technical Notes and e-mail communications by Tellus' hydrogeology contractor G. Ride;
- ▲ a number of documents concerning the proposed facility design;
- ▲ documents concerning the proposed approach to facility operation; and
- ▲ information undertaken about risk assessments undertaken for analogous international facilities.

Quintessa

The salt deposit will have been accessed by two vertical shafts, each nominally 800 m deep⁷. The shaft through which the wastes will have been emplaced will have an internal diameter of 8.5 m. The second shaft, through which the mined salt will have been transported, will have an internal diameter of 6.0 m. Dimensions of storage and disposal rooms are yet to be confirmed. However, provisional dimensions for the storage rooms are 250 m x 10 m x 6 m and provisional dimensions for the disposal rooms are 250 m x 15 m x 6 m. Pillars between the rooms are nominally sized at 15m width currently within each panel, but the widths of the rooms at the margins of the panels may be reduced to take into give an additional margin of safety with respect to creep. Overall the facility has provisional underground dimensions of 2 km x 2 km x 6 m, with a 32% extraction ratio when taken in plan view. Main development roads are to be driven in the same salt horizon and are currently assumed to be 10 m wide by 6 m high.

The wastes will exist in the closed Chandler facility in two forms:

- ▲ wastes emplaced “dry” in packages ; and
- ▲ wastes emplaced as a “hydraulic backfill”.

Dry packaged waste packages will be surrounded by crushed salt (Figure 4-2). Rooms in which wastes are emplaced hydraulically will be fully filled, apart from a small headspace volume near the entrance (Figure 4-2).

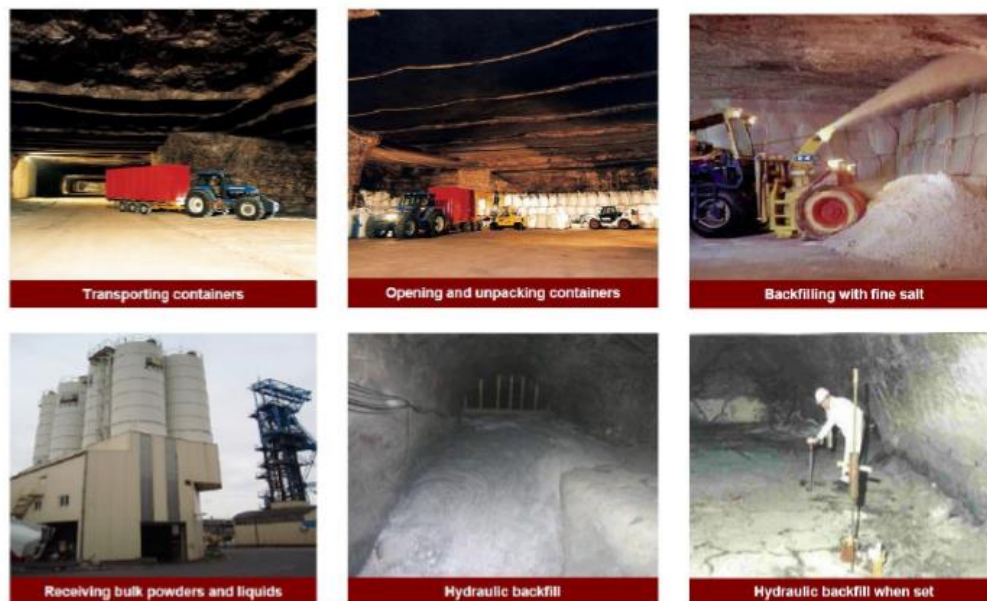


Figure 4-2: Visual representation of waste handling and storage techniques (courtesy of Tellus Holdings).

⁷ Consideration is also being given to the possibility of accessing the facility via a decline. The implications of this option for the assessment presented in the present report are given in a separate Technical Note (Quintessa Report to Tellus QRS-1809A-DC1).

All underground access roadways will be filled with crush salt at the end of their functional life.

Shaft seal designs have yet to be finalised, but are likely to be based on experience at the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, and at various facilities excavated in salt in Germany.

The closure engineering for the shafts is therefore likely to comprise:

- ▲ a concrete monolith at the base, within the salt formation;
- ▲ high integrity seal through the lower part of the rock sequence and probably through the lowest “aquifer” unit, although this depends on the depth of that unit;
- ▲ seals at the base of each aquifer unit and wall grouting through the aquifer unit (note that any areas of potentially significant flow would have been grouted for construction and operations);
- ▲ backfilling the shafts between the seals using some combination of crushed host rock, clay, cement and sand.

For the purposes of the initial post-closure assessment, the details of the construction of the seals are not important. The assessment requires the transport properties of the seal (i.e. a specification for performance) rather than the engineering details. The properties of the seals will be based on those used in the post-closure assessment of the Deep Geological Repository (DGR) at the Bruce site in Canada (Quintessa. and Geofirma Engineering, 2011).

The initial condition for the post-closure assessment is a fully backfilled facility with all of the barriers correctly emplaced. This forms the basis for the normal evolution scenario.

4.2 Location and Surface Environment

The site is located approximately 120km south of Alice Springs in the Northern Territory of Australia and lies at the transition between erosion-resistant low hills to the northwest and a sandy plain to the southwest. The closest community to the facility, Titjikala (c. 180 people) is located about 18 km to the northeast.

The region has low rainfall. URS (2012) reports a maximum annual rainfall of c. 300 mm annually, while the Australian Bureau of Meteorology (BOM) give an annual mean of 197.4 mm for the Maryvale station between the years 1948 and 2014. However there can be high, intense rainfall events and the BOM give a maximum monthly rainfall of 226.3 mm during these years. Precautions will be taken (e.g. siting on relatively high ground, drainage channels to divert water) to prevent flooding of the facility.



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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

According to Douglas Partners (2016), the basic stratigraphy at the proposed facility location is:

- ▲ surface to about 8m: recent deposits, including sand dunes;
- ▲ 8m - 343m: Horseshoe Bend Shale and Langra Formations (upper, middle and lower). The Langra Formation in this region consists of alternating thin bands of hard siltstone and very fine sandstone ;
- ▲ 343m – 390m: Parkes Siltstone;
- ▲ 390m – 503m: Stairway Sandstone, which comprises interbedded sandstone and siltstone;
- ▲ 502m – 772m: Jay Creek, which mainly comprises dolomitic siltstone;
- ▲ 772m – 1085m: Chandler Formation, which comprises anhydritic siltstone to 825m and halite below that. Core from boreholes CH001A and CH003 show the salt to be almost pure halite with very few marly beds or other impurities.

The facility will be located in the upper part of the Chandler salt formation. According to the log in the Joint Ore Reserves Committee (JORC) report (ERCOSPLAN, 2013), the upper halite bed in borehole CH001A is present in the depth interval 825m – 861m. It is overlain by siltstone and underlain by a 10m thick bed of limestone/siltstone. Below this bed, the formation is dominantly halite with minor limestones and siltstones. Interpretation of the seismic data has identified the extent of the salt horizon and suggests that it is stable (i.e. the salt does not appear to be subject to any dissolution in the recent past and it is not migrating as a diapir).

The target horizon is 35m thick in borehole CH001A and 34m thick, and at a slightly shallower depth, in borehole CH003. The intention is that there should be 20m of intact salt above the excavations, which implies that the facility would be at a depth of approximately 850 m and there would be 8-9m of salt between the facility and the underlying limestone bed.

The information obtained from boreholes and 2D seismic surveys indicates that there are no significant faults in the area immediately surrounding the facility, although as noted above, the wider Amadeus Basin has a long history of folding and faulting but is currently tectonically stable. It is anticipated in-seam seismic etc. will be used to identify faults/features of interest up to several hundred metres ahead of and prior to excavation. Therefore it can be assumed that the facility will not be intersected by any faults or features that are likely to be a pre-existing pathway to the overlying formations because the layout would be adjusted to ensure an appropriate standoff distance. Some minor concealed faults have been suggested but these do not appear to be within the footprint of the facility.

There are no known resources in the area of interest, apart from the Chandler salt formation and a much deeper salt horizon. The area has been investigated for hydrocarbons, which are found further to the west in the Amadeus Basin, but no significant hydrocarbons were found in the Chandler area and the seismic and other

data indicate that there are no obvious structures within which significant accumulations would be trapped. Similarly, previous exploration for uranium and diamonds has been unsuccessful.

Hydrogeology and Geochemistry

Average annual rainfall in the region is about 200mm per year (BOM give an overall annual mean of 197.4 mm for the Maryvale station for the years 1948 to 2014) but the rainfall is not uniformly distributed between years (BOM state that annual rainfall ranges from 45.3 mm to 521.8 mm at the Maryvale Station during the years 1948 to 2014). Rainfall tends to be concentrated in large storm events that result in extensive surface flow and flash flooding. The area around the CF drains to the Finke River and the Hugh River, which are ephemeral and flow on average less than once per year; the last major flood flow of the Finke River is thought to have been about 12 years ago. Flooding events lead to recharge of local shallow alluvial water bodies that feed water holes and some local shallow bores. It appears that these are perched water bodies. The high temperatures mean that evapotranspiration rates are high so recharge to depth is limited (estimated at order 1mm/y to the water table by URS, 2012).

Several zones that are able to sustain some flow to a borehole have been identified in the various boreholes that have been drilled. Tellus has drilled six groundwater monitoring boreholes and two investigation production boreholes to depths of up to about 360 m to monitor the groundwater levels and compositions and installed monitoring equipment in two other pre-existing boreholes. The rest water level is usually about 80 m below ground surface.

The boreholes identified several permeable medium to coarse grained sandstone units. Douglas Partners (2016) identifies three “aquifer” units from the wireline logging and drilling information:

- ▲ The upper aquifer at depths of 90 m – 102 m seen at two drilling locations had a low yield and appears to be poorly connected. It is thought to be associated with the Horseshoe Bend formation;
- ▲ The middle aquifer at depths of 151 m – 185 m was identified in most of the boreholes but has a variable yield. It is thought to correspond to the Upper Langra Formation;
- ▲ The lower aquifer at depths of 222 m -320 m, which had the highest yield and was seen in most, but not all of the boreholes. It is thought to correspond to the Lower Langra Formation.

Below these units, the Stairway sandstone (390 m – 502 m) was identified as a potentially significant aquifer in oil exploration studies but is not thought to be regionally connected. Little is known about the Jay Creek limestone, although the

lithological description implies that it is unlikely to contain significant aquifer beds. The Santo sandstone was encountered in the easternmost borehole but is not present within the footprint of the CF and is a poor aquifer if below the water table. For the purposes of the assessment it is assumed that four aquifers of varying quality are present in the immediate vicinity of the CF.

Although the sandstone beds may have a primary porosity of 10-20%, the effective porosity is thought to be significantly lower and in many places the primary porosity has been infilled with calcite or silica. The aquifer units tend to correspond to areas where the infill is absent. Groundwater inflow to boreholes often appears to be from discrete fractures, probably bedding planes.

Preliminary results are available from the Tellus groundwater monitoring boreholes; the length of the recording period is currently a significant limitation and the results from the different boreholes are sometimes contradictory. The results suggest the following:

- ▲ the water table is at about 85 m below ground surface but there may be temporary perched water bodies above this;
- ▲ the aquifers are in general poorly connected and in some cases the “expected” aquifer was not encountered in a borehole;
- ▲ head (water level measured in the piezometer) tends to increase with depth but the gradients are small. The head difference between the upper part of the Stairway and the Lower Langra seems to be of the order of 0.5 m, the head difference between the Upper and lower Langra seems to be up to half a metre and the head difference between the Upper Langra and Horseshoe Bend seems to be up to 3 m.

For assessment purposes, it is conservative to assume that an upwards head gradient is present. There is no information about the head gradient between any aquifer in the Jay Creek Limestone and the Stairway sandstone but for assessment purposes a head of a metre or so could be assumed.

The regional direction of flow in the aquifers in the area is thought to be to the southeast. Flow rates are thought to be very low, for example a rate of $<0.01\text{m/y}$ has been suggested for the Langra Formation (Graham Ride, written communication, 29th February 2016).

Groundwater salinity increases with depth but all of the sampled waters are below halite saturation. Shallower waters tend to be bi-carbonate rich and deeper waters more chloride rich. Water in the Horseshoe Bend Shale Formation is brackish to poor quality and the composition varies with time according to recharge. There is no apparent geochemical signature that would indicate upwards movement of groundwater from the deep aquifers occurring naturally within the local and regional hydrogeological system.

The current interpretation is that the low yielding aquifers intersected in the Horseshoe Bend Shale Formation are in localized very fine poor porosity sandstone beds with links to recharge locations probably through minor fracture preferential flow paths from above and in some cases below and bedding planes. The chemical water quality is poor and there can be different types of water in the different aquifers. The chemical water analyses generally indicate relatively recent recharge.

The recharge locations for the deeper aquifers are not known but likely to be some distance (at least 50 km away) from the area of interest. The discharge locations are also unknown, but are hundreds of kilometres from the proposed site of the Chandler Facility. The aquifers in the area of the proposed CF pass underneath the Pedirka Basin and discharge at an unknown very distant location.

The nearest significant town to the facility is Alice Springs. Alice Springs obtains its drinking water from the Mereenie Sandstone. This aquifer has no direct hydrogeological connection to the formations overlying the Chandler facility and in regional terms is up-gradient of the facility. Local Aboriginal communities obtain their drinking water from a shallow aquifer to the east of the Hugh River which recharges this system with water that is of a standard appropriate for drinking.

4.2.2 Hazard Identification

Waste Characteristics

The waste acceptance criteria (based on European regulations; specifically Appendix A of Council Decision (EC) 2003/33/EC and Article 5(3) of the Landfill Directive, Council Directive (EC) 1999/31/EC) rule out certain types of wastes that might result in the development of particular conditions in or pathways from the facility:

- ▲ liquid or sludge wastes that cannot be incorporated into a wasteform that is suitable for disposal (e.g. by grouting or hydraulic backfilling);
- ▲ wastes that are explosive, highly corrosive, or oxidising, highly flammable or flammable;
- ▲ tyres;
- ▲ radioactive waste, with the exception of some Naturally Occurring Radioactive Material (NORM);
- ▲ wastes that might react with water to generate auto-flammable or toxic or explosive substances or gases;
- ▲ wastes that are auto-flammable or liable to spontaneous combustion under the storage conditions, gaseous products, volatile wastes, wastes coming from collections in the form of unidentified mixtures;
- ▲ wastes that are biodegradable;

- ▲ wastes that may result in a biohazard.

Thus the assessment will assume that the waste is solid and will not react with the surrounding host rock or other waste types.

The wastes will have the following post-closure characteristics:

Wastes Emplaced in Dry Form

- ▲ Wastes will be emplaced dry in multiple rooms within the facility. Each room will have a nominally horizontal floor.
- ▲ Different categories of waste will be located in different rooms called zones to keep non compatibles wastes physically separated.
- ▲ These wastes will be typically contained in:
 - Flexible Intermediate Bulk Containers (FIBC), also termed “bulka-bags”, which are constructed of woven fabric and have a secondary liner; or
 - barrels of granular material; and
 - may have a more robust overpack if necessary.
- ▲ The waste bags or barrels will be placed on pallets for transport within 20-foot long ISO-containers. There will be up to 10 pallets on the floor of each container. Each container could contain up to 20 bags weighing about 1 tonne each.
- ▲ There will normally be entrances to both ends of the room in which the waste is emplaced, which will be sealed by doors.
- ▲ At the time of closure there will be some residual voidage, which is a combination of pore space in the packaged waste and in the backfill, and some small amount of excavated space that is not filled by backfilling material (100% filling being unattainable in practice).

Wastes Emplaced as Hydraulic Backfill

- ▲ Wastes that have been emplaced in a hydraulic backfill comprise an essentially dry solid in the post-closure phase, the backfill having been formulated to have very little free water following curing.
- ▲ The room configuration for hydraulic backfill emplacement is different to that for dry emplacement. Rooms will have a slight incline downwards from a single entrance.
- ▲ There will be almost no voidage due to imperfect filling of the emplacement rooms, apart from a small wedge-shaped void at the end nearest the door.
- ▲ The hydraulic backfill may have substantial porosity after emplacement, depending upon its formulation. A porosity of several tens of percent may be possible.

Waste Types and Inventory

A list of potential wastes has been provided by Tellus (Table A1, Appendix A), based on:

- ▲ NEPM 75 waste categories;
- ▲ the assumption that an annual average of 3400,000 tonnes will be emplaced;
- ▲ the assumption that there will be a total of c. 8.5 million tonnes of waste emplaced over the lifetime of the project; and
- ▲ market research.

A list of the top 20 waste categories which account for 99% by weight of the total inventory for disposal along with a description and identification of possible hazardous substances is given in Table 4-1.

Table 4-1: Top20 “75” code waste descriptions, expected proportions at the Chandler facility and identification of potential hazardous substances.

NEPM “75” code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (<i>NB italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (<i>NB italics indicate areas of uncertainty in future characteristics</i>)
N205	25.30%	Residues from industrial waste treatment/disposal operations	Scrubber sludge; Ion-exchange column residues, Industrial waste treatment sludges and residues nos, Residues from pollution control operations nos	heavy metals/metalloids, organic compounds, <i>possibly pesticides</i>	Large component of inventory, possibly largely immobilized in hydraulic backfill
D110	19.60%	Inorganic fluorine compounds excluding calcium fluoride (SPL)		fluoride	<i>Largely low solubility material?</i>
N120	16.60%	Soils contaminated with a controlled waste		heavy metals, hydrocarbons (see other entries)	<i>Trace/minor amounts of metals, metalloids, hydrocarbons, possible pesticides(?), assume containerised</i>
N220	10.70%	Asbestos		amosite, chrysotile, crocidolite	<i>Assumed contained in inert matrices, potential for loose fibres / degrading ACM? Potential for Hydraulic backfill</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
J120	5.60%	Waste oil/ water, hydrocarbons/ water mixtures or emulsions	Vehicle washwaters Boiler blowdown sludge Cooling tower washwaters Textile effluent & residues nos Industrial plant washwaters Ethylene glycol-water (antifreeze) Oil/hydrocarbon (<50%) mixed with water Oil/hydrocarbon (>50%) mixed with water Other (cutting oils, soluble oils) Oil/hydrocarbon mixed with water nos	numerous hydrocarbons	<i>Potentially not suitable for hydraulic backfill</i>
D220	4.90%	Lead; lead compounds	Lead acid batteries Gritblast waste Lead & lead compounds nos	lead	<i>Assume battery acid liquid, and other forms are solid, liquids not suitable for hydraulic backfill?</i>
C100	4.90%	Basic solutions or bases in solid form	Alkaline cleaners, potash, caustic soda Ammonium hydroxide Waste lime & cement (no metallic constituents) Caustic neutralised waste (metallic constituents) Other alkaline waste (inorganic) Other alkaline waste (organic)	ammonia (others such as metals)	<i>Assume solid possible sludges? Possible hydraulic backfill candidate?</i>
D230	2.90%	Zinc compounds	Zinc ash/ dust, galvaniser's ash Zinc compounds	zinc (and possibly cadmium as an impurity)	Assume solid, including particulates
NORMS	2.20%	NORMs		radium, radon, barium, (uranium?) + associated radioactivity	Assume solids, with Rn gas being generated over longer timescale by decay

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics</i> indicate areas of uncertainty in future characteristics)	Assumptions on Form and Disposal Route (NB <i>italics</i> indicate areas of uncertainty in future characteristics)
J100	2.20%	Waste mineral oils unfit for their original intended use	Mineral oils unfit for their original intended use Oil filters Transformer fluids (excluding PCB's) Waste hydrocarbons	numerous hydrocarbons	<i>Unsuitable for hydraulic backfill?</i>
D300	1.20%	Non-toxic salts	Aluminium dross, aluminium smelter waste Salt slag Non-metallic product Non-toxic salts no	aluminium compounds, other metals	Assume solid
B100	0.80%	Acidic solutions or acids in solid form	Sulfuric acid Hydrochloric acid Nitric acid Phosphoric acid Chromic acid, sodium dichromate Hydrofluoric acid Sulfuric/hydrochloric acid mixtures Mixed acids (inorganic) Organic acids Pickle liquor Acids nos	<i>Assume acids have largely been neutralised prior to disposal? may have some chromium/fluoride/sulpha te/phosphate/chloride compounds.</i>	<i>Assume insoluble salts?</i>
N160	0.50%	Encapsulated, chemically- fixed, solidified or polymerised wastes referred to in this list	Encapsulated waste Chemically fixed waste Solidified or polymerised waste	see other entries	Solids

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
F100	0.50%	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	Paints, inks, etc (aqueous non-flammable vapours) Paints, inks, etc (aqueous, flammable vapours) Paints, inks, etc (solvent combustible FP<60.5C) Paints, inks, etc (solvent combustible FP>60.5C) Paint residues nos	numerous compounds, including solvents	<i>Unsuitable for hydraulic backfill?</i>
M100	0.30%	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or polybrominated biphenyls	Oil, solvents & materials contaminated with PCB Equipment containing PCBs Polychlorinated biphenyls (PCBs) nos Equipment containing PCNs, PCTs and PBBs PCNs, PCTs and PBBs	PCBs, PCTs, PBBs	<i>Unsuitable for hydraulic backfill?</i>
N100	0.30%	Containers and drums that are contaminated with residues of substances referred to in this list	Drums containing waste which must be tracked Other containers containing waste which must be tracked Aerosol cans	see other entries	Containerised materials, probable low water content
N190	0.20%	Filter cake contaminated with residues of substances referred to in this list	Filter cake	see other entries	<i>Containerised solid?</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics</i> indicate areas of uncertainty in future characteristics)	Assumptions on Form and Disposal Route (NB <i>italics</i> indicate areas of uncertainty in future characteristics)
G110	0.20%	Organic solvents excluding halogenated solvents	Klenasol (non-chlorinated) Non-halogen organic solvents (flammable FP<60.5C) Non-halogen organic solvents (combustible FP>60.5C) Non-halogenated organic solvents nos	organic solvents	<i>Unsuitable for hydraulic backfill?</i>
M250	0.10%	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	Surfactants	surfaces, metals/metalloids	<i>Unsuitable for hydraulic backfill?</i>
A100	0.10%	Waste resulting from surface treatment of metals and plastics	Waste from metals & plastics treatment	metals, plastic degradation compounds	Possibly includes superplasticiser compounds

All substances of possible concern to the receiving environment present in each waste type have been considered. All the hazardous substances in the wastes that are listed in the relevant NEPM guideline (NEPC, 2013) are considered. These substances also include priority substances and certain other pollutants within the corresponding EU legislation (Environmental Quality Standards, Council Directive (EC) 2008/105/EC).

The first step in considering these substances is to rank them 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Appendix A, Table A2). The product of the three values is then used as an “index” value used to identify substances of greater importance, a subset of which is suggested for post closure assessment. This process identified the following substances of greatest priority:

- ▲ Beryllium (score 12);
- ▲ Chromium (as Cr(VI)) (score 12);
- ▲ Dichloromethane (score 12);
- ▲ Hexachlorobutadiene (score 12);
- ▲ Mercury (score 12);
- ▲ Benzene (score 9);
- ▲ Epichlorohydrin (score 9);
- ▲ Lead (score 9);
- ▲ Molybdenum (score 8); and
- ▲ Nickel (score 8).

A number of different pesticides/herbicides could be associated with wastes from agriculture and soils; a list of representative substances is given in Appendix A (Table A3). For post closure assessment in particular, a subset of illustrative substances has been identified based on potential toxicological hazard and aqueous solubility:

- ▲ Dieldrin;
- ▲ Fenamiphos; and
- ▲ Diquat.

NORM is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings or material used in power generation or defence activities). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are

oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate most likely from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose in Australia per year (Radiation Health & Safety Advisory Council, 2005), with about 1% being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

4.2.3 Pathways

In accordance with usual practice for risk assessments of underground waste facilities, a judgement is made of the likelihood that, in the post-closure period, a pathway could develop between the emplaced waste and receptors of concern. The approach is to consider all the kinds of natural and engineered features of the CF that could potentially form such a pathway, either individually or in combination, given unexpectedly adverse conditions. The intent is *not* to predict that such pathways will occur, but rather to identify the kinds of pathways that should be considered by subsequent “what if” analyses designed to assess the impacts of the pathways developing. It should be noted that even if a pathway were to develop unexpectedly, this would not in itself imply a high environmental risk; for a high risk to result, the consequences of the pathway developing would also need to be high.

The assessment considers the following kinds of pathways:

- ▲ shafts with impaired (degraded) seals which could allow contaminants to be transported in aqueous form to rock formations above the Chandler Formation;
- ▲ pathways linking the rooms to aquifers in the overburden:
 - transmissive fractures or faults (noting that no faults have been identified within the footprint of the facility);
 - collapse columns that would be created should the roof of a cavern fail;
- ▲ aquifers in the overburden (in combination with other kinds of pathway); and
- ▲ pathways associated with boreholes intersecting other transmissive features (it being assumed that no boreholes will penetrate from the surface into the footprint of the

facility, so that only shallower monitoring boreholes, which have depths of up to c. 360 m, could potentially form part of a pathway).

Not all these kinds of pathway could on their own, provide a route from the waste to a receiving environment, but rather would need to act in combination with one or more other pathways. For example, all the aquifers are almost horizontal and isolated from the Chandler Formation by impermeable rock formations. Hence, for an aquifer to form part of a pathway between the wastes and a receiving environment, it would need to be connected to the wastes by a different kind of pathway, such as a shaft with degraded seals. Furthermore, another pathway would be needed to connect the aquifer to a near-surface receiving environment. A borehole drilled into the aquifer in the future to obtain water for irrigation might provide such an additional pathway.

4.2.4 Receptors

In general terms a receptor is something that could be adversely affected by a contaminant, such as people, an ecological system, property, or a water body⁸. The post-closure risk assessment needs to consider both those receptors that occur at the present and also those that could potentially occur in the future. Given the very long time frame of the assessment, the receptors that need to be considered could change considerably. Furthermore, any given receptor may not be present throughout this timeframe. For example, climate change may mean that farming can occur near the CF at some times, but not at others. Owing to this variability, it is inappropriate to give detailed descriptions of the receptors. Instead, general kinds of receptor are identified.

As noted above, most of the groundwater in the vicinity of the CF is too saline to be potable and the aquifer units discussed above are not used for drinking water. Some water is extracted for stock watering, usually from the Horseshoe Bend Shale Formation or the Upper Langra Formation.

The quantitative analysis undertaken as part of the post-closure assessment treats the aquifers as the primary receptors of concern. It is the concentration in each aquifer of contaminants that originate in the waste that is taken as the comparison point. However, it should be noted that the existing water in the aquifers may not currently meet the standards set out in the various groundwater regulations (Australian Drinking Water Guidelines, v6, 2011 (updated March 2015); World Health Organization Drinking Water Guidelines, v4 (2011); Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)).

⁸ e.g. Environment Agency of England and Wales (2004); South Australian Environmental Protection Authority (2007).

Based on the quantitative assessment of the aquifers, potential impacts on the following additional receptors are then assessed:

- ▲ surface water bodies;
- ▲ surface soils;
- ▲ air;
- ▲ humans (members of the wider public, since worker health and safety is not included in this assessment);
- ▲ flora (including crops);
- ▲ fauna (including livestock).

5 Functional Analysis of the CF System

5.1 Safety Functions

A useful way to derive the scenarios when using a top down approach is to first consider the function that must be performed by each component of the multi-barrier system that will be provided by the facility and the surrounding rock and then consider how the performance of the component might be impaired. For the CF the key components from the perspective of ensuring safety components are:

- ▲ wasteform;
- ▲ any container or packaging that is present;
- ▲ backfill;
- ▲ seals;
- ▲ host rock (i.e. the Chandler Formation);
- ▲ overburden (comprising aquifers and aquitards).

These components may all have barrier functions, which prevents or impedes migration of contaminants from the wastes to the potential receptors described in Section 4.2.4. Together the components may be regarded as comprising a multi-barrier system (Figure 5-1).

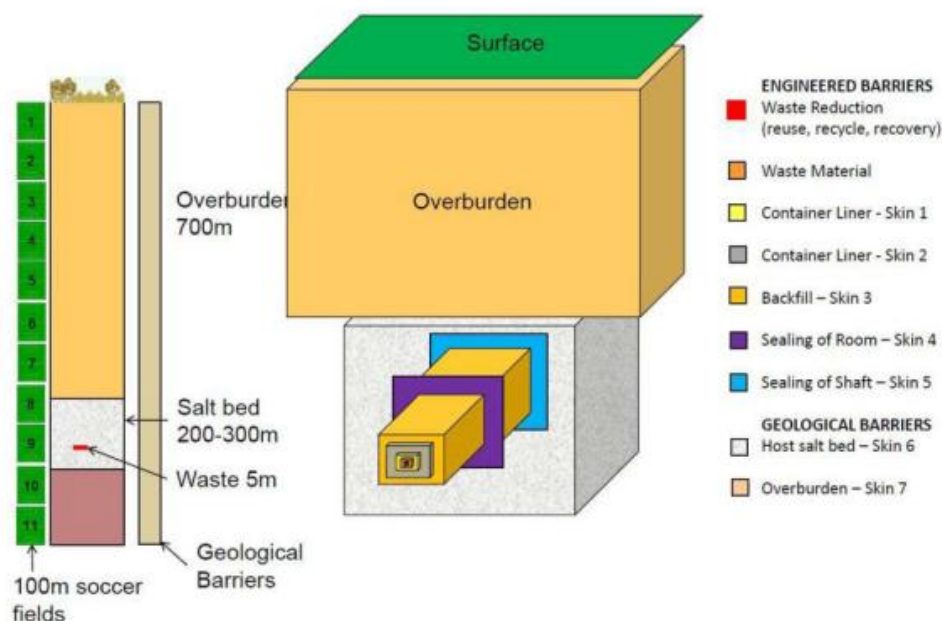


Figure 5-1: The multi-barrier system (from Tellus).

The overall safety functions of the disposal system are to isolate the waste from the surface environment and to contain it until such time as it no longer poses a danger. For waste that does not become less hazardous over time to the degree that it poses no threat to the

environment, for example certain heavy metal-bearing wastes, this implies indefinite containment or extremely slow release. In the latter case, the release rate must be sufficiently slow to allow dispersion in the rock sequence (henceforth termed “geosphere”) such that any contaminant never rises to levels that would cause unacceptable impacts. Table 5-1 summarizes the functions performed by each component and the possible threats that might degrade this performance.

Table 5-1: Safety Functions and possible threats for each component of the multi-barrier system.

Barrier	Safety Function	Threats (Potential cause of loss of safety function)
Wasteform	Immobilizes the contaminants and either prevents or retards their release to the next barrier.	Leaching by groundwater. It should be noted that many of the processes that might disrupt the wasteform or allow it to damage the other barriers have been excluded by the Waste Acceptance Criteria (WAC). Interactions between incompatible waste types prevented by zoning.
Container	Protects the wasteform and limits contact of waste with water.	Corrosion or other degradation.
Backfill	Protects the container and fills void space to provide mechanical stability. Limits the access of water to the waste and retards transport of contaminants.	Low emplacement density (or absence). Disruption by gas generated by corrosion of any metallic packaging (e.g. steel drums holding grouted waste). Dissolution due to water emplaced with the waste (e.g. porewater in grouted wasteform), especially if it is not halite saturated at time of emplacement.
Seals	Limit the potential for flow through the engineered system.	Poor specification or construction. Disruption by gas.
Host Rock	Protects the engineered structures and waste and limits or prevents access of water to the waste. It retards the transport of any contaminants that are released from the waste.	Shafts. Boreholes and faults are excluded by layout. Excessive voidage in the disposal rooms and tunnels leading to collapse zones that propagate through the whole of the roof (insufficient roof thickness in salt) as the host rock creeps. Salt does not creep as expected and fails by brittle fracture. Dissolution due to water emplaced with the waste (e.g. porewater in hydraulic

Barrier	Safety Function	Threats (Potential cause of loss of safety function)
		backfilled wasteform), especially if it is not halite saturated at time of emplacement. Dissolution by water in surrounding (overlying) formation.
Overburden	Retards the transport of any contaminants that are released from the waste. It may also dilute and disperse contamination so that contaminants are not present at concentrations that might present a danger.	Breaks in the continuity of the barrier that provide transport pathways. Potential pathways include poorly sealed shafts, poorly sealed boreholes, faults and fractures. Collapse zone propagation into the overburden.

The potential pathways by which contaminants could be transported from the facility to a receiving environment are one or a combination of:

- ▲ one or both shafts, should the emplaced seals not perform as designed;
- ▲ aquifers in the overburden (which cannot form a complete pathway owing to their geometry, but which could form part of a pathway in conjunction with other kinds of pathway);
- ▲ boreholes (noting that no boreholes penetrate from the surface into the footprint of the facility, so that only shallower boreholes, with depths of up to c. 360 m, could potentially form part of a pathway, in conjunction with other kinds of pathways). CH001A and CH003 have been cemented and future deep bore holes will either be cemented or eliminated during construction (i.e. on the centre line of a shaft).
- ▲ collapse columns that would develop above any room in which roof collapse occurred (which will not form complete pathways, but which could potentially form part of a pathway in conjunction with other kinds of pathway).
- ▲ faults or zones of fracturing that connect aquifer units, noting that none have been identified in the site characterisation activities to date and there is no evidence to support the upwards movement of water from deep aquifers via faults.

The design of the facility is such that a connected pathway should not be possible post-closure. However, it is noted that the current plan is to leave the monitoring boreholes, which extend to the base of the Lower Langra/top of the Stairway Sandstone open during the Institutional Control period. If these boreholes were not correctly sealed at the end of the Institutional Control period (yet to be agreed with Government) they could potentially form pathways via which any contamination that unexpectedly reaches the Stairway Sandstone could be conducted to the shallower formations.

5.2 Potential Interactions Among System Components

Having identified the main system components and the “high-level” threats to their proper functioning, the next stage is to identify the ways in which the various components may interact. This approach then leads naturally to identification of the ways in which the threats to the safety functions might be realized.

An interaction matrix was used to systematically identify potential interactions among different components of the CF and the surrounding geosphere. The matrix represents system components along the leading diagonal. Processes by which these components could potentially interact are then entered in off-diagonal elements. The approach is illustrated schematically in (Table 5-2). An interaction matrix for the post-closure behaviour of the CF is shown in Table 5-3. In this matrix, it is assumed that all engineered and natural systems

features (and many that could be present, such as unknown fractures) are present, and can potentially interact. It should be noted, however, that the matrix does not represent the significance of these interactions. Rather, an assessment of significance is made when developing scenarios (Section 6) and when analysing these scenarios (Section 7.2 and Section 8.4).

Table 5-2: Schematic illustration of a component interaction matrix.

Component 1	Processes by which Component 1 affects Component 2	No direct interaction between Component 1 and Component 3, so “greyed out” (-)
Processes by which Component 2 affects Component 1	Component 2	Processes by which Component 2 affects Component 3
Processes by which Component 3 affects Component 1	No direct interaction between Components 3 and Component 2 so “greyed out”(-)	Component 3

When constructing the matrix the aim has not been to document all possible interactions, but rather to represent those interactions by which one system component could potentially cause another system component to:

- ▲ be exposed to contamination arising from the wastes; and/or
- ▲ form a potential pathway for migration of contamination arising in the wastes (assuming that exposure to contamination occurs); or
- ▲ form an enhanced pathway for migration of contamination arising from the waste (assuming that exposure to contamination occurs).

Table 5-3: Potential Interaction Matrix for Chandler Facility (see text).

Hydraulic Backfill Waste	-	-	support (resists creep)	filling efficiency	support (resists creep)		loading	resist creep	resist creep	-	-	-	-	-	-	-
-	Containerized waste	-	support (resists creep)	packing efficiency, internal void space	support (resists creep)		loading	resist creep	resist creep	-	-	-	-	-	-	-
-	stress transmission to waste	Loose Salt Backfill	support (resists creep)	packing efficiency, internal void space	support (resists creep)	support (resists creep)	loading	resist creep		-	-	-	-	-	-	-
room geometry/ dimensions	room geometry/ dimensions	room geometry/ dimensions	Rooms	room geometry/ dimensions	-	connection via entrances (pathway to rooms (for water)	-	-	allows creep	-	-	-	-	-	-	-
-	-	allows settling	-	Residual Void Space	-		allows creep	allows creep	allows creep	potential pathway	potential pathway	-	-	-	-	-
-	-	-	creep, affects geometry	creep, affects void space	Pillars		loading	structural support	-	-		-	-	-	-	-
-	-	-	connection via entrances (pathway to rooms (for water)	changing tunnel geometry/ dimensions	-	Tunnels	-	-	allows creep	potential pathway	potential pathway	-	-	-	-	-
structural support	structural support	structural support	creep, affects geometry	creep, affects void space	structural support	creep, affects geometry	Underlying Salt	-	creep, affecting stress	-	-	-	-	-	-	-
loading (due to creep)	loading (due to creep)	loading (due to creep)	creep, affects geometry	creep, affects void space	loading	creep, affects geometry	-	Overlying Salt	-	creep leading to stress on shaft	potential pathway	potential pathway	potential pathway	-	-	-
loading (due to creep)	loading (due to creep)	loading (due to creep)	-	creep, affects void space	-	creep, affects geometry	-	creep, affecting stress	Laterally Confining Salt	creep leading to stress on shaft	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	Sealed Shafts	-	potential pathway	potential pathway	-	potential pathway, impact on water quality	-
potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access (if inclined)	Boreholes	potential pathway	potential pathway	potential pathway (through aquiclude)	potential water source (livestock, irrigation)	potential water source (public)
potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access	potential pathway for water access, displacement	potential pathway for water access, displacement	potential pathway for water access, displacement	potential pathway for water access	potential pathway for water access	Faults/ Fractures	potential pathway	potential pathway (through aquiclude)	-	-
-	-	-	-	-	-	-	-	-	-	pathway for water access	pathway for water access	-	Aquifers	-	potential pathway, impact on water quality	potential pathway, drinking water contamination (public)
-	-	-	-	-	-	-	-	-	-	-	-	-	confine aquifers	Aquicludes	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Biosphere Receptors (incl. surface waters)	contamination of environmental media (soil, water, air, flora and fauna)
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Consumption of food, surface water	Human Receptors

Each off-diagonal entry into the interaction matrix shows only interactions between two system components.

Linkages between the wastes (at the top left of the matrix) and receptors (at the bottom right of the matrix) can be made by tracing routes through matrix elements into which either system components or interaction processes have been entered. These linkages correspond to scenarios.

6 Scenario Development

6.1 Nature of Scenarios

Scenarios are commonly developed and analysed during risk assessments for a wide range of sub-surface storage and waste disposal projects (e.g. NEA, 2001; Robinson and Hooker, 2002; Watson et al., 2008; Capture Power and National Grid, 2016). There are several slightly different definitions, but broadly a “scenario” is *a plausible description of the potential evolution of a system according to the nature of the features, events and processes that might act within and upon it*. In the present assessment, the “system” of concern consists of the wastes, the surrounding engineered structures (e.g. backfill and shaft seals), the surrounding geosphere (rock sequences, including geological structures such as faults and fractures that may occur within them, and the groundwater) and the potential receptors that could be affected.

Generally, two types of scenario are distinguished:

- ▲ An Expected Evolution Scenario (EES) is a statement of how the system will evolve if it behaves as expected.
- ▲ An Alternative Evolution Scenario (AES) is a statement of how the system would evolve under an unexpected set of circumstances.

It is important to note that a scenario is *not a prediction* of the future behaviour of a system, but rather a representation of the (typically temporally changing) status of a system under a specified set of conditions (which may be evolving).

Scenarios form a basis for analysing system behaviour and for communicating the results of the analysis. In the present assessment, as is accepted practice for such assessments, *the AES are defined to represent extreme circumstances that are not expected to occur*. The set of defined AES aims to provide insights into:

- ▲ all the ways in which the system could impact upon the environment in the event that it behaves unexpectedly; and
- ▲ the range of environmental impacts that could arise in these circumstances.

Any impact arising should the system actually evolve in an unexpected fashion would be no greater than the greatest impact arising from the assessed scenarios.

6.2 Approach to Scenario Development

A “top-down” approach to developing scenarios was undertaken, involving the following steps:

1. The system was described to identify important operational components and the spatial and temporal relationships among them.
2. The hazard of concern to the assessment was described.
3. Potential⁹ pathways, via which contaminants could be transported to potential¹⁰ receptors were identified. These pathways would become relevant should control over the hazard be lost.
4. Potential receptors were identified. These receptors are entities that could plausibly be harmed should they come into contact with contaminants as a consequence of control being lost over the hazards identified in 1. and one or more pathways identified in 3. becoming active.
5. Possible interactions between the different components of the system were determined systematically to identify possible processes by which:
 - control over the hazard could be lost;
 - pathways between the hazard and potential receptors could become active.
6. Processes that could cause a combination of loss of control over the hazard and one or more pathways to become active were then identified.
7. Scenario descriptions were then developed consisting of:
 - an EES, which describes how the system is expected to behave, according to environmental and operational management plans being followed;
 - a set of AES, describing how the system might behave in the event that one of the processes identified in item six occurs, each one comprising:
 - i. a description of the initiating process; and
 - ii. the interactions among the components of the system that could arise as a result of the initiating process.

⁹ These are pathways that are not expected to exist, either at the present or in the future, but which could plausibly occur under certain unexpected circumstances. Therefore, the likelihood for these pathways occurring and the consequences should they occur, need to be assessed.

¹⁰ These receptors include those occurring at the present and any that might occur at some time in the future following closure of the CF. Not all potential receptors will occur throughout the assessment time frame. For example, climate change may mean that agriculture is possible near the CF at some times, but not at others.

7 Expected Evolution Scenario (EES)

7.1 EES Scenario Description

The EES is a statement of the evolution of the CF during the post-closure phase, assuming the facility behaves as designed (Figure 7-1).

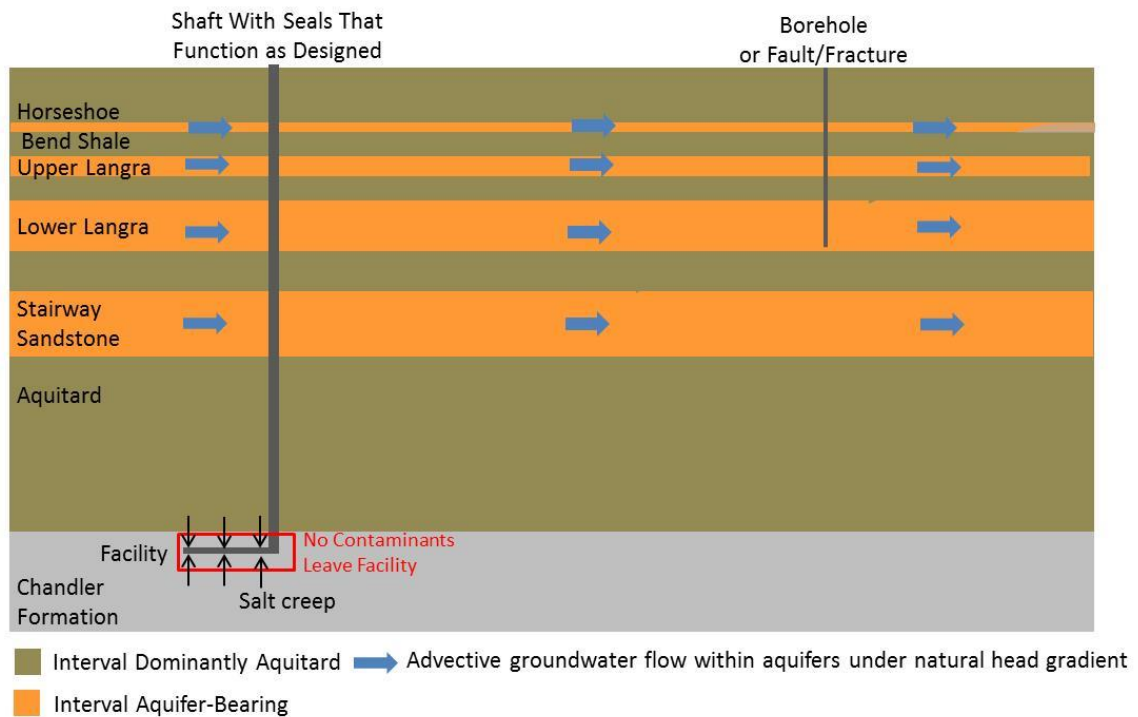


Figure 7-1: Schematic illustration of the EES. No contaminants leave the facility. The indicated "borehole or fault / fracture" represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. The fault / fracture is a feature that has not yet been detected, but which may occur, potentially some distance downstream.

In the EES nothing has occurred in the operational period that could compromise the long-term evolution of the facility (e.g. there has been no cavern roof failure during the operational period that might have produced pathways for contaminant migration post-closure). That is, the facility has been operated as planned, all of the closure engineering (backfilling and seals) has been emplaced to the design specification and the different system components (host rock, overburden etc.) have the expected properties.

The wastes will be emplaced with very little or no free water present. In this scenario the hydraulic backfill will be formulated so that after curing there will be essentially no free water. The limited supply of water means that very little gas is produced by from the wastes, by organic matter degradation or corrosion. The high salinities will also

tend to limit the activity of micro-organisms that could participate in gas-generating reactions.

At closure, the disposal rooms and access tunnels will contain significant voidage (estimated to be 20-40%, Section 4.1 and Section 4.2). This voidage is the result of porosity in the waste and backfill and the fact that 100% filling of cavities may not be achieved. However, while the excavations will be designed to remain stable during operations, it is expected that the salt host rock will creep after closure and compact and fully encapsulate the waste and backfill, eliminating most of the voidage. However, some voidage will remain within the waste, for example between grains that may compose certain wastes, or in the hydraulic backfill, that are sufficiently strong to support the imposed stress. Some voids will also remain as a result of a small proportion of water or gas that may be present; pressurisation of these fluids during creep will result eventually in no further creep being possible (the performance assessment for the WIPP estimated that as much as 20% porosity could be maintained throughout the performance period in that case (USDOE, 2014)). In the EES, the properties of the salt are such that this process does not breach the salt roof of the facility and the impacts of any minor roof falls are eliminated by creep and consolidation of the salt. The timescale on which this creep closure will occur is uncertain as the creep rate for the halite has not been determined. Based on analyses of halite formations that have been considered as hosts for radioactive waste repositories in a number of countries the timescale is likely to be at least several hundred years and possibly several thousand years (NEA, 2007). It is noted that the temperature at disposal depth will increase to about 45°C, from the lower temperature that will have been maintained by ventilation during operations, and this may serve to accelerate the creep process. For this scenario it is assumed that this creep process takes between a few hundred and a thousand years to completion.

The materials used to construct the shaft seals will similarly not be fully compacted at the time of closure and their properties will evolve over a period of time to some degree. Depending on the exact design of the seals, this evolution will involve a combination of compaction and saturation by groundwater. At the end of the process, the seals will achieve their long-term properties. In this scenario the seals have attained their long-term properties on a timescale of a few hundred years.

The CF will be located in a bedded massive halite which does not contain permeable interbeds (ERCOSPLAN, 2013). Such a halite formation is essentially impermeable.

Once the salt has crept to encapsulate the waste and the seals have attained their design properties, the disposal facility has reached its long term stable state. It is not expected to evolve further on the timescales of interest. The seals will be designed to have permeabilities as low as that of the salt and to maintain their integrity for geologically significant periods of time (>1Ma).

The salt formation remains stable, as it has for many millions of years, and no groundwater penetrates the facility. The fact that the Cambrian salt is apparently undisturbed, in spite of c. 520 million years elapsing since it was deposited shows that the CF system would be robust with respect to the climate changes and geological processes that will influence the area of the CF over timescales of millions of years.

The geological setting of the CF within the geologically stable interior of a tectonic plate, far from present dynamic tectonic plate boundaries where there is active deformation, provides further confidence that the CF will not be disturbed by geological processes within any timescale of concern to humans.

In the EES human activities (borehole drilling or mining) do not intrude into the facility in the future.

7.2 EES Scenario Analysis

In order for contaminants to leave the CF three conditions would need to be met:

1. There would need to be a potentially mobile phase (water or gas) that could transport the contaminants.
2. There would need to be a driving force to cause this phase to move.
3. There would need to be a physical pathway from the facility, such as a permeable fault, failed shaft seal, or imperfectly sealed borehole, via which the contaminants, in the mobile carrier phase, could be transported.

In the EES, all these conditions are never met simultaneously during the assessment time frame. Hence there is no way by which the contaminants can be transported out of the facility.

Arguments to support this statement are as follows:

- ▲ **Potential for a mobile phase:** In the EES, the WAC will ensure that at the time of closure the wastes themselves are essentially dry. The hydraulic backfill used in parts of the facility will be designed to ensure that immediately after curing there is very little, if any, free water. The halite itself is not entirely anhydrous, with small quantities of water being trapped in isolated fluid inclusions and potentially brine pockets. However, even though no analyses of water content in the halite exist, data from other halite formations indicates that probably the water content will be $\ll 1$ wt% (see, for example, Weber et al., 2013). Therefore, the quantities of free water that will be contributed to the facility by the salt will be minimal. The paucity of water will severely limit any inorganic or microbially mediated gas-producing reactions, which require water to proceed. In addition, the highly saline character of any small quantity

of water that does exist (owing to the presence of soluble halite) will limit the activity of micro-organisms. Following closure there is no way for water to enter the facility, since the halite of the Chandler Formation is impermeable and the shaft seals will maintain their integrity. Over time, creep of the halite will cause the original walls and roof to converge and reduce the residual voidage in the facility that could be occupied by a mobile phase.

- ▲ **Potential for a driving force:** The halite of the Chandler Formation is impermeable and will therefore effectively isolate the emplaced wastes from natural groundwater head gradients in the more permeable rock formations within the rock sequences above and below the halite. Thus, natural head gradients cannot provide a driving force to move contaminants from the CF. Even if there was a pathway between the CF and the rock formations above the halite (see below for further discussion), the relatively high density of the water within the CF, compared to shallower water, would tend to oppose upwards movement of water. Any free water present in the CF will be saturated with halite, which is highly soluble, and therefore will be substantially denser than the water present within the rocks above the CF. For example, according to URS (2012) the Stairway Sandstone contains water with Total Dissolved Solid (TDS) content of 14,998 mg/L, which implies a density of c. 1015 kg/m³. In contrast water in the Chandler Formation that has dissolved halite to the point of saturation will have a salinity of c. 360,000 mg/L, equivalent to a density of c. 1,360 kg/m³. Creep of the halite will provide a driving force, but this will cease once the residual voidage in the facility has decreased to a level that the wastes and backfill can support the halite. The timescale over which there will be a driving force caused by creep is presently unknown. However, based on analyses for radioactive waste facilities in halite formations elsewhere in the world, this period is likely to be at least several hundred years and may be several 1000 years (NEA, 2007). Chandler will be geotechnically designed to encourage creep to take place as soon as is possible without compromising operational safety. The very limited ability of the wastes to generate gas (for the reasons explained above) will ensure that any gas pressurisation that occurs will be minimal. The gas pressure will increase in response to creep of the salt, but the residual pore space will be sufficient to accommodate the small amount of gas.

- ▲ **Potential for pathways:** In the EES, the roof, walls and floor of the CF are undisturbed at the time of closure (i.e. no rock-falls in the operational period have compromised the integrity of the roof and walls). The halite will provide an excellent seal, which is of extremely low permeability owing to the lack of connected porosity and its capability for self-sealing through creep over time following any brittle failure. The ability of halite to maintain its integrity over very many millions of years is indicated by the fact that halite forms the

caprock to many hydrocarbon reservoirs throughout the world (e.g. in the North Sea, offshore Europe; Capture Power and National Grid, 2016). Had halite not been impermeable in these areas, hydrocarbons, which are less dense than formation water, would have been able to leak from the reservoirs and the hydrocarbon resource would not have been preserved. None of the available data, both from boreholes (Endeavour Geophysics, 2016; Douglas Partners, 2016) and seismic surveys (RPS, 2013) show evidence for faults through the halite. Even if undetected faults occur, the self-sealing properties of the halite would mean that they would not conduct water or gas. The only engineered structures that penetrate the Chandler Formation in the EES are the shafts. However, these will be sealed using a combination of materials that are proven to be capable of maintaining their integrity in the long-term. While the designs of the shaft seals have yet to be finalized, detailed analyses of shaft seals in similar kinds of facilities in other countries, supported by extensive research programmes, provides confidence that shaft seals can be designed to have properties similar to or better than the rocks in which they are emplaced and to maintain their integrity effectively indefinitely (e.g. USDOE, 2009; Quintessa Limited, 2011). Hence, in the EES the shafts will not form a pathway via which contaminants can leave the CF.

7.3 EES Assessed Risks

The EES is by far the most likely scenario to occur. It is highly improbable that natural processes would compromise the integrity of the facility even over timescales of many millions of years. This conclusion follows from the very stable geological setting of the CF, the abundant evidence from analogous settings (e.g. hydrocarbon reservoirs with halite caprocks that have not been breached even over many tens or hundreds of millions of years) and results from research into engineered materials throughout the world.

As the facility will maintain its integrity in this scenario, no contaminants can reach and interact with any of the identified receptors. Hence, the environmental impacts from the EES will be essentially zero.

Since the EES will result in no impacts to identified receptors, this scenario results in no significant risk.

8 Alternative Evolution Scenarios (AES)

8.1 Nature of AES

It is emphasized that the AES are not expected to occur; they are low-probability scenarios which are presented as a basis for analysing the consequences of the CF system not behaving as designed. Very generally, the more extreme (higher impact) a scenario is, the lower its probability. Certain scenarios that would have very extreme impacts are not credible, but their impacts are nevertheless assessed as they provide a basis against which to judge the impacts of more plausible scenarios.

8.2 Summary of AES

Transport of contaminated groundwater to the biosphere would require penetration of, or damage to, the host rock and overburden, consisting of the upper part of the Chandler Formation and the rock formations above it.

There are three ways in which pathways from the CF and into the overburden might develop:

1. the halite above the facility might contain a small volume of connected porosity, for example due to the slight disturbance to the halite during excavation;
2. a roof collapse that allows a pathway to develop between the waste and the part of the Chandler formation above the halite in which the CF is constructed and the overlying Jay Creek limestone;
3. failure of seals in one or both shafts.

These different, albeit remote, possibilities have been represented by a set of AES that are summarized in Table 8-1. These scenarios are described in more detail in subsequent sub-sections of the report.

Table 8-1: Summary of scenarios considered.

Scenario	Variant	Title	Description	How Assessed
AES1	None	Connected porosity through the halite roof of the facility	This scenario is the same as the EES, except that: • There is 1-2% connected porosity through the halite in the roof of the CF, providing a pathway to the formations above the halite. • The facility is water-saturated.	Numerical calculation with supporting qualitative arguments
AES2	a	Collapsed roof in the Operational Phase, combined with contaminant transport through borehole and aquifer pathways	The roof of the CF has collapsed during the operational phase (and no wastes have been retrieved) and subsequently the CF has saturated with groundwater. The collapsed roof provides a pathway for the migration of contaminated water from the CF to the overlying Jay Creek Limestone through which the water migrates by diffusion to the Stairway Sandstone Aquifer. From there, contaminated water can migrate to the biosphere via aquifer pathways operating in concert with borehole and / or fault pathways.	Qualitative arguments
	b	Collapsed roof in the Post-closure Phase, combined with contaminant transport through borehole and aquifer pathways	The same as for AES2a, except that roof collapses following closure of the facility.	Numerical calculation with supporting qualitative arguments

Scenario	Variant	Title	Description	How Assessed
AES3	None	Impaired shaft seal	The shaft seal does not perform as well as intended and is more permeable than the aquicludes in the rock sequence it seals. Water in-flows to the CF down the shaft and then transports contaminants via the impaired shaft seals, to the overburden aquifers. Transport of contaminated water is driven initially by by creep of the salt and, once creep is finished, contaminants continue to migrate by diffusion.	Numerical calculation with supporting qualitative arguments
AES4	None	Accidental human intrusion	Humans unintentionally drill into the CF.	Qualitative arguments

The groundwater in the aquifers that overlie the CF is thought to discharge several hundred kilometres away, such that lateral transport rates are of the order of a centimetre per year (Graham Ride, written communication, 29th February 2016). Consequently, the time for water to be transported between the CF and a natural discharge location via these aquifers would be millions of years, which is beyond the timescale of interest. Furthermore, over these extremely long timescales and transport pathways, there would be substantial dispersion of any contaminants that would progressively lower their concentrations with increasing distance from the CF (see Section 8.4 for analysis). For these reasons, none of the scenarios consider exposure of potential receptors at natural discharge locations.

8.3 AES Descriptions

8.3.1 AES1 Connected Porosity Through the Halite

This scenario is the same as the EES, except that:

- ▲ there is a very small volume of connected porosity through the halite in the roof of the CF, which allows transport of contaminants by diffusion in water;

- ▲ the CF contains free water which may mobilize contaminants from the waste and transport them through the connected porosity in the halite roof.

This scenario is illustrated schematically in Figure 8-1.

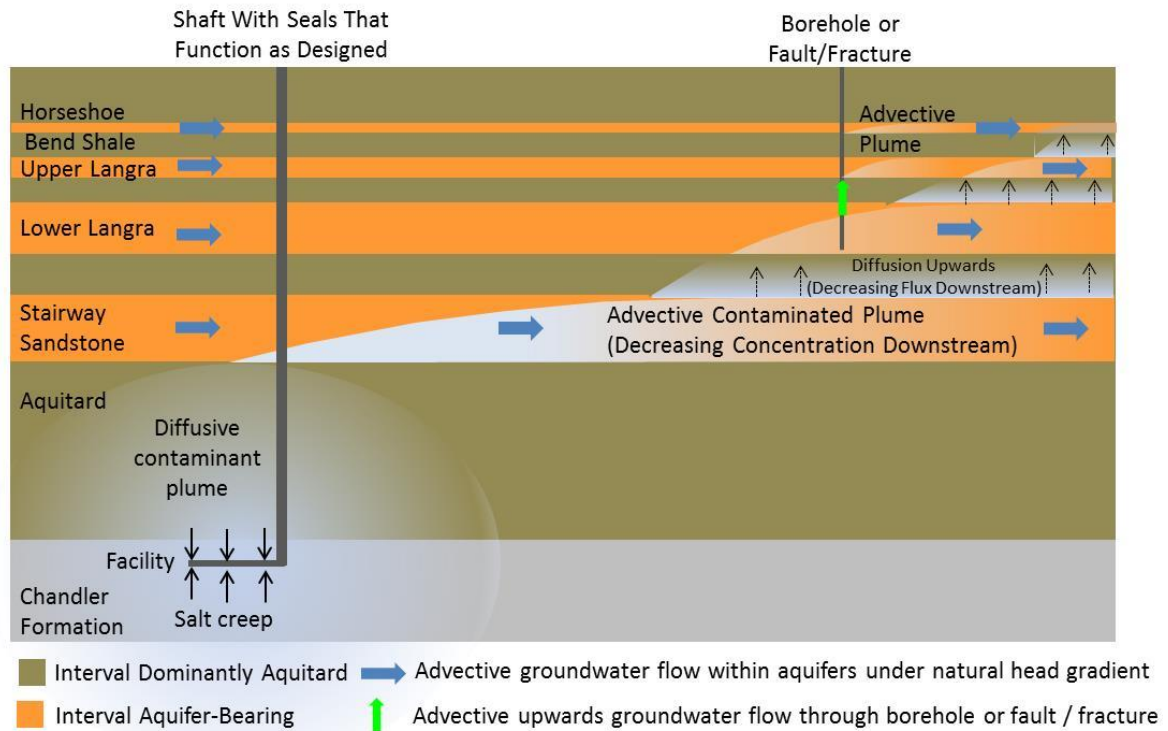


Figure 8-1: Schematic illustration of AES1. Contaminants leave the facility via the small (1-2%) amount of connected porosity in the roof. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. Alternatively this pathway could be a fault / fracture that has not yet been detected, but which may occur, potentially some distance downstream. Note that there would also be downwards diffusion of contaminants from any contaminated aquifer downstream, but this is not shown as upwards diffusion is the primary risk concern.

Beauheim and Robert (2002) report that the undisturbed halite-dominated host rock of the WIPP has connected porosity close to zero, which implies diffusive fluxes would be close to zero. Weber et al. (2013) report that a deep halite deposit at Gorleben in Germany has a water content of <0.02 wt%, which implies porosity of <0.03 (taking into account the density of the halite and water). However, this water is predominantly in unconnected porosity (fluid inclusions) within the halite and therefore is not mobile. Cardenas et al. (1999) report that at the WIPP the porosity of halite remote from excavations is up to 0.027, whereas the damaged zone around the excavations has a porosity of up to 0.04. Their evidence supports the conclusion that connected porosity in the halite would self-seal due to creep following closure. Hence, the highest porosity of 0.04 would not be sustained in the long-term. Consequently, this scenario considers

connected porosity through the roof of the facility of no more than 0.02. Diffusion through such a small degree of connected porosity would be extremely slow (e.g. Winterle et al., 2012; see Section 8.4.5 for quantitative analysis).

In this scenario the CF is water-saturated because of creep reducing the void space in combination with one or more of:

- ▲ emplaced wastes containing more free water than planned (for example because drying processes are less effective than planned);
- ▲ the hydraulic backfill contains more water than planned, such that it contains free water after curing;
- ▲ water entering the facility through the connected pore space in the halite that forms the roof;
- ▲ the halite containing undetected brine pockets.

Contaminated water travels through the connected porosity in the halite and then through the shallower parts of the Chandler Formation and the overlying Jay Creek Limestone until it encounters an aquifer within the Stairway Sandstone Formation (Figure 8-1). There, the contaminants are diluted by the groundwater that is flowing slowly and almost horizontally within the aquifer under the influence of the natural head gradient. This flow transports the contaminants laterally, accompanied by further dilution due to dispersion within the aquifer. Thus, the concentrations of contaminants within the aquifer decrease progressively with increasing distance from the facility (Figure 8-1).

In this scenario, the only way in which the contaminants that are released from the CF can impact upon shallower aquifers and other receptors is if they encounter a pathway that can transport them upwards from the Stairway Sandstone. The only plausible pathways are:

- ▲ direct abstraction of water from the Stairway Sandstone via a borehole;
- ▲ upwards migration of contaminants through such a borehole that is no longer actively exploited, but that has been left in an imperfectly sealed state between the Stairway Sandstone and a shallower receptor;
- ▲ upwards migration of contaminants from the Stairway Sandstone to a receptor via a transmissive fault;
- ▲ upwards migration of contaminants through a combination of boreholes (including ones that are actively exploited and ones that are no longer exploited, but have been left in an imperfectly sealed state) and aquifers shallower than the Stairway Sandstone;
- ▲ upwards migration of contaminants through a combination of faults and aquifers shallower than the Stairway Sandstone;
- ▲ diffusion upwards through aquitards.

It should be noted that no boreholes presently penetrate the Stairway Sandstone within the footprint of the CF, but the scenario considers:

- ▲ the possibility that contaminated water flowing in the Stairway Sandstone may encounter a borehole at some distance away from the CF in the future; and
- ▲ the possibility that new boreholes may be drilled, whether in the vicinity of the facility or remote from it, downstream, at some point in the future.

Similarly, it should be noted that no potentially transmissive fault pathways have been identified within the vicinity of the CF. There is also no reported natural discharge of deep water to the ground surface via faults outside the facility or downgradient from the facility. However, the scenario considers the possibility that presently unidentified transmissive faults may occur at some point downstream, remote from the facility. As in the EES (Section 7.1), the higher density of the saline groundwater at depth, compared to the lower density of the shallower, fresher groundwater, would tend to act against upwards movement of deep water.

8.3.2 AES2a Collapsed Roof in Operational Phase

In this AES there has been an unexpected roof fall during the Operational Phase, which has produced a pathway through the halite roof of the facility to shallower formations (**Error! Reference source not found.**).

The size of the pathway produced would depend on the degree to which the cavern had been filled at the time of rock failure. The greater the void space in the cavern into which the collapse occurs, the further will the collapse column would extend upwards from the roof. A collapse into an unfilled cavern would be most likely to produce a pathway through the halite and into the overlying rock formations.

In this scenario, the roof collapse is not mitigated during the operational phase and therefore the pathway produced by collapse persists into the post-closure period. At some point following the collapse, in the post-closure period, the scenario envisages that the facility saturates with groundwater. It is extremely unlikely that any significant water inflow would occur during the Operational Phase (see the Operational Phase assessment, Metcalfe et al., 2016). Sudden, rapid inflows are implausible and small inflows would be recognized and mitigating actions taken before significant water volumes had entered the facility.

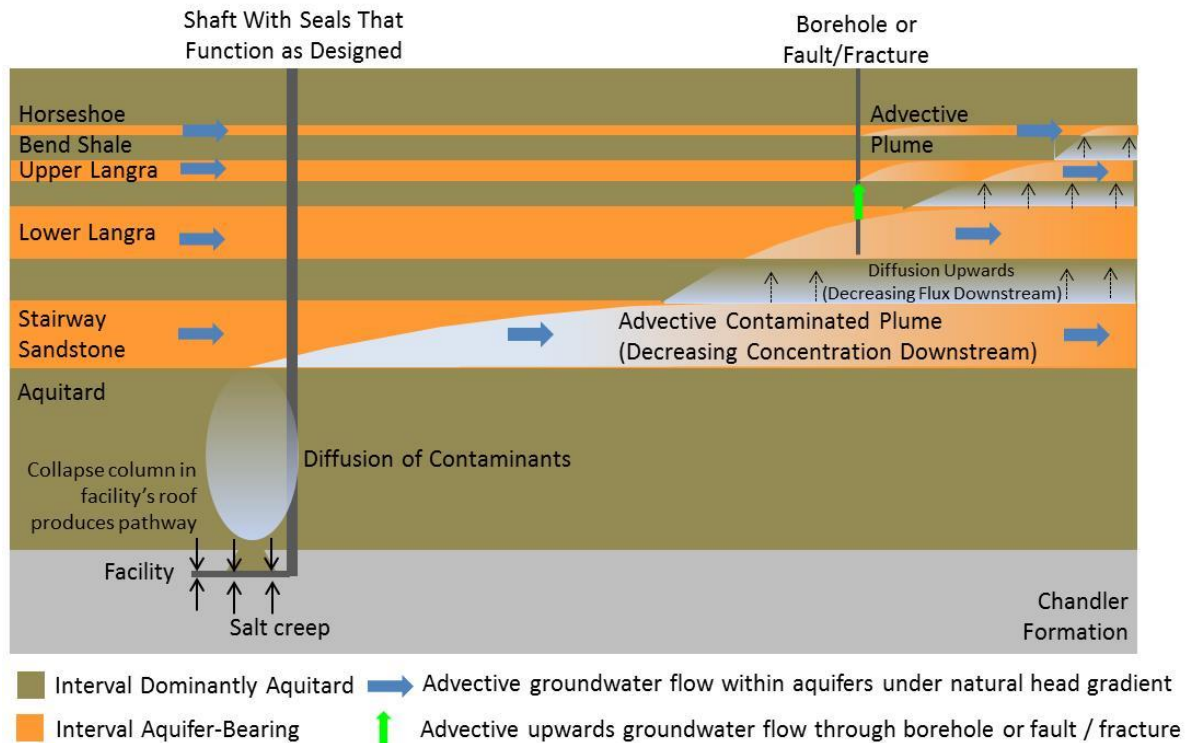


Figure 8-2: Schematic illustration of AES2. Contaminants leave the facility via a collapsed roof. The indicated “borehole or fault/ fracture” represents a borehole that may exist some distance downstream from the facility and/ or that may be drilled at some time in the future. Alternatively this pathway could be a fault/ fracture that has not yet been detected, but which may occur, potentially some distance downstream.

Water would need to enter the CF through the pathway produced by the collapse, or else via an imperfect shaft seal. After flowing into the CF, the water becomes contaminated by contact with the waste. Subsequent creep of the salt provides a driving force that causes the water to leave the CF via the collapsed roof. The length of time over which contaminated water can be expelled by creep is the minimum of:

- ▲ the time between the ingress of water and the cessation of creep; and
- ▲ the time between the ingress of water and the pathway through the halite self-sealing through creep (assuming that the collapse is not of such a large magnitude as to effectively prevent self-sealing).

Assuming that the pathway formed by the collapse column does not seal by creep first, after cessation of creep contaminated water would be able to leave the CF only by diffusion through the collapse zone.

Were this scenario to occur, then after leaving the CF contaminants would migrate through the shallower formations through the same kinds of pathways as those described for AES1.

8.3.3 AES2b Collapsed Roof in Post-closure Phase

This scenario is essentially the same as AES2a, except that the roof collapse occurs in the post-closure phase. For any such collapse to occur the waste and / or backfill would need to be compressible and / or filling of the cavern by waste and backfill would need to be incomplete. If these conditions are not met, then the roof of the cavern would be supported by the cavern's contents and collapse could not occur. In any case, in AES2b there is a lower degree of void space into which roof collapse could occur than in any partially filled cavern in AES2a.

8.3.4 AES3 Impaired Shaft Seal Scenario

In AES3 the shaft sealing system does not function as designed owing to:

- ▲ seals being improperly implemented; and / or
- ▲ because seals degrade over time.

This scenario is illustrated schematically in Figure 8-3.

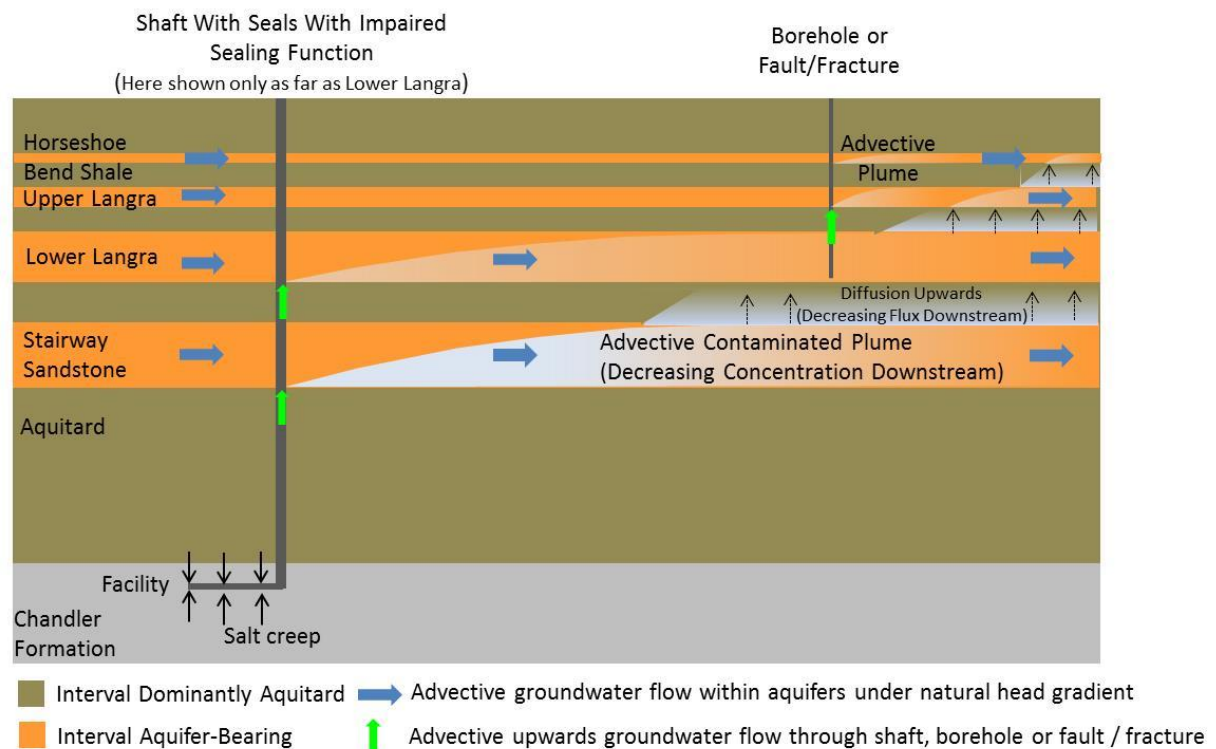


Figure 8-3: Schematic illustration of AES3. Contaminants leave the facility via a shaft with impaired seals. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. Alternatively this pathway could be a fault / fracture that has not yet been detected, but which may occur, potentially some distance downstream.

The impaired function of the sealing system allows groundwater to flow from the aquifers in the rock sequence above the Chandler Formation into the CF before creep can effectively remove the reducible residual voidage within the facility. Thereafter, the water becomes contaminated by interacting with the waste and is driven back up the shaft, through the impaired seals, by the progressive creep of the halite.

In the most extreme situation, the shaft sealing system has higher permeability than designed throughout the length of the shaft, thereby allowing the contaminated water to be transported along the shaft from the CF to the ground surface. The upper limit on transport flux for any given driving force would be one where the shaft seals offer no resistance to water and contaminant transport. However, this situation is not credible because the materials used in the shaft sealing system will contain a number of highly durable materials and it is inconceivable that these could be completely removed by any natural process that would not also remove the surrounding rocks (which will not occur on relevant timescales owing to the very stable geological setting of the CF). While the shaft seal design has not been finalized, detailed assessments of other underground waste facilities (e.g. the WIPP in New Mexico, U.S.A (USDOE, 2009) and the DGR planned for construction at Bruce in Ontario, Canada (Quintessa et al., 2011)) have demonstrated that it is possible to construct shaft seals that will maintain their functions for geologically significant periods of time ($>>1$ Ma).

Some of the contaminants would be lost from the impaired shaft seals where they cross aquifers through which groundwater is flowing sub-horizontally under the natural groundwater head gradient. This naturally flowing groundwater would tend to transport some of the contaminated water from the shaft seals, downstream along the aquifer. Additionally, groundwater that enters the shaft seals from an aquifer would tend to dilute the contaminants that remain in the shaft seals. For these reasons, the concentrations of contaminants will decrease as they are transported upwards in the impaired shaft seals (Figure 8-2).

A less extreme (and more plausible) situation is one in which the shaft sealing system is impaired for only part of its length, upwards from the CF to the level of the Stairway Sandstone. In this case, all the contaminated water would be transported downstream in the Stairway Sandstone aquifer by groundwater flowing naturally within it.

If the impaired shaft sealing system were to extend to shallower depths than the Stairway Sandstone, but not all the way to the ground surface, only a proportion of the contaminated water would be transported to shallower levels past each aquifer that is intersected by the shaft (Figure 8-2). Where an impaired shaft seal crosses an aquifer some of the contaminated water would be diluted by groundwater flowing naturally within the aquifer. Additionally, such naturally flowing groundwater would tend to mobilize the contaminated water downstream along the aquifer.

Any contaminated water that enters an aquifer in this scenario would only be able to reach shallower levels via:

- ▲ direct abstraction of water from the aquifer via a borehole;
- ▲ upwards migration of contaminants through such a borehole that is no longer actively exploited, but that has been left in an imperfectly sealed state between the aquifer and a shallower receptor;
- ▲ upwards migration of contaminants from the aquifer to a receptor via a transmissive fault;
- ▲ upwards migration of contaminants through a combination of boreholes (including ones that are actively exploited and ones that are no longer exploited, but have been left in an imperfectly sealed state) and other aquifers at shallower depths;
- ▲ upwards migration of contaminants through a combination of faults and aquifers at shallower depths; and
- ▲ diffusion upwards through aquitards.

It should be noted that the scenario considers:

- ▲ the possibility that contaminated water flowing in an aquifer may encounter a borehole at some distance away from the CF in the future; and
- ▲ the possibility that new boreholes may be drilled, whether in the vicinity of the facility or remote from it, downstream, at some point in the future.

Similarly, it should be noted that no potentially transmissive fault pathways have been identified within the vicinity of the CF. There is also no reported natural discharge of deep water to the ground surface via faults outside the facility or downgradient from the facility. However, the scenario considers the possibility that presently unidentified transmissive faults may occur at some point downstream, remote from the facility.

8.3.5 AES4 Accidental Human Intrusion Scenario

This scenario considers inadvertent human intrusion at some time in the future, after knowledge of the location and / or dimensions of the CF have been lost. Deliberate human intrusion it is not considered, as is common practice with such assessments (NEA, 2001), because the people undertaking the intrusion would be responsible for assessing the associated risks.

This scenario is illustrated schematically in Figure 8-4.

It is impossible to predict the evolution of society into the future and therefore regulators typically require the assessment of the consequences of accidental human intrusion to consider a scenario based on current day practices and technology. Given this basis, inadvertent human intrusion would consist of drilling a borehole into the

CF. The scenario does not consider excavating a mine into the facility on the basis that exploratory boreholes would have previously identified contaminated material leading to any mining plans being abandoned. Were a decision to be taken to excavate a mine even if exploratory boreholes had identified the CF, then mine excavation would constitute deliberate intrusion, which is outside the scope of this AES.

In the course of inadvertent penetration of the facility by boreholes, material from the CF would be brought surface. This material could include core/cuttings from boreholes, contaminated groundwater samples, and contaminated drilling fluid. Such material would be handled and, although personal protective equipment (PPE) would be used, there is the potential for contamination of surfaces by dust etc., which could

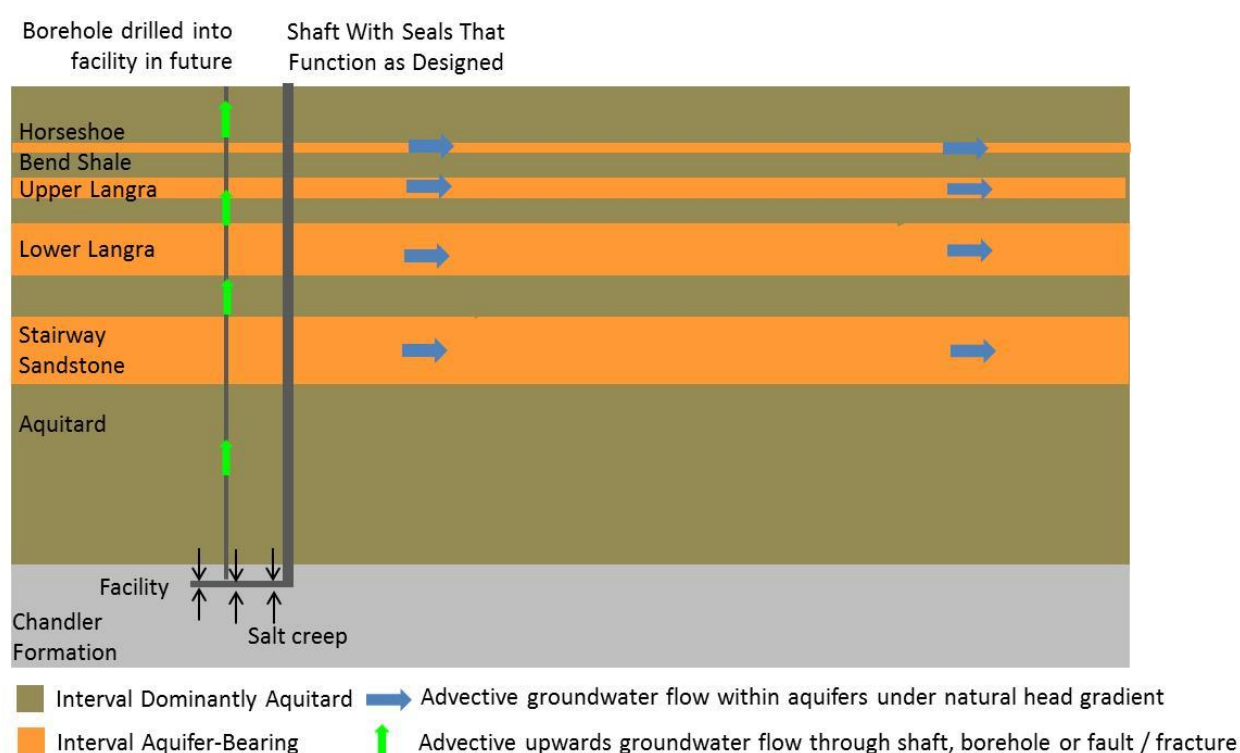


Figure 8-4: Schematic illustration of AES4, the accidental human intrusion scenario. Contaminants leave the facility via a borehole drilled accidentally at some time in the future.

result in ingestion of contaminants. Drilling fluid would be treated before discharge, but there is the potential that the treatment process would not remove the contaminants from the waste prior to discharge as they were not expected or that other equipment becomes contaminated. The scenario envisages that, once a contaminated sample had been recovered, additional precautions would be put in place to prevent contamination of workers and adverse environmental impacts.

If the core penetrated NORM waste, it would also be necessary to calculate the dose that the workers could be exposed to prior to realising that the core was radioactive

and taking appropriate precautions. The likely doses would be bounded by the operational doses incurred when processing and emplacing the NORM wastes so can be taken directly from that assessment.

8.4 Quantitative Assessment of AES

8.4.1 Nature of Assessment Models

Mathematical models have been constructed to analyse the AES. These models are “assessment level” models, which means that they are designed to represent the key aspects of the various scenarios that influence impacts. Such models are commonly developed in safety assessments (e.g. Robinson and Hooker, 2002; Quintessa et al., 2011; USDOE, 2009). An important goal of assessment models is to place limits (bounds) on impacts for a given set of assumptions. These models are not, therefore, predictive models. They are not intended to represent *all* the processes within an analysed system and all the couplings between these processes.

8.4.2 AMBER Quantitative Assessment Tool

Quantitative assessments of the AES described in Section 8.3 were undertaken using the mathematical modelling software AMBER 6.0, supported by separate scoping calculations. This software allows users to build their own dynamic compartment models to simulate the migration, degradation and fate of contaminants in environmental and engineered systems (Quintessa, 2015).

The software package is able to represent the four key hydrogeological parameters that control contaminant migration that are highlighted in the NT EPA’s siting guideline for solid waste disposal sites (NT EPA, 2013):

- ▲ hydraulic conductivity, K
- ▲ effective porosity;
- ▲ hydraulic gradient; and
- ▲ soil/rock/leachate species interaction as given by the Distribution Coefficient, K_d .

AMBER has been widely used in over 30 countries for safety assessments concerned with the management of a variety of wastes. It was employed in the long-term safety assessment of the presently operating Minosus underground disposal facility for hazardous waste, which is constructed in a halite formation in Cheshire, England (Robinson and Hooker, 2002).

The quantitative models are designed to inform judgements about risks in Section 9, rather than to output risk estimates directly. This approach is appropriate, given the uncertainties in the nature of the wastes, the fact that the design of the CF is not finalized and uncertainties about the hydrogeology of the area around the CF.

8.4.3 Assessment Model Descriptions

Representation of Scenarios

The assessment models are designed to represent important aspects of the AES described in Section 8.3 in order to gain insights into the potential magnitudes of the impacts from these scenarios, in the unexpected even that they are realized. However, within each scenario a great many variants can be envisaged, representing alternative conceptualisations and parameterizations of the different scenario components. It is not feasible, or necessary, for the assessment models to simulate all these different conceptualisations and parameterizations. Instead, the goal is to help place bounds on the impacts that could arise from the different scenarios. In other words the aim is to determine the highest contaminant concentrations that are plausible in any given location for a given set of assumptions. To achieve this goal a small number of model realizations have been run to calculate concentrations of contaminants in different locations for specified pessimistic assumptions. Where outputs from a model representing one scenario can be used to estimate limits on concentrations for another scenario, then a separate model realization has not been run for this second scenario. For example, if a borehole were to be drilled into the facility in the distant future and then imperfectly abandoned, the resulting effect would not be worse than the case where the shaft has an impaired seal (AES3). Thus, the calculation for the impaired seal also gives insights into the impact that might result from such an imperfectly sealed borehole.

System Representation

The model represents the following system components are:

- ▲ the facility, represented by a single compartment;
- ▲ salt above and below the facility;
- ▲ the aquitards between the salt and a specified aquifer;

- ▲ an aquifer, having 5 compartments corresponding to a Peclet number¹¹ of 10, which can have a specified:
 - depth to represent an aquifer in the Stairway Sandstone, Lower Langra, Upper Langra or Horseshoe Bend Shale; and
 - length to allow sampling of concentration at a chosen point downstream of the shaft;
- ▲ a shaft connecting the facility to a specified aquifer, which has 5 compartments corresponding to dispersion associated with a Peclet number of 10;
- ▲ connection between the facility and a specified aquifer, via salt of fixed thickness and an aquitard of variable thickness (depending upon which aquifer is modelled), within which transport is via diffusion only.
- ▲ connection between the facility and a specified aquifer via the shaft, where transport is all via advection during the period when creep occurs, and by diffusion thereafter, the length of the pathway depending on which aquifer has been selected.

The user selectable options/parameter values that are relevant for the facility are:

- ▲ contaminated water travel lengths, depending upon which aquifer is modelled;
- ▲ diffusion or advection, according to which leakage path is used;
- ▲ distribution coefficient (K_d) representing sorption;
- ▲ porosities of the different rock formations;
- ▲ release model (solubility-controlled or instantaneous release of a notional 1t of inventory).

The compartmental representation of the scenarios AES1, AES2 and AES3 is shown in Figure 8-5 and Figure 8-6.

¹¹ A Peclet number is a dimensionless quantity, which is the ratio advective transport rate / diffusive transport rate

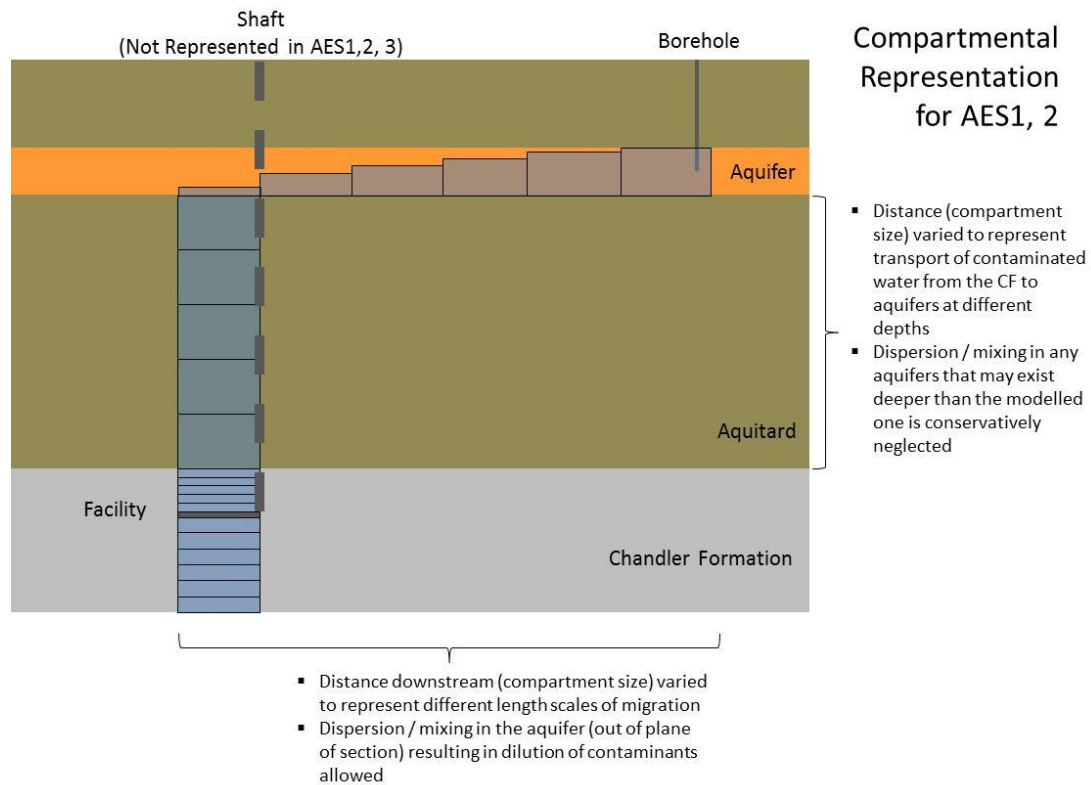


Figure 8-5: Schematic illustration of the compartmental representation in AMBER of the scenarios AES1 and AES2.

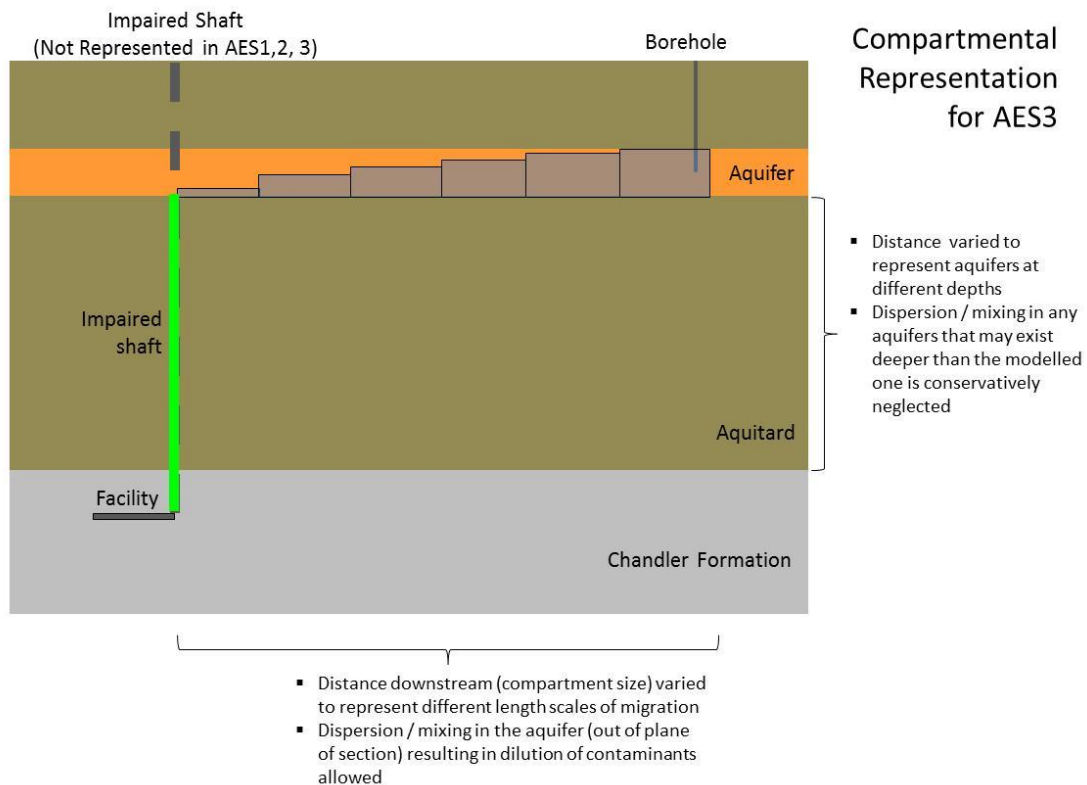


Figure 8-6: Schematic illustration of the compartmental representation in AMBER of the scenario AES3.

Stratigraphy

In the model contaminants are specified to discharge into the lowermost 10 m thickness of the aquifer. That is, at the location of discharge, each modelled aquifer is thinner than the formation within which it occurs (Stairway Sandstone, Lower Langra, Upper Langra or Horseshoe Bend Shale). Thereafter, vertical dispersion occurs along the flow path until the contaminant plume reaches the full thickness of the aquifer. This approach is pessimistic with respect to contaminants reaching an aquifer from the CF, because the transport distance is minimized. However, the approach is not conservative with respect to lateral transport since the vertical dispersion within a given formation (and hence dilution) is maximized. In practice, each formation is known to be heterogeneous and aquifers within them are heterogeneously distributed (Graham Ride, written communication, 29th February 2016). The nature and significance of this heterogeneity are presently areas of uncertainty.

Representation of the CF

The CF is represented as a single homogeneous compartment that has an average porosity, at closure, of 30% (assuming the wastes are half solid wastes with 40% porosity and half hydraulically emplaced wastes with porosity of 20%).

The volume of the wastes is calculated assuming that there are 128 rooms containing wastes emplaced in solid form and 128 rooms containing wastes emplaced in hydraulic backfill. Half the 256 rooms have a width of 15 m and half of width 10 m. All are 250 m long and 6 m high.

Over a defined period, t_{Creep} (specified to be 1000 y) creep is specified to close half of the porosity in the rooms. However, the creep is modelled so that 50% of the lost void is closed after 100 years, 75% (cumulative) after 250 years and the remaining 25% between 300 and 1,000 years. For the case that considers the release via the shaft, this defines the volumetric flow rate through the shaft (Q_{Creep} m³/y). For the geometrical assumptions described above this corresponds to an average flow rate of 360 m³/y if the shaft does not restrict flow. However, given that even in the impaired shaft seal scenario (AES3) there is always some shaft seal material present (albeit with impaired performance), in practice the shaft would resist upwards flow along it. Consequently, this average flow rate is likely to be very pessimistic. As an illustration, if the impaired shaft seals actually had a hydraulic conductivity of 1×10^{-9} m/s flow would be severely restricted and < 1 m³/y would flow up the shaft. In this case it would take 800,000 years to expel all the water from the facility.

Specific contaminants are not modelled explicitly because, while a plausible waste inventory has been specified (Section 4.2.2) the chemical composition of each kind of

waste that might be emplaced in the facility is unknown. Hence an inventory of each contaminant present cannot be calculated reliably. Additionally, the chemical forms of the various contaminants are uncertain. For these reasons, the assessment models used two approaches to calculate concentrations of contaminants in the facility:

- ▲ concentrations of contaminants in different parts of the CF / overburden system when the concentrations of contaminants in the facility are assumed to be limited by solubility; and
- ▲ concentrations of contaminants in different parts of the CF/overburden system when a notional 10^6 g (1 tonne) inventory of a contaminant in the facility is specified.

In the first approach the inventory is unlimited. Hence, if there is a continuous aqueous phase, and if the flow regime is specified to be constant in the model, then given long enough a contaminant will leave the CF and attain a constant concentration at any location in the overburden. This concentration will be lower than the initial concentration in the CF. The precise decrease in concentration will be a function of:

- ▲ the distance between the CF and the particular location of interest; and
- ▲ dispersion and dilution of the contaminant as water originating in the CF mixes with uncontaminated groundwater along the flow path.

In the model the eventual constant concentration attained at any location will be determined by a dynamic equilibrium between the rates at which contaminants are supplied to and removed from the location by the flowing groundwater.

Generally, the concentration of a contaminant will decrease with increasing distance from the CF along a flow path.

A difficulty in applying this approach is that the solubilities of the different contaminants are highly uncertain because:

- ▲ potential solubility-controlling phases are uncertain; and
- ▲ thermodynamic data appropriate for calculating solubilities in the very high-salinity (halite-saturated) solutions that will occur are unavailable for relevant contaminants.

However, scoping calculations using Geochemist's Workbench (Bethke, 1996) and the "thermoddem" database (`gwb_thermoddem_lvl2_no-org_11dec14.dat`, <http://thermoddem.brgm.fr/>) suggest that solubilities would likely lie within the range 10^{-2} mol/L to 10^{-5} mol/L, depending upon the contaminant. Therefore, for each conceptual model and set of specified transport properties, AMBER calculations were undertaken for solubilities of 10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L.

In the second approach to specifying concentrations of contaminants in the facility, the entire inventory of any contaminant is pessimistically assumed to enter the aqueous phase, and hence be mobile, instantaneously. In this case, only the barrier functions of

the geosphere and engineered barriers in the shaft, combined with the dilution effect of groundwater flowing through the shallower geosphere, limit the concentrations of contaminants in the overburden. However, because the inventory is finite, given long enough, ultimately it will be exhausted. Thus, unlike the outputs from AMBER simulations in which concentrations are solubility-controlled, the outputs from AMBER simulations with a specified 10^6 g inventory have a peak in contaminant concentrations in the overburden. The time at which this peak is calculated to occur informs an assessment of the time of peak risk.

The specified nominal inventory of 1×10^6 g for each contaminant allows easy scaling of the results to any actual contaminant inventory that it is proposed to emplace in the CF. The approach therefore can be used to help support the specification of WAC.

Diffusive Release Through Salt

In the AMBER model diffusion occurs through the halite, both upwards and downwards. The processes and characteristics of the rock are assumed to be isotropic within the salt, so only the upwards path is described below. The model incorporates a mirror image of the compartments and transport processes in the downward direction. The geometry of the system is such that there will be much less diffusion through the sides of the CF so this aspect is not represented in order to simplify the model.

Releases from the waste and through the salt are represented with a compartment-model representation of diffusion. This involves both forwards and backwards transfers between each compartment that simulate diffusion by “mixing” between the compartments at a defined rate.

The transfer rate between each compartment λ_{diff} (y^{-1}) is given by:

$$\lambda_{diff} = \frac{d_{eff} A_x}{V \theta R \Delta} \quad (1)$$

where:

- d_{eff} is the effective diffusion coefficient in the material (m^2/s);
- A_x is the interface area between the two compartments (m^2);
- V is the volume of the compartment from which the transfer originates, the “donor” (m^3);
- θ is the porosity of the donor compartment (-)
- R is a retardation factor to simulate the sorption of contaminants to solid phases (-)
- Δ is the distance between the mid-points of the two compartments (m).

The retardation factor is related to the contaminant-specific sorption coefficient for the material, K_d (m^3/kg):

$$R = 1 + \frac{\rho K_d}{\theta} \quad (2)$$

where:

$$K_d = \frac{\text{Sorbed concentration of the element of the sorbate of interest in mol kg}^{-1}}{\text{Aqueous concentration of the sorbate in mol m}^{-3}} \quad (3)$$

and ρ (kg/m^3) is the dry bulk density of the material.

In the model, a reference value of K_d is taken to be $0 \text{ m}^3/\text{kg}$, corresponding to no sorption occurring. In order to test the sensitivity of the calculated concentrations in overburden to K_d a range of values are also considered, between $10^{-6} \text{ m}^3/\text{kg}$ and $100 \text{ m}^3/\text{kg}$.

The region of salt through which diffusion occurs is represented with five compartments above the CF and five below. Discretisation in this way is necessary to adequately represent the diffusive process. It is necessary to increase the thickness of each compartment progressively; sufficient numerical accuracy is obtained if each compartment is a factor of three larger than the preceding compartment. Thus, for a system of N compartments, the m -th compartment has a thickness of:

$$L_m = \frac{L_T}{\sum_{i=0}^{N-1} 3^i} 3^{m-1} \quad (4)$$

where L_T (m) is the total thickness of the salt above the CF.

Above the salt lies the Jay Creek Limestone. The groundwater in this formation is assumed to continue to diffuse until an aquifer is met (assumed to be in the Stairway Sandstone). Transport in the aquifer is represented with an advective transfer λ_{adv} (y^{-1}) from the compartment representing the initial layer of limestone:

$$\lambda_{adv} = \frac{Q_{adv}}{V \theta R} \quad (5)$$

where Q_{adv} (m^3/y) is the volumetric flow of groundwater through the compartment. The compartment corresponds to the footprint of the CF or to the shaft width, depending upon the model. In the former case it is specified to be 1000 m wide, and the plume is assumed to have a maximum depth that is the same as the aquifer thickness, namely 10 m. The groundwater velocity is assumed to be $0.01 \text{ m}/\text{y}$.

Table 8-2: Parameter Assumptions for the Diffusion Release.

Description	Parameter	Value
Cross-sectional excavated disposal area of the rooms of the CF	A_X	$8 \times 10^5 \text{ m}^2$
Height of the CF	L	6 m
Effective diffusion coefficient of salt	d_{eff}	$4.2 \times 10^{-13} \text{ m}^2/\text{s}$
Thickness of salt above the CF	L_{salt}	20 m
Thickness of salt compartments 1 – 5	L	See Eq (4)
Density of salt	ρ	$2220 \text{ kg}/\text{m}^3$
Density of Jay Creek Limestone	ρ	$2500 \text{ kg}/\text{m}^3$
Porosity of salt	θ	0.02
Porosity of Jay Creek Limestone	θ	0.05
Sorption coefficient	K_d	0 (10^{-6} – 100) m^3/kg

Note: The reference value for K_d is $0 \text{ m}^3/\text{kg}$ but the indicated range is also considered.

Advective Release via a Shaft with Impaired / Failed Seal

Implicit in the advective release calculations is the assumption that the shaft has not been backfilled and sealed sufficiently and therefore permits release of contaminants from the CF. The pore space in the CF is pessimistically taken to be 75% water-saturated at closure. In reality, this the degree of water saturation could be less than this, since the wastes are either emplaced dry, or else in a hydraulic backfill which will be designed to contain little free water after curing, and since there is no way, in the absence of the shaft lining failing for water to inflow.

It is assumed that creep will lead to a reduction in connected void space in the facility by a factor of two at most. As the pore space decreases, the water present is squeezed out through a shaft with impaired or failed seals. It is assumed that the only the smaller shaft has failed (6m in diameter) and conducts water. This leads to the most rapid transport toward overlying aquifers and hence is the most pessimistic situation.

Advection of contaminants up the shaft is then modelled using Equation (4), with the flow rate being:

$$Q_{\text{creep}} = \frac{V_{\text{waste}}(\theta_{\text{waste}}^i - \theta_{\text{waste}}^f)}{t_{\text{creep}}} \quad (6)$$

It should be noted that the parameters in this equation that are subscripted “waste” do not refer to the wastes per se, but to the properties of the disposal rooms containing waste, plus backfill or hydraulic backfill.

There is no flow up the shaft until all the unsaturated pore space is closed. T_{creep} for this process is determined by an unrestricted creep curve elicited by Tellus and takes 70 years. Creep and upflow is then controlled by the permeability of the shaft seals, with the driving force being the difference between lithostatic and hydrostatic pressure. Accordingly, there is unrestricted creep as porosity decreases from 0.3 to 0.225 and no flow. As porosity decreases further to 0.15 the flow and creep rate is controlled by the permeability of the shaft seals. At this latter porosity there is no more creep or flow.

The shaft is assumed to provide a pathway vertically upwards for expelled water to leak into an aquifer. The model is configured so that the point of release can be selected from an aquifer in:

- ▲ the Horseshoe Bend Shale;
- ▲ the Upper Langra Formation;
- ▲ the Lower Langra Formation; or
- ▲ the Stairway Sandstone.

The properties of each aquifer can be defined, but given the uncertainties and the scoping nature of the model, each is assigned a nominal flow rate of 0.01 m/y, an initial plume thickness of 10 m, a density of 2100 kg/m³ and a porosity of 0.2. The maximum contaminant concentration to which a receptor such as humans or livestock could be exposed would be the concentration in an aquifer that is sampled directly by a borehole.

The downstream width of the plume can be approximated by:

$$W_{\text{Downstream}} = \sqrt{(W_{\text{Initial}})^2 + \frac{L_{\text{downstream}} \alpha_{\text{trans}}}{4}} \quad (7)$$

Where $L_{\text{downstream}}$ (m) is the distance between the point of release from the shaft and the borehole, and α_{trans} is the transverse dispersion length (m).

Additional material-specific parameters used in the modelling of advective release via a shaft with failed or impaired seals are given in **Error! Reference source not found..** Corresponding dimensions used in these models are given in Table 8-4.

Table 8-3: Material-specific parameter values for the advection case.

Material	Density (kg/m ³)	Porosity (-)	Notes
Waste-filled emplacement rooms	2000	0.3	Initial porosity given - reduces by 50% due to creep during model (density not varied since has no effect on contaminant concentrations)
Shaft	2000	0.15	Assume like concrete
Salt	2220	0.02	Half the maximum value reported for the disturbed zone around excavations at the WIPP (Cardenas et al., 1999), variant with 0.01 also run
Stairway Sandstone	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Lower Langra	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Upper Langra	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Horseshoe Bend Shale	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra

Table 8-4: Dimensions assumed for the advection case.

Description	Parameter	Value
Cross-sectional excavated disposal area of the rooms of the CF	A_X	$8 \times 10^5 \text{ m}^2$
Height of CF	L	6 m
Timescale for creep to close porosity	t_{Creep}	1000 y unless shaft content restricts water flow in which case calculated
Diameter of Shaft	W_{Shaft}	6 m
Distance contaminants travel in Shaft (to Stairway)	L_{Shaft}	355 m
Distance contaminants travel in Shaft (to Lower Langra)	L_{Shaft}	530 m
Distance contaminants travel in Shaft (to Upper Langra)	L_{Shaft}	665 m
Distance contaminants travel in Shaft (to Horseshoe Bend)	L_{Shaft}	750 m
Distance travelled between shaft/boreholes in aquifer	$L_{\text{downstream}}$	10 km and 20 km
Transverse dispersion in aquifers	α_{Trans}	1 % of pathlength

8.4.4 Performance Metrics

Over the long time period covered by the assessment (quantitative calculations are undertaken to 1 Ma), the surface environment, and consequently potential receptors, will change considerably. While scenarios can be specified for the nature and evolution of these receptors (e.g. nature and evolution of ecosystems) and impacts on them could be calculated, such a detailed approach is inappropriate given the uncertainties about the site. Instead, the approach is to calculate contaminant levels at different locations as a function of time and compare these with a number of groundwater quality standard and guideline values.

It should be noted that, even if a concentration does exceed a groundwater quality standard or guideline concentration, this does not necessarily mean that there will be any adverse environmental impact.

As described in Section 8.4.3, the contaminant concentrations output by the AMBER models may be subdivided into two groups:

- ▲ those obtained when concentrations of contaminants in the facility are assumed to be limited by solubility; and
- ▲ those obtained when a notional 10^6 g (1 tonne) inventory of a contaminant in the facility is specified.

Outputs of the second kind cannot be meaningfully compared with groundwater quality standards and guideline values because, for any given contaminant, the inventory may be lower or higher than the notional 10^6 g specified in the models. However, these outputs are useful because they illustrate the general variation in concentration over time (i.e. an increase to a peak and then a decrease). These outputs also provide a general indication of the plausible timescales over which the inventory would be lost from the facility in the unexpected AES.

Comparing the outputs of the solubility limited calculations with groundwater quality standards and guidelines is necessary. In principle, the concentration of any contaminant in the facility should be equal to or lower than a limit at which some solid phase that contains the contaminant would precipitate. While the actual phases that might form and their solubilities are uncertain, the calculations were undertaken for a wide range of plausible solubilities.

The outputs of the AMBER models given in the remainder of this section can be compared with permissible concentrations of contaminants in groundwater quality standards and guidelines. Relevant concentrations are tabulated in Table 8-5**Error! Reference source not found..**

Table 8-5: Groundwater standard and guideline values for the priority contaminants given in Section 4.2.2.

Substance	Australian Drinking Water Guidelines, v6, 2011 (updated March 2015) (mg/L)		World Health Organization Drinking Water Guidelines, v4 (2011) (mg/L)		Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) (mg/L)	
	mg/L	mol/L	mg/L	mol/L	mg/L	mol/L
Beryllium (Be)	0.06	6.66E-06	-		-	
Lead (Pb)	0.01	4.83E-08	0.01 (Provisional)	4.83E-08	0.001	4.83E-09
Chromium (Cr)	0.05 (CrVI)	9.62E-07	0.05 (Total)	9.62E-07	0.00001	1.92E-10
Mercury (Hg)	0.001	4.99E-09	0.006 (Inorganic)	2.99E-08	0.00006	2.99E-10
Benzene	0.001	1.28E-08	0.01	1.42E-07	0.6	7.68E-06

8.4.5 AES1 Assessment - Connected Porosity Through Halite

In calculations analysing this AES, the halite has connected porosity of either 0.01 or 0.02, allowing contaminants to diffuse out of the facility through the halite. After leaving the halite, contaminants then diffuse further through the rock before encountering an aquifer. Diffusion is represented as being directly up and directly down. There is no broadening of the plume in the horizontal direction.

Example outputs from these simulations are shown in Figure 8-7 and Figure 8-8. These figures show that even in the Stairway Sandstone, where the closest known aquifer to the facility occurs, groundwater standards / guidelines would not be exceeded for at least 100,000 years for any contaminant, given the specified solubility ranges. These figures also show that, for contaminants with solubilities towards the lower end of the considered range, even after 1 Ma, groundwater standard / guideline values are unlikely to be exceeded.

The calculated concentrations for the case with porosity 0.01 (Figure 8-7) are slightly greater at any given time than for the case with porosity 0.02 (Figure 8-8). While counter-intuitive, this result is a consequence of both cases having the same diffusion

coefficient. Thus, effectively in the case with porosity of 0.01, the flux of contaminants is actually slightly higher than in the case with porosity 0.02

In fact, the diffusion coefficient would vary as a function of porosity, such that the lower the porosity, generally the lower the diffusion coefficient. However, there are no data available with which to judge this relationship for the halite of the Chandler formation.

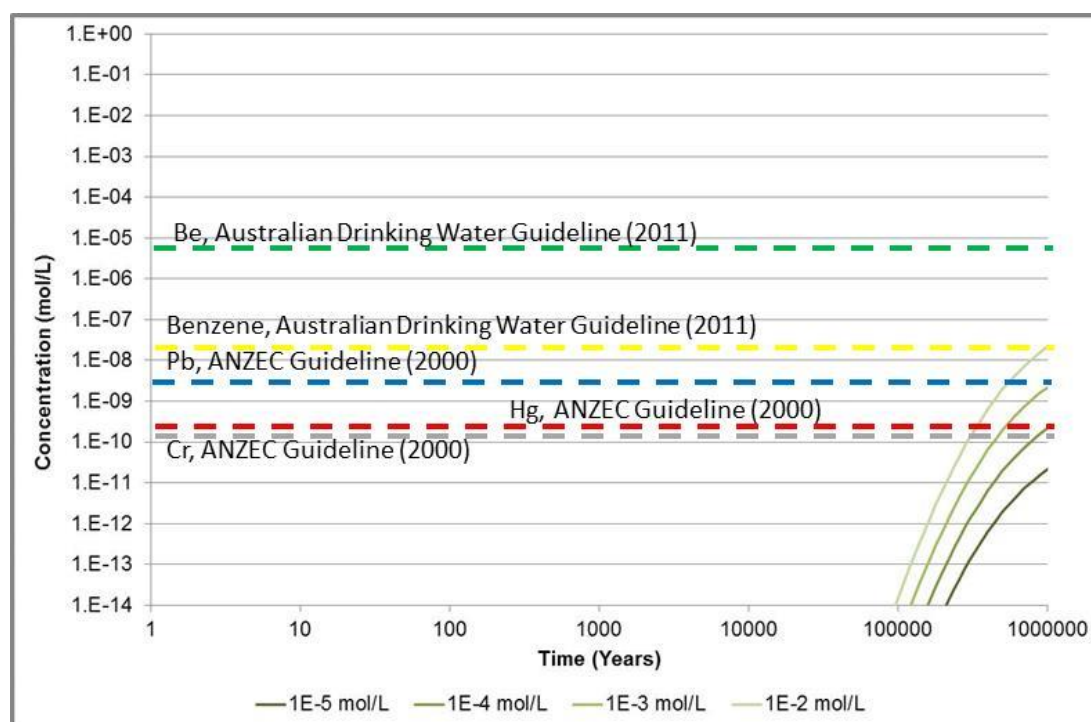


Figure 8-7: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES1. Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport to the Stairway Sandstone is by diffusion. Connected porosity in the halite roof is 0.01. There is no sorption.

The results shown in Figure 8-8 and Figure 8-8 were obtained while neglecting sorption. The effects of sorption can be appreciated by comparing these figures with Figure 8-9.

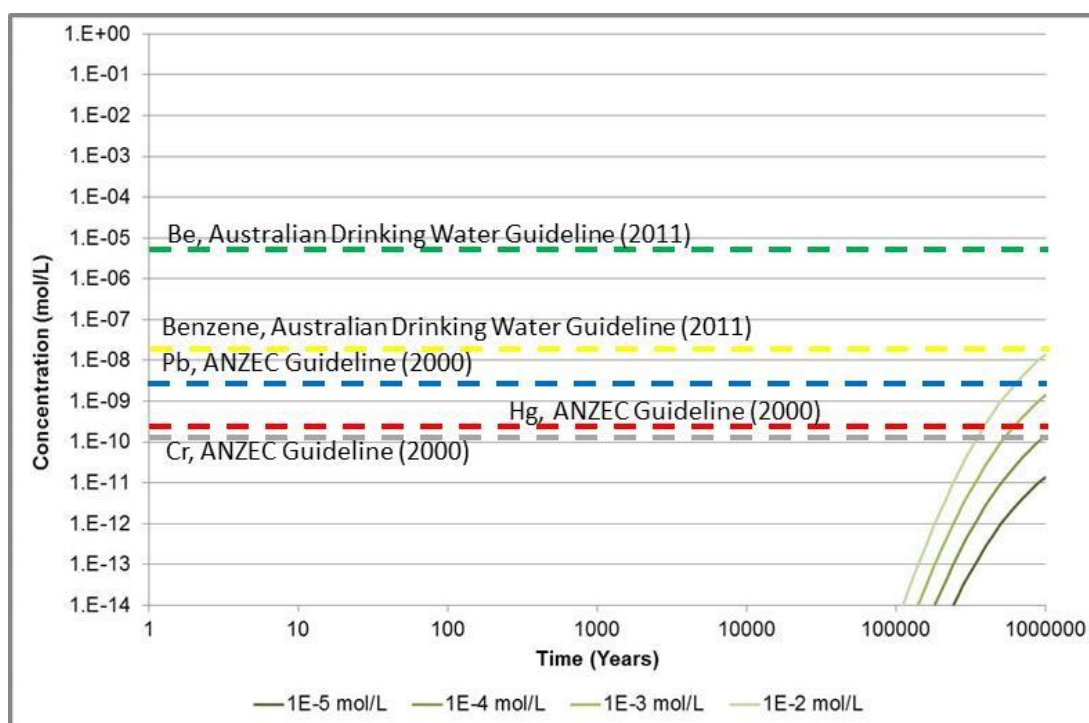


Figure 8-8: As for Figure 8-7, but the connected porosity of the halite is 0.02.

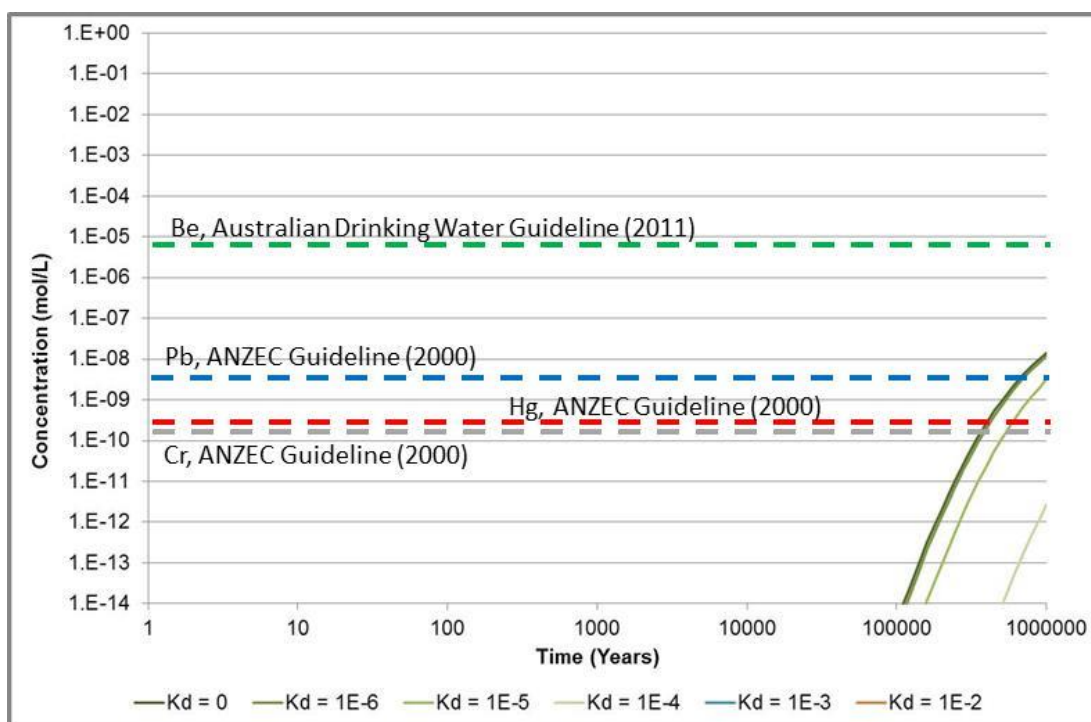


Figure 8-9: As for Figure 8-7, the connected porosity of the halite being 0.02, but with the effects of various sorption coefficients (K_d) being taken into account; the larger the sorption coefficient, the greater is the partitioning of a contaminant onto the solid (immobile) phases present. The guideline value for Benzene has been removed because this constituent is unlikely to sorb to any significant degree.

It can be seen that sorption reduces significantly the concentration of each contaminant at any particular location and time. For K_d values $>10^{-5}$ the calculated contaminant concentrations are >2 orders of magnitude below the lowest considered groundwater contaminant guideline (the one for Cr) at 10,000 m from the facility, even after 1 Ma following closure.

It is also important to note that these concentrations are calculated for an aquifer in the Stairway Sandstone Formation. This formation contains saline water (TDS = 15000 mg/L according to Douglas Partners, 2013) and hence is unlikely to be exploited for water resources. Were the water to be used for human consumption it would need to be diluted (either during transport to shallower aquifers that contain less saline water or conceivably by the people extracting the resource) to TD of <1000 mg/L and more likely $<<600$ mg/L (e.g. WHO, 2011). Thus, the contaminant concentrations in the Stairway Sandstone would be decreased by well over an order of magnitude before human consumption would be considered.

In practice, as explained in Section 8.3, during transport upwards from the Stairway Sandstone by any plausible pathway other than via direct abstraction from an open borehole section within the Stairway Sandstone, there would be significant dispersion and dilution of the contaminants.

8.4.6 AES2a Assessment - Collapsed Roof in Operational Phase Assessment

The probability that roof collapse during the operational phase would lead to a pathway for contaminant transport out of the facility in the post-closure phase is very small. The facility will be designed to prevent such collapses and, in the even that such a collapse occurs, remedial action is likely to be taken. However, collapse in the operational phase, into an unfilled cavern, would produce a maximally adverse transport pathway. It is therefore appropriate here to estimate the magnitude of such collapses.

Rockfall into an excavation can occur until a self-supporting collapse column develops. The total void volume is unchanged but is distributed throughout the collapse column, i.e. the rock is not compressible so there is no change in voidage due to compression / relaxation of the matrix porosity (or minerals) in the rock.

The expansion of the rock volume upon collapse is described by a bulking factor that varies with rock type (Figure 8-10).

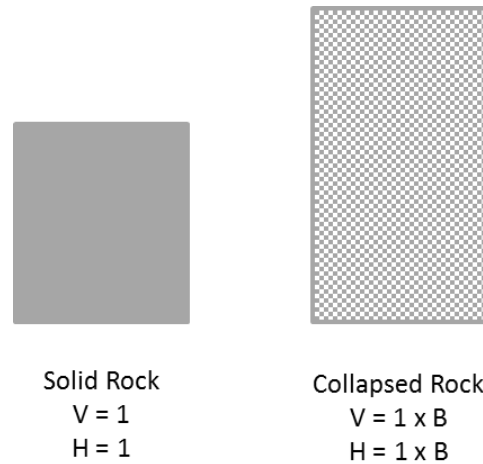


Figure 8-10: Definition of bulking factor: V = volume, H = height, (constant width and depth).

The bulking factor generally increases with rock quality and strength. The height of the collapse column depends on the void height, bulking factor and shape of the collapse column.

In its assessment of the planned Deep Geological Repository (DGR) at Bruce in Ontario, Canada, NWMO used a bulking factor of 1.3 for crystalline limestone, a moderately strong rock (Quintessa Ltd, 2011). A bulking factor of 1.1 was used for salt caverns overlain by sedimentary formations in the Netherlands (Metcalf et al., 2013). However, the bulking factor of 1.1 assumed that “peeling” and collapse of individual beds (layers) of rock led to a layered collapse column and limited bulking.

The height of the collapse column can be calculated using a volume balance:

$$h_c v_r + h_{r0} v_{r0} = (h_c + h_{r0}) v_c \quad (8)$$

Where:

h_c is the height of the collapse zone above the original roof of the excavation (m)

v_r is the void fraction in the undamaged rock (effectively zero)

h_{r0} is the height of the tunnel/vault (m)

v_{r0} is the void fraction in the tunnel / vault (equals 1 if there is no waste or backfill)

v_c is the void fraction in the collapsed rock, which is equal to $(B-1)/B$

B is the bulking factor

These parameters are illustrated in Figure 8-11.

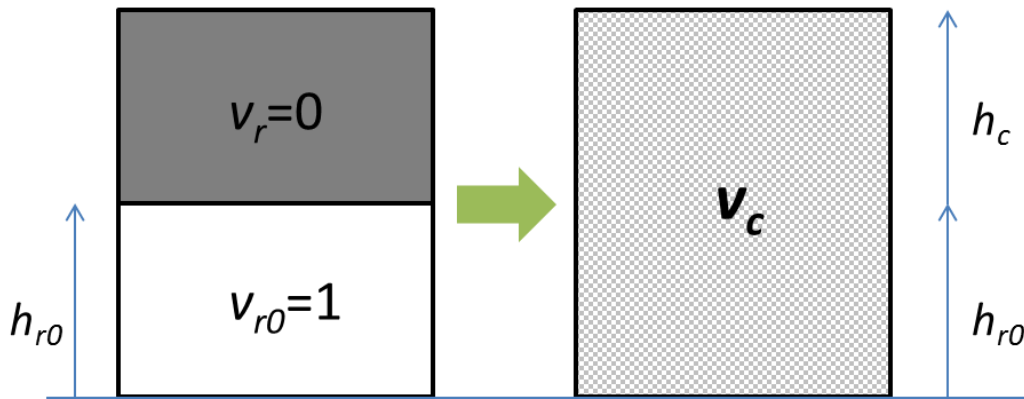


Figure 8-11: Volume balance for calculation of bulking factor.

The assumption of a rectangular collapse column does not take into account that voids would naturally evolve towards a more stable geometry, leading to an arch of rock above the collapse column. Therefore the collapse column could be higher than suggested assuming regular collapse. This is bounded by the assumption of a wedge collapse, where the height of the collapse column (h_c) is twice that for a rectangular collapse.

Solid wastes will be emplaced in the CF in large bulka-bags or in drums / boxes. A gap of about 0.5 m will be left between the waste stacks and the disposal room walls and ceiling. Ideally, these gaps will be filled with fine salt at the time of waste emplacement. However, some waste will initially be accepted for storage that ultimately becomes disposal. It will be very difficult to fill the gaps in these rooms. As the dry waste packages may themselves contain significant porosity and be compactible to some degree, there is clearly the potential for significant porosity in the rooms. A scoping calculation assuming 25% porosity in the waste stacks suggests that the porosity of a closed room could be up to about 40%.

Calculated potential heights of the collapse column, based on these assumptions, are shown tabulated in Table 8-6.

Table 8-6: Potential height of collapse column

Form	Bulking factor	Height of collapse above original roof of the excavation (m)
Rectangular	1.1	24.0
Rectangular	1.3	8.0
Wedge	1.1	48.0
Wedge	1.3	16.0

A bulking factor of 1.3 is considered to be a realistic assumption. There is a degree of caution because the calculation assumes the waste packages will compact under the load from the rock to the extent that all voidage is “expressed” and is filled with collapsed rock.

The roof of the excavations will be 20 m below the top of the Chandler formation, so with a bulking factor of 1.3 the collapse column will not extend into the overlying Jay Creek Limestone. However, there would also be a zone of damaged (fractured) rock above the collapse column. For a wedge collapse, fractures could potentially extend to the Jay Creek Limestone.

With a bulking factor of 1.1, the collapse column could extent into the Jay Creek Limestone. However, a bulking factor of 1.1 is considered to be cautious, because there is no reason to assume a layered, well ordered collapse column in this instance. Again the calculation is also cautious because it assumes the waste packages will compact under the load from the rock to the extent that all voidage is “expressed” and is filled with collapsed rock.

Implications for contaminant transport in the post-closure phase of the maximal collapse that could occur in the operational phase were calculated using the AMBER model. The key results for the Stairway Sandstone are presented in Figure 8-12.

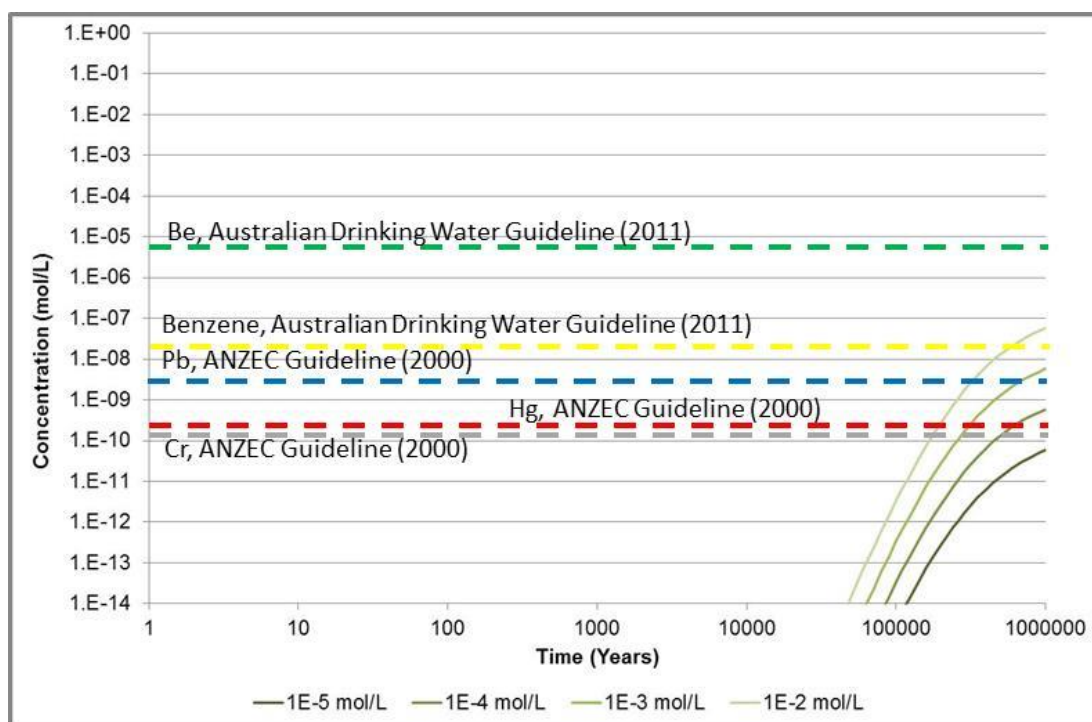


Figure 8-12: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES2a. Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport through the Jay Creek Limestone to the Stairway Sandstone is by diffusion. There is no sorption.

In this calculation, the groundwater standard / guideline values are exceeded for most of the considered contaminants after a few hundred thousand years when all except the lowest solubility constraint is considered. However, a contaminant with the lowest considered solubility (10^{-5} mol/L) would not exceed any of the standard / guideline values considered after 1 Ma. Additionally, there are some contaminants (exemplified by Be) with standard / guideline values that are sufficiently high that they would not be exceeded after 1 Ma even for the highest solubilities considered.

As explained for AES1 (Section 8.4.5), maximum contaminant concentrations in the Stairway Sandstone will likely be much higher than in any shallower rock formation owing to the dispersion and dilution that will accompany upwards transport along any plausible transport path. Only if the Stairway Sandstone was sampled directly by a groundwater well could shallower receptors, including humans, be exposed to the maximum concentrations reached in the Stairway Sandstone.

8.4.7 AES2b Assessment – Collapsed Roof in Post-Closure Phase

Were roof collapse to occur in the post-closure phase, it would result in substantially less upwards propagation of a transport pathway than would be the case should collapse occur into an un-filled cavern in the Operational Phase. The effects of a roof collapse in the Post-closure Phase would therefore be less than those calculated by AMBER for AES2a (Section 8.4.6).

Although the potential for a collapse column to extend into the overlying Jay Creek Limestone is low, the potential post-closure impacts if it did occur are:

- ▲ Any post-closure roof collapse would not provide a continuous pathway to the deepest known aquifer, the Stairway Sandstone. Instead in the most extreme case the collapse would affect directly only the Jay Creek Limestone, which is believed to have low permeability causing it to hydraulically isolate the Chandler Formation over geological timescales, thereby preventing salt dissolution.
- ▲ As a result of such roof collapse, there would be a smaller thickness of low-permeability Jay Creek Limestone between the top of the Chandler Formation and the aquifers of the Stairway Sandstone Formation than would be the case in the absence of roof collapse.
- ▲ Roof collapse post-closure would not cause a driving force for fluid movement out of the CF. The reason is that formation of a collapse column would not

result in any volume changes, only a re-distribution of the macro-voidage. Except in the unlikely case that the facility has flooded during the operational phase and not been pumped dry subsequently, the facility will initially be at atmospheric pressure. Thus any collapse of the roof would result in water flowing into the facility in the short-term. In the longer term it would be salt creep that would provide a driving force for this water to be expelled from the CF, by closing macro-voids and compressing the wastes, thereby expelling any water into the Jay Creek Limestone¹².

8.4.8 AES3 Assessment – Impaired Shaft Seal

The scenario of a leaking shaft is very cautious, since many studies have shown that it is possible to seal a shaft to be at least as effective a seal as natural aquitards (e.g. USDOE, 2009; Quintessa and Geofirma, 2011). However, some simple calculations have been undertaken to scope the potential significance of such failure should it occur. The shaft was cautiously assumed to provide a route from the wastes to all of the aquifers present in the overburden above the Chandler Formation. Furthermore, it was specified extremely pessimistically that the void space in the facility is water-saturated at the time of closure. In practice this is an extremely unlikely situation since, as noted previously, the wastes will be emplaced either in a dry form or in a hydraulic backfill; the latter is likely to contain very little free water after the backfill has cured.

Key results from this simulation are shown in Figure 8-13.

¹² This driving force is not included in the AMBER models of this scenario, which include only diffusion, but the effects would be similar to the impaired shaft seal (AES3), which is analysed by AMBER models (Section 8.4.8).

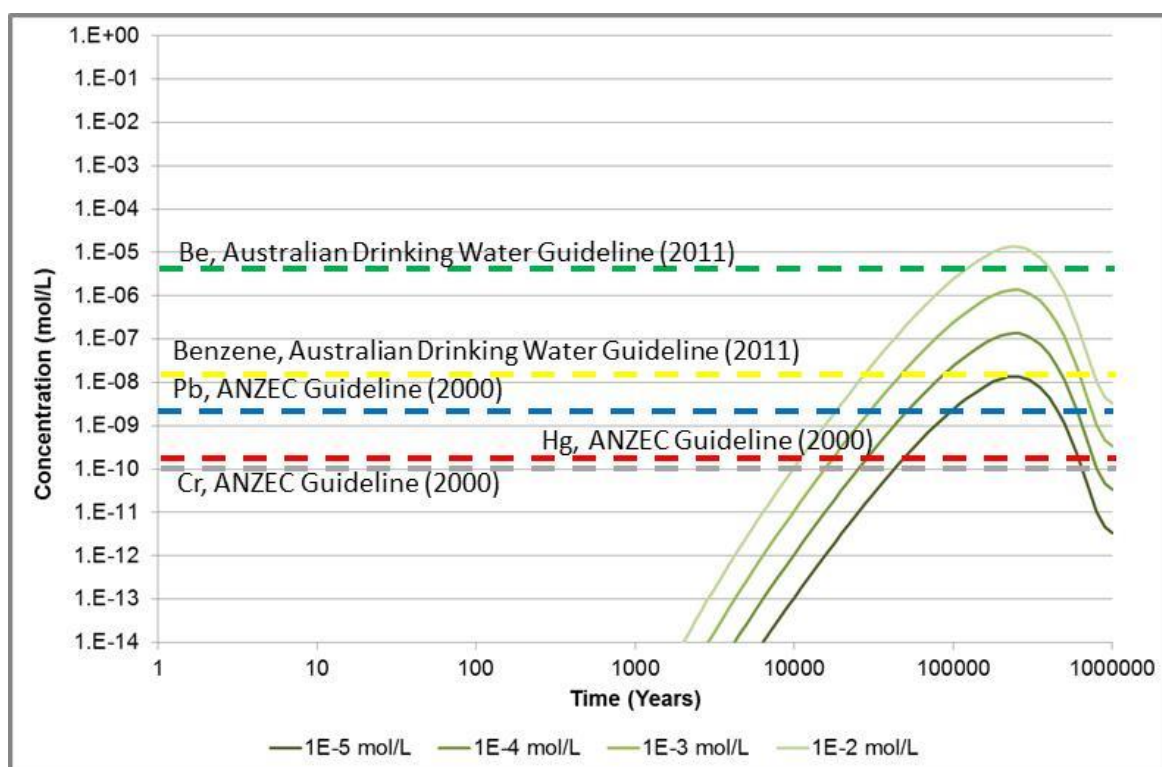


Figure 8-13: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES3. Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport to the Stairway Sandstone is by advection up the impaired shaft until creep ceases and by diffusion thereafter. The hydraulic conductivity of the impaired shaft seal is 10^{-9} m/s.

In this calculation, the concentrations of contaminants in the aquifer within the Stairway Sandstone Formation increase to a maximum after about 220,000 years and thereafter decrease before beginning to level off (although they are calculated to continue to decrease at 1 Ma). The initial rising concentrations reflect contaminants being driven out of the CF by creep of the salt. The peak reflects the cessation of creep and thereafter contaminant diffuse from the facility at a much slower rate, leading to the fall in concentrations. The concentrations begin to level off as a dynamic equilibrium is approached between supply of contaminants to the aquifer from the CF and transport of the contaminants away by the groundwater flowing naturally through the aquifer. The peak occurs long after the cessation of creep owing to the length of time taken for the contaminants to travel between the shaft and the point 10,000 m distant for which the calculation is undertaken.

This simulation shows that, depending upon its solubility and corresponding standard or guideline concentration, a contaminant's concentration could conceivably exceed the standard or guideline value in as little as 10,000 years at a distance of 10,000 m. On the other hand, it is also feasible that for those contaminants with solubilities towards the low end of the considered range and for which standard or guideline concentrations

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are relatively high, groundwater standard or guideline values would never be exceeded.

As explained for AES1 (Section 8.3.1), the maximum concentrations attained by contaminants in the Stairway Sandstone Formation aquifers would be lower than maximum concentrations that could be attained within shallower aquifers. Unless contaminated groundwater was sampled directly from the Stairway Sandstone Formation, near-surface receptors, including humans, would not come into contact with contaminants with concentrations as high as those in the Stairway Sandstone.

Additionally, with increasing distance from the CF the peak concentrations attained by contaminants in the Stairway Sandstone Formation would decrease. This can be appreciated by comparing Figure 8-13 with Figure 8-14.

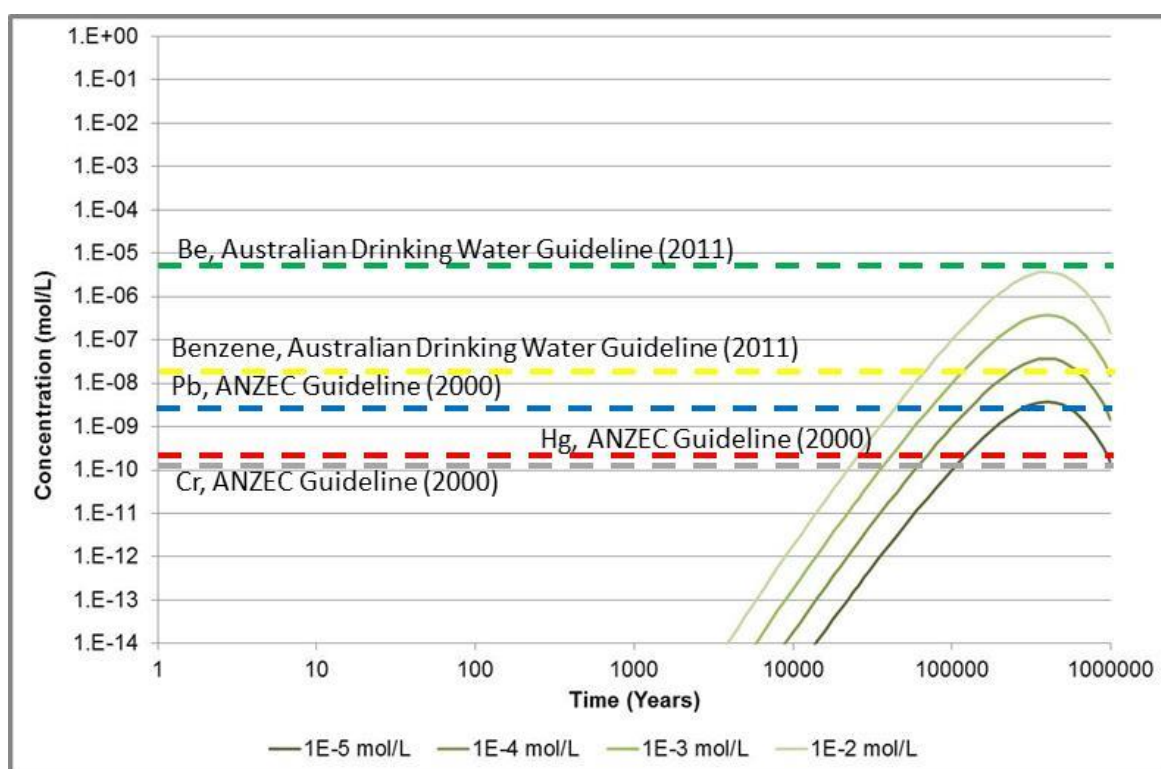


Figure 8-14: As for Figure 8-13 except that results are given for a point within the Stairway Sandstone Formation a distance of 20 km from the CF.

Comparing these two figures shows that for the parameterization used, contaminant concentrations at any given time decrease by around half an order of magnitude as the distance from the CF increases from 10 km to 20 km. The time taken for a particular contaminant to reach a given concentration is much longer at 20 km distance than at 10 km.

This general result is applicable to any of the AES considered; dilution and dispersion would result in the concentrations of contaminants decreasing by around half an order of magnitude for each 10 km increase in distance from the facility. However, it should

be noted that this conclusion is very dependent upon the values assigned to the parameters that represent dispersion. There are presently no hydrogeological data with which to judge these values. It is conceivable that, owing to the heterogeneous and nature of the aquifers, dispersion could result in a greater degree of dilution than has been calculated in these simulations.

The effect of increasing distance can also be appreciated by comparing the calculated contaminant concentrations at different locations in the Stairway Sandstone Formation when a notional 1t of contaminant is specified to be able to be released from the CF, rather than specifying a solubility control. Such results are shown for distances of up to 20,000 m from the facility in Figure 8-15.

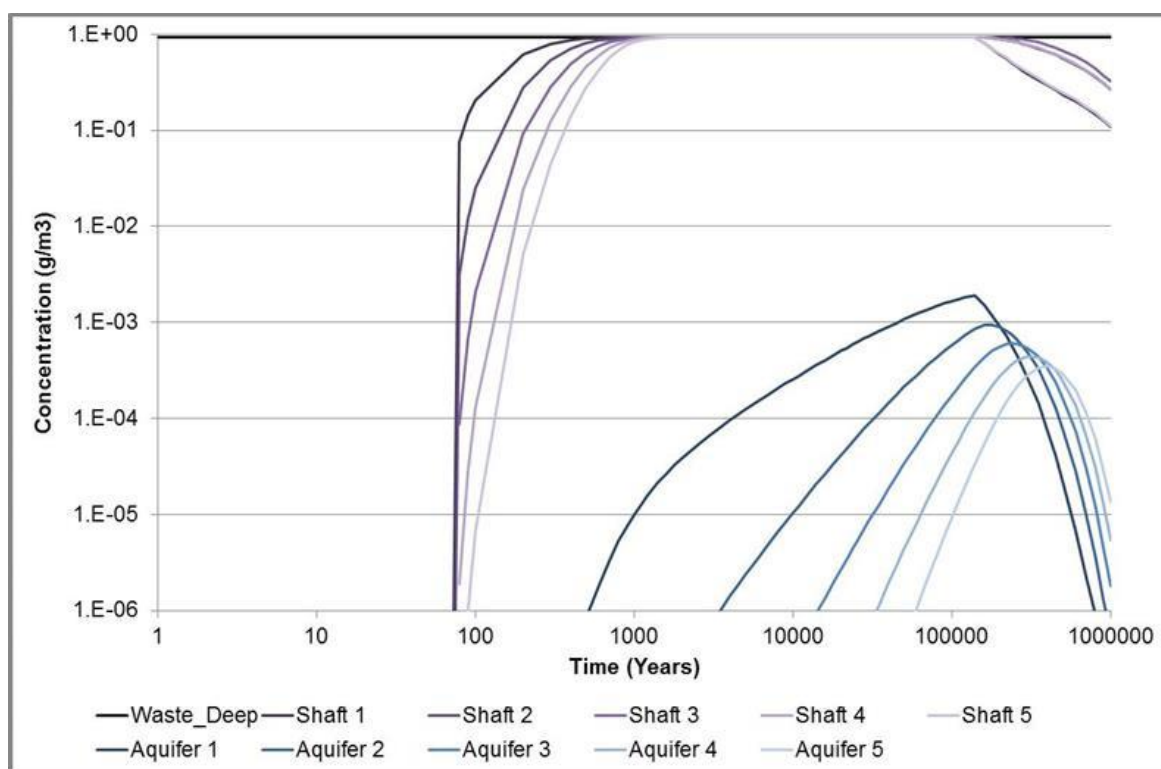


Figure 8-15: Results obtained when a notional 1t of a contaminant is released instantaneously to water saturating the CF at the time of closure and thereafter allowed to escape up a shaft with an impaired seal. Concentrations are given for each compartment in the model (see Figure 8-6) with "Shaft 1" and "Aquifer 1" representing the closest shaft and aquifer compartments to the CF respectively. "Aquifer 1" to "Aquifer 5" here represent the Stairway Sandstone, with "Aquifer 5" being up to 20,000 m from the CF. There is no retardation by sorption.

The absolute concentrations shown in Figure 8-15 cannot be compared with the groundwater standard or guideline levels, because they reflect the notional 1t inventory rather than the actual inventory. However, they do illustrate that in reality, there limited inventory would place a limit on the concentration attained by any contaminant at any point in the system. That is, concentrations would initially rise to a

peak, before falling as the contaminant becomes exhausted. The size of the peak would depend upon the size of the inventory.

For some contaminants in the facility it is conceivable that this inventory size limitation would prevent groundwater standard or guideline concentrations from being attained. Once data become available that allow the total inventories of all contaminants to be determined, then greater clarity will be possible concerning those contaminants for which this limitation might occur

For the parameterization used, the inventory-limited calculations give rise to peak contaminant concentrations in the Stairway Sandstone Formation after around 400,000 years at a distance of 20 km from the facility.

8.5 NORM Wastes

It is possible that some NORM may be included in the wastes to be emplaced in the CF.

The dominant radionuclide in the NORM inventory for the CF is Ra-226. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales (Section 4.2.2). If all of the 200 m³ per year of such wastes that arise each year in Australia were sent to the CF for the 25 year operational life, a total of 5000 m³ of NORM waste would be in the CF at closure. Assuming a waste density of 2000 kg/m³ gives 10¹⁰g of waste.

Section 4.2.2 indicates that the typical activity of such waste is 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales. Assuming that all of the activity is attributable to Ra-226, 1 Bq/g Ra-226 corresponds to 2.7×10^{-11} g Ra-226 per g waste. If the activity of the NORM wastes is 1 Bq/g, the initial inventory of Ra-226 is 0.3 g and if it is 10 Bq/g the initial inventory of Ra-226 is 3 g.

The WHO drinking water standard for Ra-226 is 1Bq per litre (WQA Technical Fact Sheet), which corresponds to 2.7×10^{-11} g/L or 2.7×10^{-8} g/m³. Therefore the results for a non-decaying contaminant provide a starting point for determining whether or not the drinking water standard would be exceeded.

Taking the results of the calculations for a non-sorbing contaminant for the EES at 1km, 10km and 20km, the peak concentrations seen in the Stairway aquifer are 4×10^{-4} g/m³, 3×10^{-6} g/m³ and 1×10^{-8} g/m³ respectively for an initial inventory of 10⁶ g. For the EES the contamination does not reach detectable concentrations in the aquifer sampling point for at least 70,000 years (1 km case; 350,000y for the 10 km case) Scaling by the inventory (0.3 to 3 g Ra-226) suggests that the drinking water standard would be met even before sorption and decay have been taken into account.

Ra-226 has a half-life of 1600 years. After 10 half-lives (16,000 years) the activity will have reduced by a factor of 1000 and after 20 half-lives (32000 years) by a factor of 10^6 . Thus decay rapidly reduces the concentration of Ra-226 and it could only conceivably be a threat for alternative evolution scenarios that assume rapid release to the aquifers and sampling close to the facility (the Ra-226 will decay to negligible activities during 10 km transport in the aquifer takes 20,000 years). Finally, sorption would be expected to further retard transport and reduce concentrations in water.

9 Risk Assessment

9.1 Terminology Used to Describe Risk

The risk due to any particular kind of event or process is dependent upon both:

- ▲ the likelihood of that event or process; and
- ▲ the potential impact of the event or process should it occur.

Thus an event or process will be “low-risk” if it has a very low probability of occurrence and / or it has a very low impact should it occur.

Here, the approach is to judge both the likelihood and potential impacts of each of the scenarios specified in Section 7 and Section 8, using a combination of qualitative and quantitative evidence, including outputs from the quantitative analysis described in Section 8.4. The judgements are represented on the “risk matrix” shown in Figure 9-1. **Error! Reference source not found.**

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely						
Possible						
Unlikely						
Highly Improbable						

Figure 9-1: Risk Matrix Approach (red = high risk; yellow = moderate risk; blue = low risk; green = effectively no risk).

A judgement of the likelihood of each scenario occurring is subject to uncertainty due a combination of the inherent variability of the considered system (aleatory uncertainty) and lacking knowledge (epistemic uncertainty). Descriptions of the terms used to describe likelihood are given in Table 9-1.

For each category considered, possible impacts have to be considered on a qualitative scale, ranging from “None” to “Very High”. Descriptions of these terms with regards to environmental impacts are given in Table 9-2.

Table 9-1: Description of terms used to scale likelihood.

Highly Improbable	Unlikely	Possible	Likely	Highly Probable
Virtually certain <i>not</i> to occur. The evidence base ¹ is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur and <u><i>none of the available evidence</i></u> indicates that the phenomenon / scenario will occur.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u><i>will not</i></u> occur than there is that it will occur. It is judged <u><i>clearly that the phenomenon / scenario will probably not occur.</i></u>	The evidence base is substantial, but some evidence indicates that the phenomenon / scenario will occur, whereas other evidence indicates that it will not occur. However, the evidence that the phenomenon / scenario will occur has about the same weight as the evidence that the phenomenon / scenario will not occur. In other words there is <u><i>no clear balance of evidence</i></u> that the phenomenon / scenario will occur as opposed to it not occurring.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u><i>will occur</i></u> than there is that it will not occur. <u><i>It is judged clearly that the phenomenon / scenario will probably occur.</i></u>	Virtually certain <i>to</i> occur. The evidence base is sufficient to reach a clear conclusion about whether a phenomenon / scenario will / will not occur and <u><i>all available evidence</i></u> points to the phenomenon / scenario occurring.

Notes: 1. Application of this scale is predicated on there being sufficient evidence (in terms of “quantity” and “quality”) to make a judgement of likelihood. That is, aleatory uncertainties (related to the inherent variability of a phenomenon) are encompassed by the scale, but epistemic uncertainties (arising from lacking knowledge) are not.

Table 9-2: Description of terms used to scale impacts.

None	Very Low	Low	Medium	High	Very High
None	Negligible contamination of environmental media Negligible ecological impact Negligible / immeasurable public exposure to contaminants and no significant public health implications Negligible livestock exposure to contaminants	Minor contamination of environmental media (measurable) Minor potential for ecological impact (possibly short-term/reversible) Very low level of public exposure, theoretical possibility of health effects (acute/chronic) Possible minor livestock (e.g. cattle) exposure	Low-level contamination of environmental media (potential exceedances of environmental quality indicators) Potential for ecological impact (possibly short-term/reversible) Low level public exposure, possibility of increased risks to health, possible observation of related acute health effects in susceptible individuals Livestock exposed to contaminants need to consider potential tainting of animal products Overall impacts result in regulatory observations	Significant contamination of environmental media Ecological impact (possibly irreversible) Significant public exposure, expected increased risks to health and/or observation of acute health effects in population Livestock exposed to contaminants, possible detrimental health effects, animal products deemed unfit for human consumption Overall impacts result in regulatory intervention	Catastrophic contamination of environmental media (including loss of any local crops) Major potentially irreversible ecological damage Major widespread public exposures resulting in significant observable adverse health effects, and/or loss of life) Complete loss of livestock and need for disposal of animal products as unfit for human consumption

9.2 Application of Risk Terminology to the CF

The scale of likelihood given in Table 9-1 is applied to the various scenarios specified for the CF (Section 7 and 8) in Table 9-3. For each specification of likelihood an explanation is also given.

Table 9-3 shows only the likelihood that each scenario will occur *at some time* during the future evolution of the facility and does not indicate the likelihood at any particular time.

Table 9-4 uses the terminology explained in Table 9-2 to summarize the worst impacts that could plausibly arise should a scenario be realized. It is conceivable that should one of the AES occur the impact could be less severe than is indicated; the EES is judged to have no significant adverse impact and therefore could not have a smaller impact than is given in Table 9-4.

Table 9-3: Summary of judgements of likelihood that each scenario will occur.

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
EES	None	Expected Evolution Scenario	Likely	There is theoretical and analogue evidence from studies in other countries that the natural and engineered barriers will maintain their integrity in the long-term (e.g. USDOE, 2009; Quintessa, 2011; Quintessa and Geofirma, 2011). Geomechanical models have shown that the roof of the facility will not undergo collapse during the Operational Phase or thereafter, with a large margin for safety, provided that the facility is appropriately implemented (Atkins, 2016). There are no boreholes penetrating to the depth of the facility within its footprint. Furthermore, the CF will be an inherently dry environment and will initially contain very little mobile free water at the time of closure and entry of water to the facility from the surrounding geosphere will be very slow owing to the extremely low permeability of the halite. Post-closure, creep will reduce the connected void space in the facility before any formation water is able to enter the facility. In the absence of creep there is very little force to drive water from the facility. Thus, at the time when the driving force is at its maximum there will be very little water present that is able to transport contaminants, while there will be very little driving force during the time period when water is available to mobilize this water.
Alternative Evolution Scenarios				
AES1	None	Connected porosity through the halite roof of the facility	Unlikely	There is abundant evidence from many localities throughout the world that halite contains no connected porosity and is impermeable. Furthermore, halite has an inherent self-sealing capability owing to its ability to creep. In many hydrocarbon fields halite forms the caprock to oil and gas reservoirs and has retained hydrocarbons for many millions

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
				of years (e.g. Capture Power and National Grid, 2016). However, the halite deposit in which the CF will be constructed is only 80-95% pure halite (ERCOSPLAN, 2013), which raises some possibility that other materials present (e.g. anhydrite interbeds) could contribute to connected porosity
AES2	a	Collapsed roof in the Operational Phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Highly Improbable	There is abundant evidence from underground excavations in salt deposits elsewhere in the world (e.g. the WIPP in New Mexico (Matthews and Eriksson, 2003); Winsford Salt Mine, Cheshire, UK (Swift and Reddish, 2005)) to support the conclusion that the CF can be designed and constructed so as to prevent roof collapse during the Operational Phase of a magnitude sufficient to compromise the integrity of the halite. Geomechanical modelling also supports this conclusion for the specific case of the CF (Atkins, 2016).
	b	Collapsed roof in the Post-closure Phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Highly Improbable	Once the facility is filled with waste and backfilled there will be a much smaller void space into which a roof collapse could occur than in the Operational Phase. Hence roof collapse of a sufficient magnitude to compromise the barrier function of the halite is highly improbable. Scoping calculations (Section 8.4.6) support this conclusion.
AES3	None	Impaired shaft seal scenario	Unlikely	There is theoretical and analogue evidence that shaft seals can be constructed so as to maintain their integrity in the long-term (e.g. assessments for the WIPP in New Mexico, U.S.A (USDOE, 2009) or for the DGR planned for Bruce in Ontario (Quintessa, 2011; Quintessa and Geofirma, 2011)). The main reason why this scenario is not highly improbable is that there remains some possibility that imperfect implementation of the shaft seals will cause their performance to be impaired compared to the EES.

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
AES4	None	Accidental human intrusion	Unlikely	Accidental human intrusion can never be ruled out entirely. However, the remote geographical location of the CF and the lack of any obvious natural resources at the depth of the facility make this scenario unlikely. It cannot be assumed that records of the facility's location and characteristics (e.g. emplaced wastes) will be available to future generations. However, it is technically demanding to drill boreholes or undertake excavations to the depth of the CF. It is a reasonable assumption that any future society with the technical capability to undertake such activities would also undertake prior investigations (e.g. seismic surveys) that would identify the facility, thereby enabling intrusion to be avoided.

Table 9-4: Summary of judgements of maximum potential impact of each scenario should it occur.

Scenario	Variant	Title	Impact	Rationale for Likelihood Judgement
EES	None	Expected Evolution Scenario	None	The expected evolution scenario is that contaminants will not leak from the facility. There is abundant evidence from many localities throughout the world that halite contains no connected porosity and is impermeable. In many hydrocarbon fields halite forms the caprock to oil and gas reservoirs and has retained hydrocarbons for many millions of years (e.g. Capture Power and National Grid, 2016). The site of the CF lies in the stable interior of a tectonic plate, far from the zones of active deformation which characterise the boundaries of such plates. The Chandler Formation shows no evidence for significant tectonic disturbance over the >500 million years since it was deposited and there is every reason to suppose that it will not be disturbed over any relevant future time period. The shafts will be sealed with multiple seals that contain materials that will not degrade significantly over relevant timescales. Assessments of similar kinds of sealing system for other deep waste facilities elsewhere in the world have demonstrated the feasibility of constructing shaft seals that will maintain their performance for at least 1 Ma (e.g. USDOE, 2009; Quintessa and Geofirma, 2011).
Alternative Evolution Scenarios				
AES1	None	Connected porosity through the halite roof of the facility	Low	Evidence for this comes from calculations described in Section Error! Reference source not found. These suggest even in the unlikely, pessimistic situation where the facility is water-saturated at closure and where contaminant migration is unretarded by sorption it will take at least several hundred thousand years for contaminant concentrations to exceed water quality standard or guideline values at distances of more than 10 km from the facility, even in the deepest aquifers of the Stairway

Scenario	Variant	Title	Impact	Rationale for Likelihood Judgement
				Sandstone Formation.
AES2	a	Collapsed roof in the Operational Phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Medium	Were roof collapse to occur during the operational phase, a contaminant transport pathway to the Stairway Sandstone could develop. However, the only way that the contaminants could then be transported to shallower aquifers that might be exploited for groundwater supplies would be via boreholes with imperfect seals, open boreholes, transmissive faults or diffusion.
	b	Collapsed roof in the Post-closure Phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Medium	As for AES1a
AES3	None	Impaired shaft seal scenario	Medium	Calculations to explore the effects of impaired shaft seal performance suggest that groundwater standard or guideline levels for contaminants could be exceeded within the aquifers on timescales of as little as 10,000 years at a distance of 10,000 m from the facility (Section 8.4.8). However, levels of contamination would decrease rapidly with respect to distance from the shaft. Additionally the concentrations could be several orders of magnitude lower than this, should account be taken of retardation due to sorption.
AES4	None	Human intrusion	High	While the effect of human intrusion could be high, it is likely that the adverse effects of human intrusion could be mitigated more readily than the case of the failed shaft (largely because it is more likely that such effects would be recognized by the people responsible for the human intrusion). Hence the impact is judged to be less than the impact for the failed shaft seal.

The judgement of risk, based upon the judgements of likelihood that each scenario will occur and the impacts should it occur, presented in Table 9-3 and Table 9-4 respectively, are summarized in Figure 9-2.

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely	EES					
Possible						
Unlikely			AES1	AES3	AES4	
Highly Improbable				AES2a, AES2b,		

Figure 9-2: Risk Matrix Approach (green = no risk).

The following conclusions can be drawn about relative risks:

- ▲ The EES would give rise to zero risk, since contaminants have no impact beyond the CF itself.
- ▲ AES1, AES2a and AES2b would give rise to the lowest risk among the different AES.
- ▲ AES3 would have the highest (though still low) risk among the scenarios that represent possible contaminant leakage paths that either exist or develop without human intervention.
- ▲ AES4 could potentially give rise to the highest risk among the AES, although the fact that this scenario is unlikely and any impact would likely be of restricted spatial extent means that the overall risk is not judged to be particularly high.

9.3 Temporal Variations in Risk

9.3.1 Factors Affecting Temporal Variations in Risk

At increasingly long times in the future, the uncertainties concerning the behaviour of the CF become progressively greater and quantitative estimates of risk become increasingly less meaningful. However, the most likely scenario is for an indefinite

continuation of containment (i.e. for the EES to continue indefinitely¹³). The key uncertainty is the degree to which any small contaminant flux from the CF would be diluted within the overlying aquifers, such that groundwater standards / guideline values are not exceeded anywhere. This uncertainty reflects uncertainties in:

- ▲ groundwater recharge rates;
- ▲ hydraulic head gradients;
- ▲ the hydraulic properties of the aquifers; and
- ▲ the properties of the rocks that govern contaminant transport and retardation processes.

If a pathway via which contaminants can leave the CF were to develop unexpectedly (i.e. an AES is realized) plausibly, given long enough, groundwater standards/guideline values could be exceeded in one or more aquifers. However, even in these circumstances, the likelihood that the standard / guideline values would be exceeded is lower for shallower aquifers than for deeper ones since upwards transport of contaminants will be accompanied by at least some dilution and dispersion.

Even given some very pessimistic parameterization (e.g. assuming the CF is water saturated at closure and that there is no retardation of contaminants by sorption), it would require several hundred thousand years for groundwater standard / guideline values to be exceeded at a distance of 10 km from the facility.

Even though the temporal variations in risk cannot be estimated confidently, confident pessimistic estimates of risk can be made, as described in Section 9.2. It is also possible to identify a number of temporally varying factors that have the potential to affect risk:

- ▲ Over time, “societal memory” of the facility is likely to become weaker and eventually will be lost altogether. This factor will tend to influence the risk that human intrusion will occur (i.e. the likelihood that AES4 will be realized). However, the actual risk of human intrusion will also depend upon other factors, such as the spatial distributions of human populations in the future and the level of technological development that these populations possess.
- ▲ Future climate change will influence the hydrogeology of the area around the CF. If rainfall in future is higher than at the present, potentially hydraulic gradients could be increased compared to current ones and the groundwater fluxes through the various aquifers in the geological sequence above the CF could be greater than now. Increased fluxes could lead to increased dilution of any contaminants that were to be released from the CF into these aquifers. This dilution in turn could diminish the likelihood that contaminant concentrations that entered the aquifers might exceed groundwater standard / guideline values there. Such dilution might also have the effect, however, of making the

¹³ Here “indefinitely” refers to the maximum period that is of concern to stakeholders.

aquifers more attractive targets for groundwater abstraction, which would increase the likelihood of borehole drilling, thereby producing pathways for contaminant transport. Decreases in rainfall could possibly have the reverse implications, but it seems unlikely that rainfall, and hence recharge, could diminish much from their present values, given the desert conditions of the area. The preservation of the salt in the Chandler Formation for approximately 520 million years, during which time there have been profound environmental changes, provides evidence that future climate change will not cause significant environmental changes at the level of the facility.

- ▲ Changes in population distributions and land use, potentially related to climate change, could cause a greater likelihood that humans, animals and vegetation could be exposed to any contaminants that were to enter the aquifers in the overburden above the CF. Over the very long timescales that must be considered, it is conceivable that climate change could enable increased human populations to inhabit the area around the CF and / or enable agriculture to be undertaken in this area.
- ▲ Irrespective of any changes in human activity and resultant variations in land use, ecosystems in the vicinity of the CF could change naturally, in response to climate change or, given long enough, evolution. Conceivable consequences could be changes to the nature of biological receptors that might be impacted by any contaminants that were to be transported into the overburden.

9.3.2 25 years to 300 years (potential institutional control period)

During the potential institutional control period¹⁴ the engineered and natural barriers in the system are expected to work as designed; the EES is by far the most likely scenario. Only in the event that shaft seals were not emplaced properly is it conceivable that shaft seals would not function as designed. However, even in the event of impaired shaft seal function due to this cause, it is not credible that during this relatively short period contamination could migrate via the shaft sufficiently far to contaminate any aquifer that might be exploited for groundwater.

In principle, were contaminants to be transported from the CF to the overburden during this period, open monitoring boreholes could form all or part of pathways to the near-surface biosphere (depending on the depth of the boreholes). However, in practice this is extremely unlikely as there will be very little, if any, mobile water within the facility. Additionally there will be very little driving force to cause

¹⁴ The institutional period for Chandler has still to be determined in conjunction with regulators.

contaminated water to migrate into the overburden, even assuming that there are sufficiently transmissive pathways via which the water could be transported (considered unlikely). It is therefore highly unlikely that, within this time frame, contaminant concentrations within aquifers that might be exploited for groundwater could exceed groundwater quality standard or guideline values. Support for this conclusion is provided by the numerical models presented in Section 8.4.

Accidental human intrusion is considered even more unlikely to occur in this period than in later (and longer) time periods, owing to the presence of people with knowledge of the facility (by definition, since monitoring is on-going).

9.3.3 300 years to 1,000 years

The EES continues to be the most likely scenario throughout this time period.

During this period creep is likely to provide a driving force for any water that might be in the facility. However, there is likely to be little free, mobile water present and hence creep will not result in any significant increase in the likelihood of contaminants leaving the facility. Engineered barriers (principally shaft seals) are highly likely to retain their function. Even in the unlikely event that contaminants were to leave the facility during this period, numerical models presented in Section 8.4 suggest that contaminant concentrations within the aquifers that might be exploited for groundwater resources would not exceed groundwater standard or guideline values. During this period climate change of a sufficiently great magnitude to cause large changes in human activity, and consequent agriculture and land use, is considered unlikely. However, “societal memory” of the existence of the CF could decrease progressively and the possibility of human intrusion cannot be ruled out. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

9.3.4 1000 years to 10,000 years

During this period, the EES remains by far the most likely scenario. While there is considerable uncertainty (geomechanical models have not fully explored this interval; Atkins, 2016), it is possible that significant creep will have ceased prior to the start of this period. It also seems unlikely that even in this period there will be sufficient free water to transport contaminants from the facility at a significant flux. Even in the event that contaminants were to leave the facility during this period, numerical models presented in Section 8.4 suggest that contaminant concentrations within the aquifers

that might be exploited for groundwater resources would not exceed groundwater standard or guideline values.

During this period, potentially climate change and consequent variations in human populations, land uses and ecosystems could occur. It cannot be assumed that there would be any “societal memory” of the existence of the facility. Were human populations to increase in the future, then the potential for accidental human intrusion would likely increase. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

9.3.5 10,000 years to 1 million years

During this period, the EES remains by far the most likely scenario, but the effectiveness of engineered barriers in the shafts becomes more uncertain with increasing time. Nevertheless, there is considerable analogue and theoretical evidence that properly designed and emplaced shaft seals will retain their barrier function at least throughout this long period and that consequently the shaft seal impairment scenario (AES3) will not be realized.

It seems likely that even in this period there will be little free water, and a very small force driving groundwater flow. Therefore, even if a pathway via which contaminants can leave the CF were to develop unexpectedly (i.e. an AES is realized) any flux of contaminants from the facility would be very small. However, numerical models presented in Section 8.4 suggest that under these circumstances, over this very long time period, contaminant concentrations within the aquifers that might be exploited for groundwater resources could conceivably exceed groundwater standard or guideline values. Nevertheless, there are large outstanding uncertainties concerning the hydrogeology of the area. Taking these uncertainties into account it is plausible that contaminant dispersion in these aquifers could be sufficient to prevent these groundwater standard or guideline values from ever being exceeded. Further modelling, based on a more complete hydrogeological dataset than is available at the present, could improve confidence in judgements as to whether or not such dispersion would occur in future.

During this period, climatic conditions will certainly fluctuate considerably. For at least a substantial proportion of the period these conditions will be considerably different from those of the present. Consequently there will be variations in human populations, land uses and ecosystems. It is almost certain that there will be no “societal memory” of the existence of the facility, even assuming that humanity continues to exist throughout this period. Were human populations in the area near the CF to increase in the future, then the potential for accidental human intrusion would likely increase as

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well. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

10 Conclusions

The assessment provides confidence that, for the proposed categories of wastes and with appropriate facility design, there will be no significant risks arising from the CF in terms of environmental safety.

The most probable scenario for the future evolution of the CF is that the facility behaves as planned and no significant contamination leaves it following closure (the Expected Evolution Scenario, EES).

To assess the risks of the CF unexpectedly not behaving as designed (i.e. the EES not being realized) four Alternative Evolution Scenarios (AES) have been defined:

- ▲ AES1, Connected porosity through the halite roof of the CF;
- ▲ AES2, Collapsed roof of the CF, with the variants:
 - AES2a, Collapsed roof in the Operational Phase;
 - AES2b, Collapsed roof in the Post-closure Phase;
- ▲ AES3, Impaired shaft seal;
- ▲ AES4, Accidental human intrusion.

These scenarios are *not* predictions of future CF behaviour. Instead, they are designed to illustrate alternative ways in which contaminated water might leave the facility and be transported through the surrounding geological system to potential receptors, in the unlikely event that the EES is not realized. AES1, AES2 and AES3 have been analysed by means of numerical models, whereas AES4 has been analysed qualitatively.

Very probably no actual future system evolution that hypothetically departs from expectations (as represented by the EES) would result in greater impacts than the highest impacts caused by any of the analysed set of AES. That is, the analyses of the AES are designed to “bracket” any plausible actual behaviour predicated upon the assumption of containment loss.

None of these AES is likely to occur. AES1 is judged unlikely based on available data and may prove to be highly improbable when uncertainties concerning the characteristics of the halite are reduced. AES3 is judged to be unlikely and both variants of AES2 are judged highly improbable if the CF is implemented as designed. AES4 is judged to be unlikely given the presently remote location and the fact that intruding into the facility by humans in the future implies significant technological capabilities which could be employed to avoid or mitigate environmental impacts.

Even if containment of the CF were to be lost, any contaminated water present would not necessarily travel to near-surface receptors. Under these circumstances the contaminated water may travel upwards only as far as the aquifers in the Stairway Sandstone. The Stairway Sandstone contains saline water and is therefore very unlikely to be exploited as a water resource.

Any contaminants that enter the aquifers of the Stairway Sandstone would be diluted and transported laterally by groundwater flowing slowly under the natural head gradient. The contaminant concentrations would then decrease downstream owing to dispersion. Calculations show that it would take more than a hundred thousand years for the concentrations of any contaminants in the Stairway Sandstone to exceed groundwater standard/guideline values at a distance 10 km downstream from the facility in AES1 and both variants of AES2. In the case of AES3, it would take more than 10,000 years for these groundwater standard/guideline values to be exceeded in the Stairway Sandstone at a distance of 10 km downstream.

The Stairway Sandstone Formation contains saline water (TDS = 15,000 g/L; Douglas Partners, 2013) and hence is unlikely to be exploited as a groundwater resource. Consequently it is unlikely that near-surface receptors, including humans, would be exposed to the peak contaminant concentrations calculated for the Stairway Sandstone, even if one of the AES were to be realized.

Were contaminants to be transported via any conceivable pathway from the Stairway Sandstone to shallower aquifers that are more likely to be exploited as water resources, the contaminants would be diluted and dispersed along the pathway. Thus, these shallower aquifers would tend to have lower contaminant concentrations than those in the Stairway Sandstone at the location where the contaminants left the Stairway Sandstone.

If a shallower aquifer was to become contaminated in this way, contaminants would be transported laterally within the aquifer by groundwater flowing under the influence of the natural head gradient, in the same way as contaminants within the Stairway Sandstone. Thus, contaminant concentrations would decrease laterally within the aquifer, with increasing distance from the CF.

In the event that the shaft seals are impaired (AES3) contaminants would be diluted and dispersed during upwards transport through impaired shaft seals.

There are uncertainties about the release, migration and attenuation of contaminants in the event of the CF losing containment (an AES being realized), principally reflecting the fact that the following characteristics are not well known at this stage:

- ▲ behaviour of the wastes under the conditions within the CF (notably the chemical forms in which contaminants occur and their solubilities);
- ▲ driving force provided by the creep of the halite in the post-closure period;
- ▲ magnitudes of processes controlling retardation of migrating contaminants (sorption, diffusion into parts of the rock matrix where there is no advection);
- ▲ hydraulic conductivities of the different rock formations;
- ▲ porosities of the different rock formations;
- ▲ groundwater head gradients;
- ▲ groundwater recharge rates;

- ▲ dispersivity of the aquifers; and
- ▲ lateral connectivity of the aquifers.

These uncertainties have been treated in the assessment by using pessimistic values of relevant parameters, consistent with the currently available data. It is therefore likely that calculated contaminant concentrations in the aquifers tend to over-estimate the concentrations that would actually occur in the rock formations above the CF at any particular location and time in the future, should the CF lose containment.

Taking into account these uncertainties, it is conceivable that, should containment of the CF be lost, no contaminant concentrations in the Stairway Sandstone would ever exceed groundwater standard / guideline values beyond a distance of 10 km from the facility. Since the shallower aquifers are likely to contain even lower concentrations of contaminants than the Stairway Sandstone, it follows that it is even less likely that under these circumstances the shallower aquifers could contain concentrations of contaminants in excess of groundwater standards or guideline values.

Further numerical modelling of the system could reduce the outstanding uncertainties once complete compositions of the wastes have been established and relevant hydrogeological information becomes available.

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Appendix A: Waste Screening

Waste stream data ("75" code) supplied by Tellus are given in Table A1.

Table A-1: Waste Descriptions and Projected Inventory

		200,000		8,500,000
		tpa		t LOM
'75' code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (tpa)	Chandler Facility (%)	Chandler Facility (t LOM)
	Total Haz chem waste	200,000	100.0%	8,499,984
	Total NORM's	0	0.0%	0
	Commercial and Industrial (passed onto to 3rd party landfill)		0.0%	
	Total (Haz. waste & NORM's)	200,000	100.0%	8,499,984
N205	Residues from industrial waste treatment/disposal operations	50,570	25.3%	2,149,216
D110	Inorganic fluorine compounds excluding calcium fluoride (SPL)	39,201	19.6%	1,666,026
N120	Soils contaminated with a controlled waste	33,117	16.6%	1,407,492
N220	Asbestos	21,323	10.7%	906,247
J120	Waste oil/water, hydrocarbons/water mixtures or emulsions	11,231	5.6%	477,320
D220	Lead; lead compounds	9,778	4.9%	415,552
C100	Basic solutions or bases in solid form	9,724	4.9%	413,252
D230	Zinc compounds	5,788	2.9%	246,007
	NORMs	4,386	2.2%	186,398
J100	Waste mineral oils unfit for their original intended use	4,376	2.2%	185,986
D300	Non-toxic salts	2,355	1.2%	100,080
B100	Acidic solutions or acids in solid form	1,691	0.8%	71,855
	Encapsulated, chemically-fixed, solidified or polymerised wastes referred to in this list	1,025	0.5%	43,550
F100	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	970	0.5%	41,225
M100	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or polybrominated biphenyls	663	0.3%	28,185
N100	Containers and drums that are contaminated with residues of substances referred to in this list	566	0.3%	24,038
	Filter cake contaminated with residues of substances referred to in this list	450	0.2%	19,120
N190	list	344	0.2%	14,606
G110	Organic solvents excluding halogenated solvents	248	0.1%	10,546
M250	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	237	0.1%	10,080
A100	Waste resulting from surface treatment of metals and plastics			
	Fly ash, excluding fly ash generated from Australian coal fired power stations	215	0.1%	9,154
N150	Tannery wastes (including leather dust, ash, sludges and flours)	209	0.1%	8,899
K140	Waste from the production, formulation and use of resins, latex, plasticisers, glues and adhesives	182	0.1%	7,756
F110	Waste tarry residues arising from refining, distillation, and any pyrolytic treatment	172	0.1%	7,311
J160	Waste from the production, formulation and use of organic solvents	138	0.1%	5,885
G160	Waste pharmaceuticals, drugs and medicines	137	0.1%	5,842
R120	Triethylamine catalysts for setting foundry sands	113	0.1%	4,810
M230	Waste from the production, formulation and use of biocides and phytopharmaceuticals	109	0.1%	4,643
H100	Waste chemical substances arising from research and development or teaching activities, including those which are not identified and/or are new and whose effects on human health and/or the environment are not known	99	0.0%	4,197
T100	Ceramic-based fibres with physico-chemical characteristics similar to those of asbestos	88	0.0%	3,729
N230	Mercury; mercury compounds	55	0.0%	2,351

D190	Copper compounds	45	0.0%	1,916
D140	Chromium compounds (hexavalent and trivalent)	40	0.0%	1,720
R140	Waste from the production and preparation of pharmaceutical products	34	0.0%	1,434
K190	Wool scouring wastes	30	0.0%	1,265
M150	Phenols, phenol compounds including chlorophenols	30	0.0%	1,259
G150	Halogenated organic solvents	29	0.0%	1,217
N140	Fire debris and fire wash waters	27	0.0%	1,166
G100	Ethers	27	0.0%	1,152
T200	Waste of an explosive nature not subject to other legislation	25	0.0%	1,060
T120	Waste from the production, formulation and use of photographic chemicals and processing materials	23	0.0%	961
D330	Inorganic sulfides	20	0.0%	870
H110	Organic phosphorous compounds	18	0.0%	749
D130	Arsenic; arsenic compounds	16	0.0%	681
M220	Isocyanate compounds	11	0.0%	468
D360	Phosphorus compounds excluding mineral phosphates	10	0.0%	423
E100	Waste containing peroxides other than hydrogen peroxide	10	0.0%	413
D210	Nickel compounds	7	0.0%	314
M260	Highly odorous organic chemicals (including mercaptans and acrylates)	7	0.0%	312
H170	Waste from manufacture, formulation and use of wood-preserving chemicals	7	0.0%	293
D100	Metal carbonyls	4	0.0%	174
A130	Cyanides (inorganic)	3	0.0%	134
M210	Cyanides (organic)	3	0.0%	123
D270	Vanadium compounds	3	0.0%	122
M160	Organo halogen compounds—other than substances referred to in this Table or Table 2	3	0.0%	110
D150	Cadmium; cadmium compounds	1	0.0%	62
A110	Waste from heat treatment and tempering operations containing cyanides	1	0.0%	60
T140	Tyres	1	0.0%	43
D160	Beryllium; beryllium compounds	1	0.0%	38
D350	Chlorates	1	0.0%	25
D170	Antimony; antimony compounds	1	0.0%	25
D250	Tellurium; tellurium compounds	0	0.0%	13
D340	Perchlorates	0	0.0%	9
D200	Cobalt compounds	0	0.0%	6
D310	Boron compounds	0	0.0%	5
D290	Barium compounds (excluding barium sulphate)	0	0.0%	3
D240	Selenium; selenium compounds	0	0.0%	1
D180	Thallium; thallium compounds	0	0.0%	1
M170	Polychlorinated dibenzo-furan (any congener)	0	0.0%	1
M180	Polychlorinated dibenzo-p-dioxin (any congener)	0	0.0%	1
K100	Animal effluent and residues (abattoir effluent, poultry and fish processing wastes)	-	0.0%	-
K110	Grease trap waste	-	0.0%	-
K130	Sewage sludge and residues including nightsoil and septic tank sludge	-	0.0%	-
R100	Clinical and related wastes	-	0.0%	-
	Imports	-	0.0%	-
	Exports	-	0.0%	-
Other categories from previous ASBG Study			0.0%	0

The substances in Table A1 have been screened to identify representatives for detailed analysis, using expert knowledge and Australian drinking water guidelines. Substances are identified in Table A2. Pesticides are considered separately. For both operation and post-closure risk assessment, substances of possible concern present in each waste type have been considered. Illustrative substances potentially of concern have been identified based on expert judgement and a consideration of substances typically included in environmental risk assessment (including a consideration of the substances included in Australian drinking water guidelines). The substances are then ranked 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Table A2). The product of the three values is then used to derive an “index” value used to identify substances of greater importance, a subset of which is suggested for post closure assessment in particular. This approach gives the following top ten ranked contaminants:

1. Beryllium (score 12);
2. Chromium (as Cr(VI)) (score 12);
3. Dichloromethane (score 12);
4. Hexachlorobutadiene (score 12);
5. Mercury (score 12);
6. Benzene (score 9);
7. Epichlorohydrin (score 9);
8. Lead (score 9);
9. Molybdenum (score 8); and
10. Nickel (score 8).

When account is taken of the different chemical properties of these elements and their likely forms in solution, it is suggested that from this list the following elements are considered in more detail in the analysis:

1. Beryllium;
2. Chromium;
3. Mercury;
4. Benzene; and
5. Lead.

Table A-2: Substances potentially present in wastes (excluding pesticides/herbicides/fungicides), Australian drinking water guidelines, rankings (1-3) and index of potential impact (product of values for 1-3).

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Aluminium (acid soluble)	c	0.2	based on post-flocculation problems	3	1	1	3	component of waste metals, possibly high volume, low solubility, low toxicity, not suitable for hydraulic backfill
Ammonia	c	0.5	typically associated with sewage contamination/microbial activity	1	2	1	2	probably only present in small amounts, soluble in water
Antimony	0.003		guidelines note that exposure may rise with increasing use of antimony-tin solder	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils)
Arsenic	0.01		natural sources, mining/industrial/agricultural wastes	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, some degree of sorption to minerals likely, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils, mining wastes)
Barium	2		primarily from natural sources	2	2	1	4	possible associated with mineral scales from oil industry, mobility in environment depends on

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								sulphate availability
Benzene	0.001		human carcinogen	1	3	3	9	associated with petroleum products (one of the "BTEX" compounds), possible present in small amounts (trace level/as breakdown product), highly flammable .
Beryllium	0.06		fossil fuel burning	2	2	3	12	associated with specialist alloys, possibly anionic speciation in water and relatively higher mobility than other metals
Cadmium	0.002		industrial/agricultural contamination, impurities in galvanised (zinc) fittings, solders and brases	2	1	3	6	heavy metal, numerous sources (including soils, mining wastes), potentially solubility-limited, likely to sorb to minerals, some waste streams may be suitable for hydraulic backfill
Chloride		250		2	3	1	6	from rock salt, drinking water guideline based on aesthetics
Chlorobenzene	0.3	0.01	intermediate, solvent, taste/odour threshold lower than health based concentrations	1	3	2	6	possibly present as waste from chemical industry or solvent, soluble in water to some extent

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Chromium (as Cr(VI))	0.05		associated with industrial/agricultural contamination	2	2	3	12	Cr(VI) from industrial waste of greater concern than Cr(III), which is found in stainless steel, Cr(VI) generally of more concern via inhalation exposure so index value possibly a little unrepresentative
Copper	2	1	associated with metal pipe corrosion	3	1	1	3	could be present in relatively large volume compared to other metals for some waste streams, of less concern than heavy metals in terms of toxicological properties, likely to have low solubility in water
Cyanide	0.08		associated with industrial waste	1	2	3	6	cyanide associated with wastes, not clear as to how likely it is to be present, presumably in relatively smaller amounts
1,2 dichlorobenzene	1.5	0.001	chemical intermediate, may be used as a solvent in some applications; taste/odour threshold lower than health based concentrations	1	1	3	3	possibly from chemical industry, may be used as a solvent
1,3 dichlorobenzene	c	0.02	taste/odour threshold lower than health based concentrations	1	1	3	3	

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
1,4 dichlorobenzene	0.04	0.0003	disinfectant, pesticide odour threshold lower than health based concentrations	1	1	3	3	
1,2-dichloroethane	0.003		vinyl chloride manufacture, intermediate, solvent	1	2	3	6	possibly from chemical industry, may be used as a solvent, limited solubility in water
1,1-dichloroethene	0.03			1	1	3	3	possibly largely immobilized in hydraulic backfill depending on waste streams that are disposed in such a manner, poorly soluble in water
1,2-dichloroethene	0.06			1	1	3	3	
Dichloromethane	0.004		widely used solvent	2	2	3	12	volatile liquid
Epichlorohydrin	0.0005d		used in manufacture of resins for water treatment	1	3	3	9	possibly associated with waste from water treatment, moderately soluble in water
Ethylbenzene	0.3	0.003	component of petrol and petroleum products	1	2	2	4	associated with petroleum products, may be used as solvent, possibly present in trace quantities (flammable), partly soluble in water, can be mobile in sub-surface environment
Ethlenediamine tetraacetic acid (EDTA)	0.25		metal complexing agent commonly used in industry	1	3	1	3	presumably could be present as residue from cleaning metals/ other

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								materials, mobile in the environment
Hexachlorobutadiene	0.0007		Industrial solvent	2	2	3	12	relatively greater potential toxicological hazard compared to other materials, could be present as solvent residue
Lead	0.01			3	1	3	9	heavy metal, could be associated with different waste streams, relatively low solubility under most conditions, neurotoxin
Manganese	0.5	0.1		2	2	1	4	possibly present in some metal wastes
Mercury	0.001		Industrial sources	2	2	3	12	possibly present in some waste streams (including as a lower volume mercury waste stream). Forms amalgams with some metals, native form volatile, limited solubility of oxidised species in water. International efforts to reduce use given toxicological hazard

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Molybdenum	0.05		associated with mining, agriculture and fly ash	2	2	2	8	chemical and metallurgical applications, associated with mineral residue in fly ash, can have relatively high solubility in water compared with other metals, possibly associated with waste streams that could be hydraulic backfill (e.g. soil)
Nickel	0.02			2	2	2	8	associated with many metal products, can have relatively high solubility in water compared with other metals
Di(2-ethylhexyl)phthalate	0.01		associated with PVC products, may leach from them over prolonged periods of time	2	2	2	8	possibly associated with plastics (plasticiser) and may leach from them
Benzo(a)pyrene	0.0001		can leach from bituminous materials (linings in water distribution systems)	2	1	3	6	genotoxic carcinogen, polycyclic aromatic hydrocarbon (PAH), very low solubility, sometimes found in drinking water that has been transport through systems containing bituminous materials
Styrene	0.03	0.004	associated with industrial contamination	1	2	2	4	volatile oily liquid, limited solubility in water

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Tetrachloroethene	0.05		solvent (dry cleaning especially), degreaser	2	2	2	8	colourless liquid, possibility that it is present in small quantities in some waste streams, classed as a dense non-aqueous phase liquid (DNAPL)
Toluene	0.8	0.025	petrol, natural gas, industrial contamination	2	1	1	2	industrial solvent and feedstock, low solubility in water
Trichlorobenzenes(total)	0.03	0.005	solvent and precursor chemical	2	1	2	4	possibly associated with some wastes
Uranium	0.017		associated with mill tailings, combustion of coal	1	1	2	2	possibly present in mineral residue from coal combustion, likely to have relatively low solubility, especially under anoxic conditions, possibly in waste streams suitable for hydraulic backfill
Zinc	c	3	associated with corrosion of galvanised pipes/fittings and brasses	3	2	1	6	associated with numerous metals and alloys, possibly in waste streams suitable for hydraulic backfill

Key

(i)c = insufficient data to generate value

(ii)d = issues with detecting concentrations associated with health guideline

Agricultural wastes and soil could potentially include pesticides, herbicides, fungicides and related compounds. A large number of such substances exist with varying compositions and physico-chemical and toxicological properties. A number of representative substances have been selected based on potential for environmental impact (i.e. lower drinking water guideline values) and solubilities in water which is of particular relevant to post closure risk assessment modelling. The following substances have been considered in post closure modelling, given their relatively low drinking water guideline values and ranges of solubility in water:

- ▲ Dieldrin
- ▲ Fenamiphos
- ▲ Diquat

Table A-3: Representative pesticides and herbicides, material types, Australian Drinking Water Guidelines and reported aqueous solubilities.

Substance	Australian Drinking Water Guideline	Type of material	Solubility (mg/L)	Source of solubility data
	mg/L			
Aldrin (+dieldrin)	0.0003	organochlorine pesticide	0.011 (aldrin) 0.11 (dieldrin)	ATSDR (2002) Chapter 4 of Toxicological Profile for Aldrin/Dieldrin. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp1-c4.pdf
Heptachlor	0.0003	organochlorine pesticide	0.05	ATSDR (2007) Chapter 4 of Toxicological Profile for Heptachlor. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp12-c4.pdf
Profenofos	0.0003	organophosphorous pesticide	28	PUBCHEM Open Chemistry Database https://pubchem.ncbi.nlm.nih.gov/compound/profenofos#section=Top
Fenamiphos	0.0005	organophosphorous pesticide	700	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/jmpr/jmpmono/v074pr23.htm
Aldicarb	0.004	carbamate insecticide	6000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/0304_72/en/index3.html
Paraquat	0.02	herbicide	620 000	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/icsc/icsc/eics0005.htm
Diquat	0.007	herbicide	718 000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/diquat.pdf
Molinate	0.004	herbicide	880	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/molinate.pdf

The wastes that may be disposed of at the Chandler facility also include NORM (naturally-occurring radioactive material). NORM is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose per year, with about 1% being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

Integrated Risk Assessment

Chandler Facility Risk Assessment

Integrated Risk Assessment



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James Wilson

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Quintessa

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Summary

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF). The development will involve the excavation of rooms in a deep underground salt formation and the subsequent storage and isolation of wastes in these rooms. The project will be located approximately 120 km south of Alice Springs in the Northern Territory of Australia.

This document presents an initial Integrated Risk Assessment (IRA) for the project, using information available at the end of August 2016. It brings together outputs from two supporting assessments:

- ▲ an initial Operational Phase Risk Assessment (OPRA), which assesses risks to the environment around the CF and to the facility's operability that arise prior to closure of the facility (Quintessa report to Tellus, QRS-1809A-OP1); and
- ▲ an initial Post-Closure Risk assessment (PCRA), which assesses risks to the environment around the CF that arise following closure of the facility (Quintessa report to Tellus, QRS-1809A-PC1).

The overall approach to the IRA followed best international practice¹, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia.

Both the OPRA and PCRA were carried out in a "top-down" fashion, such that the starting point was identifying the main threats to operability during the operational phase and the main threats to the environment posed by the facility during both the operational phase and post-closure phase. This process involved assessing the following aspects:

- ▲ the geological environment;
- ▲ the geomechanical behaviour of the CF;

¹ Here "best practice" refers to the well-established approaches and methodologies that are widely applied throughout the world for assessing the performance and safety of various kinds of underground waste disposal and storage facilities. These approaches and methodologies have been developed over several decades during many projects, including ones concerned with radioactive waste disposal, CO₂ storage, natural gas storage, and hazardous waste disposal. No single document describes this best practice, but rather the approaches and methodologies are documented in numerous reports by international agencies such as the International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), International Energy Agency (IEA), International Standards Organisation (ISO), national regulators, and project implementers.

- ▲ the hydrogeology of the site of the CF and its surrounding region;
- ▲ the geochemistry of the site of the CF and its surrounding region;
- ▲ the biosphere.

Phenomena that could cause the identified threats to be realized were determined iteratively, to a level of detail commensurate with the available data and with the goal of achieving a robust assessment while not introducing undue complexity. The likelihood of each threat was then estimated and the possible effects assessed. When doing this, the approach was plausibly conservative, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern. Risks were considered as a product of the probability of a threat and its impact, both being represented on qualitative, linguistic scales on the basis of the available information. To ensure that no key issues had been missed, the assessment was audited against experience in other, similar projects and, where appropriate, lists of Features Events and Processes (FEPs) that had been developed in these other projects.

The operational period covered by the risk assessment is nominally 25 years. Risks to the health and safety of workers are outside the scope of this assessment and are covered by a separate assessment commissioned by Tellus.

The post-closure period considered by the risk assessment is open-ended, but a quantitative assessment was carried out for a period of 1Ma. At increasing times after closure the evolution of the CF and its surrounding environment (e.g. changing climatic conditions and the characteristics of the biosphere) is increasingly uncertain. For this reason the post-closure assessment gives greater weight to qualitative arguments at longer timescales.

The OPRA involved specifying 7 different scenarios for the behaviour of the CF:

- ▲ an Expected Evolution Scenario (EES), which is a statement of how the CF and its surroundings are expected to behave in the operational phase of development and operational plans are implemented properly.
- ▲ six Alternative Evolution Scenarios (AES), which are statements of how the system would behave in the operational phase under alternative sets of circumstances, different to those of the EES.

It is important to note that an AES is *not a prediction* of the future behaviour of the system, but rather a representation of the status of the system under a specified set of conditions.

To assess the risks of operations not proceeding as planned, or the CF unexpectedly not behaving as designed during the operational period (i.e. the EES not being realized), the six analysed AES were:

1. AES 1: Rockfall (in an unfilled or partially-filled room, tunnels);

2. AES 2: Vehicle fire;
3. AES 3: Fixed infrastructure fire;
4. AES 4: Waste package (ISO container or bulka-bag) failure;
5. AES 5: Hydraulic backfill emplacement system failure; and
6. AES 6: Impaired shaft lining performance.

A similar approach was adopted for the PCRA. The most probable scenario (EES) for the post-closure future evolution of the CF is that the facility behaves as planned and no significant contamination leaves it.

To assess the risks of the CF unexpectedly not behaving as designed in the post-closure period (i.e. the EES not being realized), four post-closure AES have been defined:

1. AES1, Connected porosity through the halite roof of the CF;
2. AES2, Collapsed roof of the CF, with the variants:
 - AES2a, Collapsed roof in the operational phase;
 - AES2b, Collapsed roof in the post-closure phase;
3. AES3, Impaired shaft seal;
4. AES4, Accidental human intrusion.

The results of the OPRA and PCRA are presented as risk matrices, which show the highest plausible probability of threat versus plausibly conservative impact if realized.

The IRA provides confidence that, for the proposed categories of wastes and with appropriate facility design and operation, there will be:

- ▲ no significant unmanageable risks in terms of the operability and operational environmental safety of the CF;
- ▲ no significant risks arising from the CF in terms of environmental safety following closure of the facility.

The most probable scenario for the operation of the CF is that it follows the operational plan and that if there are accidents, the consequences can be managed so that there are no lasting unacceptable impacts. Other risks are assessed to be of sufficiently low probability and/ or of insufficient impact, to cause concern.

The risks to the environment beyond the CF that could be caused by plausible deviations from facility development and operation plans are assessed to be less than the risks to the operability of the facility.

No significant post-closure risks to the environment are assessed to arise from the CF in the post-closure phase in the most likely case that the EES is realized and containment is maintained. However, even if containment of the CF were to be lost (i.e. an AES were to be unexpectedly realized), contaminated water would not necessarily

travel to near-surface receptors. Under these circumstances the contaminated water may travel upwards only as far as the aquifers in the Stairway Sandstone. The Stairway Sandstone Formation contains saline water (Total Dissolved Solid content, TDS = 15,000 g/L; Douglas Partners, 2013) and hence is unlikely to be exploited as a groundwater resource. Consequently it is unlikely that near-surface receptors, including humans, would be exposed to the peak contaminant concentrations calculated for the Stairway Sandstone, even if one of the AES were to be realized.

Any contaminants that enter the aquifers of the Stairway Sandstone would be diluted and transported laterally by groundwater flowing slowly under the natural head gradient. The contaminant concentrations would then decrease downstream owing to dispersion. Calculations show that it would take >100,000 years for the concentrations of any contaminants in the Stairway Sandstone to exceed groundwater standard/guideline values at a distance 10 km downstream from the facility in AES1 and both variants of AES2. In the case of AES3, it would take as long as 10,000 years for these groundwater standard/guideline values to be exceeded in the Stairway Sandstone at a distance of 10 km downstream. However, even in the case of AES3 being realized it is possible that some contaminants would never exceed groundwater standard or guideline concentrations at this location.

Were contaminants to be transported via any conceivable pathway from the Stairway Sandstone to shallower aquifers that are more likely to be exploited as water resources, the contaminants would be diluted and dispersed along the pathway to some degree. Thus, these shallower aquifers would tend to have lower contaminant concentrations than those in the Stairway Sandstone at the location where the contaminants left the Stairway Sandstone.

If a shallower aquifer was to become contaminated in this way, contaminants would be transported laterally within the aquifer by groundwater flowing under the influence of the natural head gradient, in the same way as contaminants within the Stairway Sandstone. Thus, contaminant concentrations would decrease laterally within the aquifer, with increasing distance from the CF.

The most significant uncertainties associated with the IRA arise due to:

- ▲ the detailed designs and operational plans for the CF not yet being finalized;
- ▲ the final characteristics and quantities of the wastes not having been defined; and
- ▲ uncertainties in the:
 - behaviour of the wastes under the conditions within the CF (notably the chemical forms in which contaminants occur and their solubilities);
 - driving force provided by the creep of the halite in the post-closure period;

- magnitudes of processes controlling retardation of migrating contaminants (sorption, diffusion into parts of the rock matrix where there is no advection);
- uncertain hydrogeological data, including:
 - hydraulic conductivities of the different rock formations;
 - porosities of the different rock formations;
 - groundwater head gradients;
 - groundwater recharge rates;
 - dispersivity of the aquifers; and
- uncertain lateral connectivity of the aquifers.

These uncertainties have been treated in the assessments by making cautious qualitative arguments and using pessimistic values of relevant parameters, consistent with the available data. It is therefore likely that calculated contaminant concentrations in the aquifers for the post-closure AES tend to over-estimate the concentrations that would actually occur in the rock formations above the CF at any particular location and time in the future, should the CF lose containment.

Taking into account these uncertainties, it is conceivable that, should containment of the CF be lost, no contaminant concentrations in the Stairway Sandstone would ever exceed groundwater standard / guideline values beyond a distance of 10 km from the facility. Since the shallower aquifers are likely to contain even lower concentrations of contaminants than the Stairway Sandstone, it follows that it is even less likely that under these circumstances the shallower aquifers could contain concentrations of contaminants in excess of groundwater standards or guideline values.

It is expected that, as the designs and operational plans mature further, and as the waste characteristics and waste streams become more precisely defined, risks will be reduced further, below those assessed in this report.

Further numerical modelling of the system could reduce the outstanding uncertainties once complete compositions of the wastes have been established and relevant hydrogeological information becomes available.

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1 Introduction

Tellus Holdings Ltd (Tellus) is developing the Chandler Facility (CF), at a site located approximately 120 km south of Alice Springs in the Northern Territory of Australia. The project will involve the excavation of rooms at a depth of approximately 850 m below the ground surface in a halite stratum within the Cambrian age Chandler Formation².

The following risk assessments are required in support of operator and regulatory requirements for this project:

- ▲ an Operational Phase Risk Assessment (OPRA), covering the period between the first emplacement of wastes in the facility and the closure of the facility, nominally 25 years ;
- ▲ a long-term³, Post-closure Risk Assessment (PCRA), covering the period after facility closure, for sufficiently long to ensure that maximum risks have been considered (i.e. considering longer periods would not cause greater maximum risks to be estimated at a point in the future); and
- ▲ an Integrated Risk Assessment, taking into account the OPRA and the PCRA.

These risk assessments will be inputs to the overall safety case for the CF, which in turn will underpin the Environmental Impact Assessment (EIA) that forms a basis for the license application.

The present report aims to deliver an initial IRA, based on information available at the end of August 2016. The considered risks are those arising from the wastes, other risks being outside the scope of the assessment. Health and safety risks to workers are outside the scope of this assessment, but will be covered by a separate assessment that has been commissioned by Tellus.

This report is structured as follows.

² The Chandler Formation is a halite mineral formation that is approximately 520 million years old which corresponds to a time in the Middle Cambrian Period.

³ The overall timescale to be considered by the post-closure assessment is sufficiently long to ensure that maximum risks have been considered. A period of 1 million years is considered quantitatively, consistent with common practice internationally in safety assessments concerned with the underground disposal of radioactive wastes (e.g. NEA, 2007). Beyond this time qualitative arguments are presented, again consistent with common international practice, which recognizes that quantitative assessments become increasingly uncertain over increasingly long time intervals in the future.

- ▲ Section 2 describes the overall approach to the assessment.
- ▲ The context for the assessment is summarized in Section 3.
- ▲ A description of the CF is provided in Section 4.
- ▲ A geological assessment is presented in Section 5.
- ▲ A geomechanical assessment is presented in Section 6
- ▲ A hydrogeological assessment is presented in Section 7
- ▲ A geochemical assessment is presented in Section 8
- ▲ A biosphere assessment is presented in Section 9.
- ▲ The Operational Phase Risk Assessment (OPRA) is presented in Section 10.
- ▲ The long-term Post-closure Phase Risk Assessment (PCRA) is presented in Section 11
- ▲ Overall conclusions are given in Section 12.

2 Overall Approach

The overall approach followed best international practice, in accordance with the requirements of Australian and international regulations, and successful assessments of underground facilities in countries other than Australia.

The approach is consistent with the Northern Territory's WorkSafe Regulations for major hazard facilities (Safe Work Australia, 2012a,b), and covers the following topics that are required under these regulations⁴:

- ▲ establishment of the context (covered by Section 3 of the present report); and
- ▲ safety assessment:
 - hazard identification (covered by Section 4.2.2 of the present report);
 - identification of existing risk controls (covered in part by Section **Error! Reference source not found.** and in part by Section 10.3.3 of the present report);
 - risk assessment, including consequence estimation, likelihood estimation and risk analysis (covered by Section 5, Section 6, Section 7, Section 8, Section 9, Section 10 and Section 11 of the present report);
 - risk evaluation against the adopted criteria (covered by Section 10.3, Section 10.4 and Section 11.2.4 of the present report); and
 - identification of additional risk controls (covered by Section 10.3.3, Section 11.1.3 and Section 11.2.4 of the present report).

The assessment is also designed to meet the requirements of the European Union's regulations governing underground storage and disposal of hazardous materials (specifically Appendix A of Council Decision (EC) 2003/33/EC) and accordingly explicitly:

- ▲ identifies the hazard (in this case the deposited wastes; Section 4.2.2),
- ▲ identifies the receptors (in this case the biosphere⁵ and possibly groundwater; Section 4.2.4),
- ▲ identifies the pathways by which substances from the wastes may reach the biosphere (Section 4.2.3);

⁴ These topics are a subset of all those that need to be considered by a Safety Case developed in accordance with the WorkSafe regulations, consistent with this OPRA being only one of the inputs to the Safety Case.

⁵ The term "biosphere" covers that part of the environment normally inhabited by living organisms at sufficiently shallow depths that might typically be affected by basic human actions such as farming (e.g. see IAEA, 2007).

- ▲ assesses the impact of substances that may reach the biosphere (Section 9, Section 10.3 and Section 11.2.4)

The approach follows closely that which has been adopted in a number of other relevant assessments outside Australia:

- ▲ the assessment by Minosus Limited of an underground waste management facility at the Winsford Rock Salt Mine in Cheshire, UK, in support of a successful license application under the UK's Integrated Pollution Prevention and Control (IPPC) regulations (Hooker et al., 2002);
- ▲ an assessment by Quintessa Limited, on behalf of AkzoNobel Industrial Chemical's B.V. to determine the feasibility of using residual materials from a waste-to-energy plant operated by Twence B.V. to stabilise caverns developed in halite deposits in the eastern Netherlands (Metcalf et al., 2013);
- ▲ assessments for a number of underground radioactive waste disposal facilities, following a general methodology described by the International Atomic Energy Agency (IAEA, 2004).

More specifically, important principles followed during the assessment are:

- ▲ **The approach adopted for the OPRA was consistent with that adopted for the PCRA**, so that the former can provide suitable input to the latter.
- ▲ **The overall approach was “top-down”**, such that the starting point was identifying the main threats to the environment posed by the CF during the operational phase. The factors that influence the likelihood of each threat and their impacts were then identified to a level of detail appropriate for assessing risks in a plausibly conservative manner.
- ▲ **The overall approach was plausibly conservative**, meaning that no analysed threat to the environment is physically impossible and that most people would agree that there is a sufficiently high probability of the threat occurring as to be of concern.
- ▲ **The assessment was structured by carrying out a functional analysis of the CF system** during the operational phase, which was audited against experience in other, similar projects (e.g. Metcalfe et al., 2013; Hooker et al., 2002) and, where appropriate, FEPs⁶. Consistent with the first point, the emphasis is on

⁶There are many slightly different formal definitions of the term “FEP” (e.g. IAEA, 1997; 2004), but fundamentally the meaning of these terms is as follows: A “Feature” is a physical component of a system, or a physical entity that influences a system. An “Event” is a process that influences the evolution of the system over a time period that is short compared to the time frame being considered. A “Process” is a dynamic interaction between “Features”, which may operate over any particular time interval of interest.

identifying threats to the safe functioning of the system, with scenarios⁷ being defined by threats / specific combinations of threats. .

- ▲ **Risk were treated as a product of the probability of a threat and its impact**, the former being estimated qualitatively and the latter being estimated qualitatively.
- ▲ Outputs are presented using commonly-used:
 - **risk matrices**, which show highest plausible probability of threat versus plausibly conservative impact if realized;
 - **bowties** (in the case of the OPRA only), which illustrate graphically, relationships between threats, hazards and potential consequence (if a threat is realized) and provide a basis for risk mitigation planning; and
 - associated **qualitative safety arguments**.

⁷ Following IAEA (2007) a scenario is “A postulated or assumed set of conditions and/or events.”

3 Assessment Context

3.1 Scope of the Risk Assessment

The aims were:

- ▲ to undertake an objective assessment of environmental safety during the operational phase of the facility, covering the following topics:
 - risks arising from the wastes, affecting the overall operation of the facility, including the stability of the storage rooms; and
 - risks of a pathway⁸ developing during the operational period between the wastes and the biosphere during the operational period, such that there is an impact on receptors;
- ▲ to undertake an objective assessment of environmental safety during the post-closure phase of the facility, covering the following topics:
 - describe the properties of the various barriers that act to prevent contaminants travelling from the CF to the biosphere⁹ (equivalent to the “receiving environment” in Australian environmental assessment literature) and hence establish what processes might threaten their barrier function, considering in particular:
 - the wasteforms themselves;
 - engineered materials, such waste containers and backfills;
 - shaft seals;
 - the host rock; and
 - the rocks surrounding the host rock, principally the overburden.
 - risks of a pathway developing between the wastes and the receiving environment, such that there is an impact on receptors;

A goal was to undertake the assessment on a systematic and structured basis, reported in qualitative terms and supported by a range of different information types.

The overall timescale considered by the assessment is open-ended, although in practice the focus has been on the period within which peak risks occur. That is, considering

⁸ A “pathway” is a physical route via which contaminants could potentially move, should they be released from the waste. For example, the possibility that the shafts could form such pathways is considered by the assessment.

⁹ The term “biosphere” covers that part of the environment normally inhabited by living organisms at sufficiently shallow depths that might typically be affected by basic human actions such as farming (e.g. see IAEA, 2007).

longer periods would not cause greater maximum risks to be estimated at a point in the future. While this timescale is not defined precisely, an overall period of 1 million years is deemed sufficient for quantitative analysis, as is common practice internationally in safety assessments concerned with the underground disposal of radioactive wastes (e.g. NEA, 2007).

At increasing times after closure the evolution of the CF and its surrounding environment (e.g. changing climatic conditions and the characteristics of the biosphere) is increasingly uncertain. For this reason the post-closure assessment gives greater weight to qualitative arguments at longer time timescales.

In addition, within the overall time considered frame the assessment discusses in more detail variations in risk over the following time intervals:

- ▲ 300 years (likely institutional control period);
- ▲ 1,000 years (a millennium);
- ▲ 10,000 years; and
- ▲ 10,000 years to 1 million years.

A goal was to undertake the assessment on a systematic and structured basis, reported in qualitative terms and supported by a range of different information types.

Impacts to workers (as opposed to human receptors not part of the facility workforce) are explicitly out of scope, and are instead considered in separate safety case / HAZOP documents.

3.2 Key Regulatory Requirements

The principle regulatory submissions that will be underpinned by this work are listed below but it is stressed this is not a complete list and other submissions will draw on the IRA and the PSC.

- ▲ Environmental Impact Assessment Guidelines for the Chandler facility project, (<http://www.ntepa.nt.gov.au/environmental-assessments/assessment/register/chandler-salt-mine>);
- ▲ Northern Territory of Australia *Waste Management and Pollution Control Act*, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/waste%20management%20and%20pollution%20control%20act>);
- ▲ Northern Territory of Australia *Mining Management Act*, (<http://notes.nt.gov.au/dcm/legislat/legislat.nsf/linkreference/MINING%20MANAGEMENT%20ACT>);

- ▲ Northern Territory Environmental Protection Authority (NT EPA) Guidelines for the Siting, Design and Management of Solid Waste Disposal Sites, (https://ntepa.nt.gov.au/__data/assets/pdf_file/0006/284685/siting_design_1_andfills.pdf);
- ▲ Mining Management Plan requirements for the mining of minerals, http://www.nt.gov.au/d/Minerals_Energy/index.cfm?header=Mining;
- ▲ Northern Territories Worksafe Major Hazard Facilities guidance on the form and structure of the required risk assessment, (<http://www.worksafe.nt.gov.au/IndustrySectors/Pages/Major-Hazard-Facilities.aspx>)

3.3 Information and Data Sources

Information and data from a wide range of sources have been reviewed and assessed in preparing this IRA. References to relevant documents are provided in context in subsequent sections, and listed in Section 13. Additional information supplied directly to the authors is summarized in the Appendices. The assessment is primarily based upon information made available by late August 2016. Types of information and data sources reviewed include the following.

- ▲ regulatory guidance documents (Australian and international regulatory sources; including those given in Section 3.2 above);
- ▲ information on potential/projected wastes streams;
- ▲ geological and geotechnical reports;
- ▲ groundwater analyses from the Maryvale property and from the wider region;
- ▲ information on the hydrogeology of the Maryvale property and surrounding region, including a number of Technical Notes and e-mail communications by Tellus' hydrogeology contractor G. Ride;
- ▲ a number of documents concerning the proposed facility design;
- ▲ documents concerning the proposed approach to facility operation; and
- ▲ information undertaken about risk assessments undertaken for analogous international facilities.

4 Description of the Chandler Facility (CF)

4.1 Facility Description¹⁰

The current underground CF design (illustrated in **Figure 4-1**), which was developed during the pre-feasibility study, consists of a uniform room and pillar system with long rectangular pillars. Systematic roof bolting is assumed to be required in the access roads and storage rooms. This provisional underground layout is currently being reviewed as part of a geotechnical work programme.

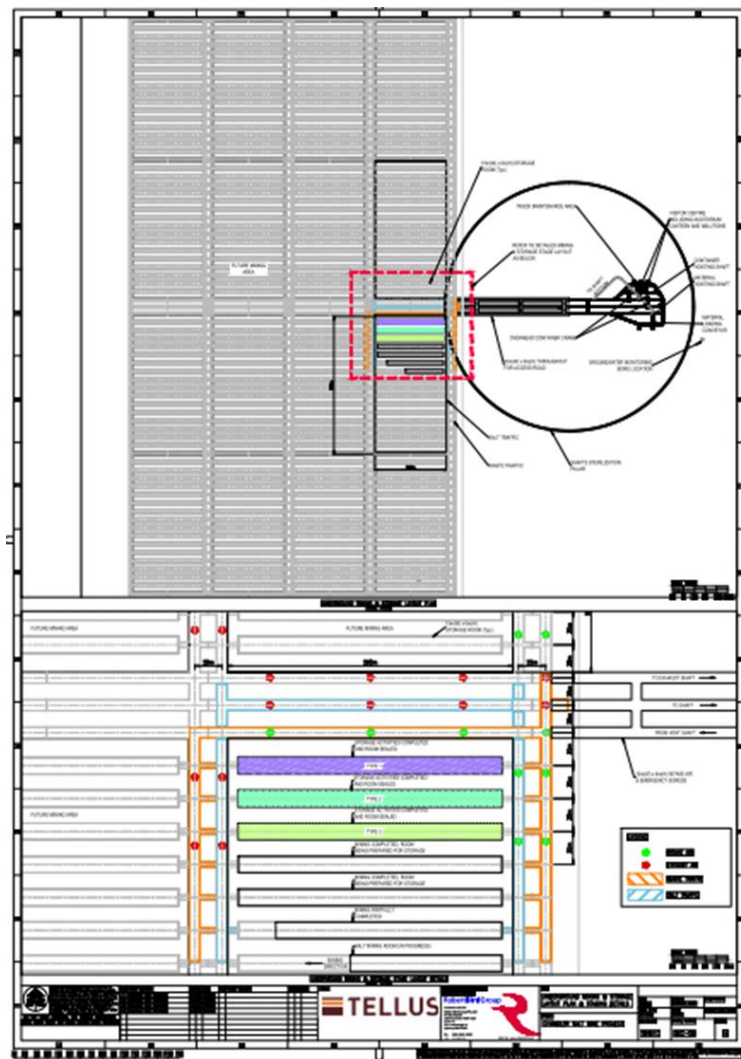


Figure 4-1: Illustration of CF layout.

¹⁰ The facility description set out in the following pages is based upon discussions with Tellus and references including: K-UTEC, 2015; RPS, 2013; TELLUS, 2015; Douglas Partners, 2013; URS, 2012; and underpinning and related references.

Quintessa

The salt deposit will have been accessed by two vertical shafts, each nominally 800 m deep¹¹. The shaft through which the wastes will have been emplaced will have an internal diameter of 8.5 m. The second shaft, through which the mined salt will have been transported, will have an internal diameter of 6.0 m. Dimensions of storage and disposal rooms are yet to be confirmed. However, provisional dimensions for the storage rooms are 250 m x 10 m x 6 m and provisional dimensions for the disposal rooms are 250 m x 15 m x 6 m. Pillars between the rooms are nominally sized at 15m width currently within each panel, but the widths of the rooms at the margins of the panels may be reduced to take into give an additional margin of safety with respect to creep. Overall the facility has provisional underground dimensions of 2 km x 2 km x 6 m, with a 32% extraction ratio when taken in plan view. Main development roads are to be driven in the same salt horizon and are currently assumed to be 10 m wide by 6 m high.

The wastes will exist in the closed Chandler facility in two forms:

- ▲ wastes emplaced “dry” in packages ; and
- ▲ wastes emplaced as a “hydraulic backfill”.

Dry packaged waste packages will be surrounded by crushed salt (**Figure 4-2**). Rooms in which wastes are emplaced hydraulically will be fully filled, apart from a small headspace volume near the entrance (**Figure 4-2**).

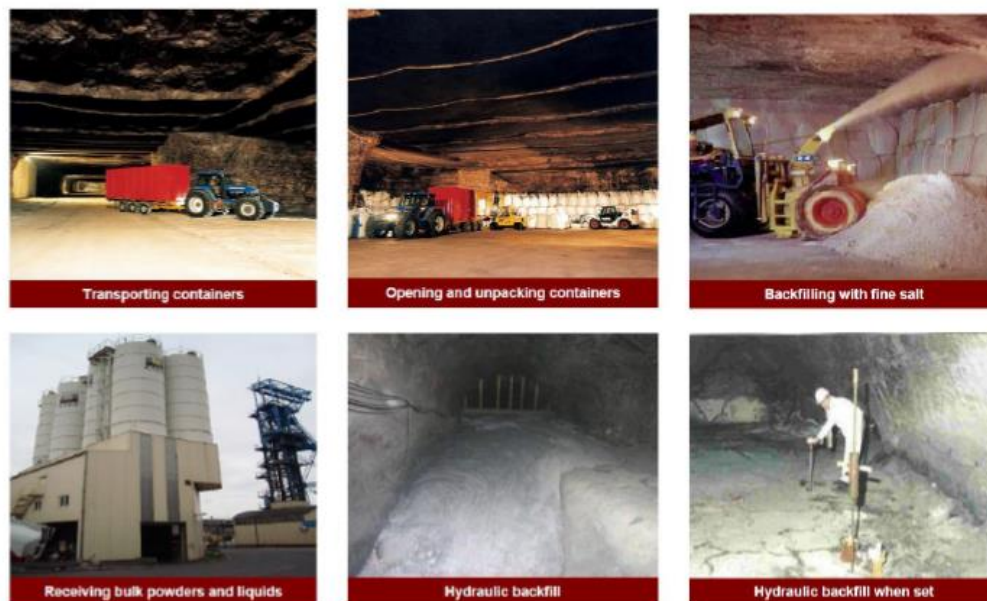


Figure 4-2: Visual representation of waste handling and storage techniques (courtesy of Tellus Holdings).

¹¹ Consideration is also being given to the possibility of accessing the facility via a decline. The implications of this option for the assessment presented in the present report are given in a separate Technical Note (Quintessa Report to Tellus QRS-1809A-DC1).

Shaft seal designs have yet to be finalised, but are likely to be based on experience at the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, and at various facilities excavated in salt in Germany.

The closure engineering for the shafts is therefore likely to comprise:

- ▲ a concrete monolith at the base, within the salt formation;
- ▲ high integrity seal through the lower part of the rock sequence and probably through the lowest “aquifer” unit, although this depends on the depth of that unit;
- ▲ seals at the base of each aquifer unit and wall grouting through the aquifer unit (note that any areas of potentially significant flow would have been grouted for operations);
- ▲ backfilling the shafts between the seals using some combination of crushed host rock, clay, cement and sand.

For the purposes of the initial post-closure assessment, the details of the construction of the seals are not important. The assessment requires the transport properties of the seal (i.e. a specification for performance) rather than the engineering details. The properties of the seals will be based on those used in the post-closure assessment of the Deep Geological Repository (DGR) at the Bruce site in Canada (Quintessa. and Geofirma Engineering, 2011).

The initial condition for the post-closure assessment is a fully backfilled facility with all of the barriers correctly emplaced. This forms the basis for the normal evolution scenario.

4.2 Location and Surface Environment

The site is located approximately 120km south of Alice Springs in the Northern Territory of Australia and lies at the transition between erosion-resistant low hills to the northwest and a sandy plain to the southwest (Figure 4-3). The closest community to the facility, Titjikala (c. 180 people) is located about 18 km to the northeast.

The region has low rainfall. URS (2012) reports a maximum annual rainfall of c. 300 mm annually, while the Australian Bureau of Meteorology (BOM) give an annual mean of 197.4 mm for the Maryvale station between the years 1948 and 2014. However there can be high, intense rainfall events and the BOM give a maximum monthly rainfall of 226.3 mm during these years. Precautions will be taken (e.g. siting on relatively high ground, drainage channels to divert water) to prevent flooding of the facility.

4.2.2 Hazard Identification

Waste Emplacement Strategy

Two emplacement methods will be used at the Chandler facility:

- ▲ “dry” solid waste emplacement; and
- ▲ “hydraulic backfill” emplacement.

Details are summarized below:

Dry Emplacement

- ▲ Wastes will be emplaced dry in multiple locations (different rooms) simultaneously.
- ▲ Different categories of waste will be located in different rooms called zones to keep non compatibles wastes physically separated.
- ▲ These wastes will be contained in:
 - double-lined Flexible Intermediate Bulk Containers (FIBC), also termed “bulka-bags”, which are constructed of woven fabric; or
 - barrels of granular material; and
 - may have a more robust over pack if necessary.
- ▲ The waste-containing bulka-bags or barrels will be placed on pallets within 20-foot long ISO-containers. There will be 10 pallets on the floor of each container. Each container could contain up to 20 bags weighing about 1 tonne each.
- ▲ Each ISO-container will be transported into the facility via the wider shaft and opened in the room within which the waste is to be emplaced.
- ▲ There will normally be entrances to both ends of the room in which the waste is emplaced, which will be sealed by doors.
- ▲ At the time of closure there will be some residual voidage, which is a combination of pore space in the packaged waste and in the backfill, and some small amount of excavated space that is not filled by backfilling material (100% filling being unattainable in practice).
- ▲ Air circulating in the rooms will be filtered using standard dust filters that are commonly used in mines.

Hydraulic backfill Emplacement

- ▲ Wastes emplaced in a hydraulic backfill will be wet at the time of emplacement, but will subsequently cure to form a dry solid.

- ▲ Wastes will be emplaced in this form in only a single location at any one time.
- ▲ The room configuration for hydraulic backfill emplacement is different to that for dry emplacement. Rooms will have a slight incline downwards from a single entrance, so that a tendency for the wastes to flow will be directed away from the entrance.
- ▲ Following waste emplacement there will be almost no voidage due to imperfect filling of the emplacement rooms apart from a small wedge-shaped void at the end nearest the door. The backfill itself will contain some inter-grain porosity after curing.
- ▲ During filling there will be no workers within a room.
- ▲ In order to emplace the hydraulic backfill, pipes will be installed within the facility. Only the last part of the pipe, within the emplacement room, will be flexible.
- ▲ There will be pressure monitors within the pipe network.
- ▲ Potential bursts have been considered in the conceptual design of the facility. There will be valves within the pipe network enabling emergency shut-offs to minimise the volume of waste that might be spilt. Depending upon the mix used, the hydraulic backfill could become solidified within the pipe, if for any reason pumping needs to be stopped. For example such solidification may potentially follow a shut-off after a leakage event. In such a case the pipe will need to be replaced and the replaced section of pipe will effectively become solid waste.

Mobile and Static Infrastructure

- ▲ Movement of salt and wastes will be via diesel vehicles.
- ▲ It can be assumed that while rare in normal operation, over the course of the 25 year long operational period there will be some vehicle or machinery fires. However, if these do occur, there will be a mitigation strategy in place to reduce possible impacts.
- ▲ Leaks of any fuel/oil would be recognised and remediated.

Post-closure Waste Characteristics

The wastes will have the following post-closure characteristics:

Wastes Emplaced in Dry Form

- ▲ At the time of closure, the wastes will be in the form in which they have been emplaced, surrounded by salt backfill.
- ▲ At this time there will be some residual voidage, which is a combination of pore space in the packaged waste and in the backfill, and some small amount of excavated space that is not filled by backfilling material (100% filling being unattainable in practice).

Wastes Emplaced as Hydraulic Backfill

- ▲ Wastes that have been emplaced in a hydraulic backfill comprise an essentially dry solid in the post-closure phase, the backfill having been formulated to have very little free water following curing.
- ▲ There will be almost no voidage due to imperfect filling of the emplacement rooms, apart from a small wedge-shaped void at the end nearest the door. There will be some intergranular porosity within the cured backfill.
- ▲ The hydraulic backfill may have substantial porosity after emplacement, depending upon its formulation. A porosity of several tens of percent may be possible.

Waste Types and Inventory

A list of potential wastes has been provided by Tellus (Table A1, Appendix A), based on:

- ▲ National Environment Protection Measures (NEPM) 75 waste categories;
- ▲ the assumption that an average of 340,000 tonnes per annum (tpa) will be emplaced, starting by receiving waste at the storage and transfer station during construction at 30,000 tpa, increasing to 90,000 tpa for the next three years followed by a steady state of 200,000 tpa plus annual growth, with an overall design capacity of 400,000 tpa;
- ▲ the assumption that there will be a total of c. 8.5 million tonnes of waste emplaced over the 25 year operational lifetime of the project; and
- ▲ market research.

A list of the top 20 waste categories along with a description and identification of possible hazardous substances is given in Table 4-1.

It should be noted that Waste Acceptance Criteria (WAC) will be developed and adopted that are consistent with European legislation (specifically Appendix A of Council Decision (EC) 2003/33/EC and Article 5(3) of the Landfill Directive, Council

Directive (EC) 1999/31/EC). Accordingly, a number of waste types / forms will not be permitted:

- ▲ wastes listed in Article 5(3) of the Landfill Directive:
 - liquid waste¹²;
 - waste which, in the conditions of landfill, is explosive, corrosive, oxidising, highly flammable or flammable (as defined in Annex III to Directive 91/689/EEC);
 - hospital and other clinical wastes arising from medical or veterinary establishments, which are infectious as defined by (property H9 in Annex III) Directive 91/689/EEC);
 - whole used tyres and shredded used tyres.
 - wastes and their containers which might react with water or with the host rock under the storage conditions and lead to:
 - generation of auto-flammable or toxic or explosive substances or gases; or
 - any other reactions which could endanger the operational safety and/or the integrity of the barrier.
- ▲ wastes which might react with each other must be defined and classified in groups of compatibility (the different groups of compatibility must be physically separated in the storage);
- ▲ wastes that are biodegradable;
- ▲ wastes that have a particularly pungent smell;
- ▲ wastes that can generate a gas-air mixture which is toxic or explosive, in particular that:
 - cause toxic gas concentrations due to the partial pressures of their components
 - form concentrations when saturated within a container, which are higher than 25 % of the concentration which corresponds to the lower explosive limit);
- ▲ wastes with insufficient stability to correspond to the geo-mechanical conditions
- ▲ wastes that are auto-flammable or liable to spontaneous combustion under the storage conditions, gaseous products, volatile wastes, wastes coming from collections in the form of unidentified mixtures; and

¹² Initially liquid wastes may be accepted if they have undergone a process to incorporate them into a wasteform suitable for disposal prior to emplacement in the facility.

- ▲ wastes that contain, or could generate pathogenic germs of communicable diseases.

Table 4-1: Top 20 “75” code waste descriptions, expected mass proportions at the CF and identification of potential hazardous substances.

NEPM “75” code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
N205	25.30%	Residues from industrial waste treatment/disposal operations	Scrubber sludge; Ion-exchange column residues, Ind waste treatment sludges and residues nos, Residues from pollution control operations nos	heavy metals/metalloids, organic compounds, <i>possibly pesticides</i>	Large component of inventory, possibly largely immobilized in hydraulic backfill
D110	19.60%	Inorganic fluorine compounds excluding calcium fluoride (SPL)		fluoride	<i>Largely low solubility material?</i>
N120	16.60%	Soils contaminated with a controlled waste		heavy metals, hydrocarbons (see other entries)	<i>Trace/minor amounts of metals, metalloids, hydrocarbons, possible pesticides(?), assume containerised</i>
N220	10.70%	Asbestos		amosite, chrysotile, crocidolite	<i>Assumed contained in inert matrices, potential for loose fibres / degrading ACM? Potential for Hydraulic backfill</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
J120	5.60%	Waste oil/ water, hydrocarbons/ water mixtures or emulsions	Vehicle washwaters Boiler blowdown sludge Cooling tower washwaters Textile effluent & residues nos Industrial plant washwaters Ethylene glycol-water (antifreeze) Oil/hydrocarbon (<50%) mixed with water Oil/hydrocarbon (>50%) mixed with water Other (cutting oils, soluble oils) Oil/hydrocarbon mixed with water nos	numerous hydrocarbons	<i>Potentially not suitable for hydraulic backfill</i>
D220	4.90%	Lead; lead compounds	Lead acid batteries Gritblast waste Lead & lead compounds nos	lead	<i>Assume battery acid liquid, and other forms are solid, liquids not suitable for hydraulic backfill?</i>
C100	4.90%	Basic solutions or bases in solid form	Alkaline cleaners, potash, caustic soda Ammonium hydroxide Waste lime & cement (no metallic constituents) Caustic neutralised waste (metallic constituents) Other alkaline waste (inorganic) Other alkaline waste (organic)	ammonia (others such as metals)	<i>Assume solid possible sludges? Possible hydraulic backfill candidate?</i>
D230	2.90%	Zinc compounds	Zinc ash/dust, galvaniser's ash Zinc compounds	zinc (and possibly cadmium as an impurity)	Assume solid, including particulates
NORM ¹³	2.20%	NORMs	Mining related resins, oilfield sludges etc., but <i>not</i> NORM derived from the Nuclear Fuel Cycle.	radium, radon, barium, (uranium?) + associated radioactivity	Assume solids, with Rn gas being generated over longer timescale by decay

¹³ Naturally Occurring Radioactive Material

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
J100	2.20%	Waste mineral oils unfit for their original intended use	Mineral oils unfit for their original intended use Oil filters Transformer fluids (excluding PCB's) Waste hydrocarbons	numerous hydrocarbons	<i>Unsuitable for hydraulic backfill?</i>
D300	1.20%	Non-toxic salts	Aluminium dross, aluminium smelter waste Salt slag Non-metallic product Non-toxic salts no	aluminium compounds, other metals	Assume solid
B100	0.80%	Acidic solutions or acids in solid form	Sulfuric acid Hydrochloric acid Nitric acid Phosphoric acid Chromic acid, sodium dichromate Hydrofluoric acid Sulfuric/hydrochloric acid mixtures Mixed acids (inorganic) Organic acids Pickle liquor Acids nos	<i>assume acids have largely been neutralised prior to disposal? may have some chromium/fluoride/sulphate/phosphate/chloride compounds.</i>	<i>Assume insoluble salts?</i>
N160	0.50%	Encapsulated, chemically-fixed, solidified or polymerised wastes referred to in this list	Encapsulated waste Chemically fixed waste Solidified or polymerised waste	see other entries	Solids

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics</i> indicate areas of uncertainty in future characteristics)	Assumptions on Form and Disposal Route (NB <i>italics</i> indicate areas of uncertainty in future characteristics)
F100	0.50%	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	Paints, inks, etc. (aqueous non-flammable vapours) Paints, inks, etc. (aqueous, flammable vapours) Paints, inks, etc. (solvent combustible FP<60.5C) Paints, inks, etc. (solvent combustible FP>60.5C) Paint residues nos	numerous compounds, including solvents	<i>Unsuitable for hydraulic backfill?</i>
M100	0.30%	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or polybrominated biphenyls	Oil, solvents & materials contaminated with PCB Equipment containing PCBs Polychlorinated biphenyls (PCBs) nos Equipment containing PCNs, PCTs and PBBs PCNs, PCTs and PBBs	PCBs, PCTs, PBBs	<i>Unsuitable for hydraulic backfill?</i>
N100	0.30%	Containers and drums that are contaminated with residues of substances referred to in this list	Drums containing waste which must be tracked Other containers containing waste which must be tracked Aerosol cans	see other entries	Containerised materials, probable low water content
N190	0.20%	Filter cake contaminated with residues of substances referred to in this list	Filter cake	see other entries	<i>Containerised solid?</i>

NEPM "75" code	%	Waste Description (NEPM schedule A, list 1)	NSW Description from https://www.epa.nsw.gov.au/owt/wclist.htm	Possible Hazardous Substances (NB <i>italics indicate areas of uncertainty in future characteristics</i>)	Assumptions on Form and Disposal Route (NB <i>italics indicate areas of uncertainty in future characteristics</i>)
G110	0.20%	Organic solvents excluding halogenated solvents	Klenasol (non-chlorinated) Non-halogen organic solvents (flammable FP<60.5C) Non-halogen organic solvents (combustible FP>60.5C) Non-halogenated organic solvents nos	organic solvents	<i>Unsuitable for hydraulic backfill?</i>
M250	0.10%	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	Surfactants	surfaces, metals/metalloids	<i>Unsuitable for hydraulic backfill?</i>
A100	0.10%	Waste resulting from surface treatment of metals and plastics	Waste from metals & plastics treatment	metals, plastic degradation compounds	Possibly includes superplasticiser compounds

For both the OPRA and PCRA, all substances of possible concern to the receiving environment present in each waste type have been considered. All the hazardous substances in the wastes that are listed in the relevant NEPM guideline (NEPC, 2013) are considered. These substances also include priority substances and certain other pollutants within the corresponding EU legislation (Environmental Quality Standards, Council Directive (EC) 2008/105/EC).

The first step in considering these substances is to rank them 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Appendix A, Table A2). The product of the three values is then used to derive an “index” value used to identify substances of greater importance, a subset of which is suggested for consideration by the PCRA in particular. This index does not take into account interactions that occur because of the mixing of compounds that might in turn result in a product with higher solubility/mobility and/or toxic potential. However, the index approach is appropriate for the present assessment, taking into account that:

- ▲ the waste will be emplaced within a virtually dry salt formation, such that toxic compounds will not be mobilized significantly by water; and
- ▲ wastes will be emplaced in such a manner as to prevent such interactions.

Once more detailed information becomes available about the nature of the wastes, further assessment will be needed to determine any potential interactions that might be detrimental to safety. This knowledge can be used to ensure that waste handling and emplacement are carried out in a way that appropriately separates different waste types if needed to prevent such interactions.

This ranking process identified the following substances of greatest priority:

- ▲ Beryllium (score 12);
- ▲ Chromium (as Cr(VI)) (score 12);
- ▲ Dichloromethane (score 12);
- ▲ Hexachlorobutadiene (score 12);
- ▲ Mercury (score 12);
- ▲ Benzene (score 9);
- ▲ Epichlorohydrin (score 9);
- ▲ Lead (score 9);
- ▲ Molybdenum (score 8); and
- ▲ Nickel (score 8).

A number of different pesticides/herbicides could be associated with wastes from agriculture and soils; a list of representative substances is given in Appendix A (Table A3).

For the PCRA in particular, a subset of illustrative substances has been identified based on potential toxicological hazard and aqueous solubility:

- ▲ Dieldrin;
- ▲ Fenamiphos; and
- ▲ Diquat

Naturally-occurring radioactive material (NORM) is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate most likely from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose per year, with about 1 % being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

Releases of the substances underground could take the form of:

- ▲ spills from containers of solids, leading to dusts being introduced to the cavern atmosphere; and
- ▲ leakage from pipes carrying hydraulic backfill, leading to waste slurry being released to the roadways or shafts, depending upon the leak location (although this waste would solidify during curing of the backfill).

4.2.3 Pathways

In accordance with usual practice for risk assessments of underground waste facilities, a judgement is made of the likelihood that a pathway could develop between the emplaced waste and receptors of concern, either in the operational period or the post-closure period. The approach is to consider all the kinds of natural and engineered features of the CF that could potentially form such a pathway, either individually or in combination, given unexpectedly adverse conditions. The intent is *not* to predict that such pathways will occur, but rather to identify the kinds of pathways that should be considered by subsequent “what if” analyses designed to assess the impacts of the pathways developing. It should be noted that even if a pathway were to develop unexpectedly, this would not in itself imply a high environmental risk; for a high risk to result, the consequences of the pathway developing would also need to be high.

The potential for the following kinds of pathways to connect hazardous substances and receptors during the operational phase are assessed:

- ▲ shafts, which could allow any dusts/aerosols released underground to be transported to the surface during operations;
- ▲ pathways linking the caverns to aquifers in the overburden:
 - transmissive fractures or faults (noting that no faults have been identified within the footprint of the facility);
 - collapse columns that would be created should the roof of a cavern fail;
- ▲ aquifers in the overburden (in combination with other kinds of pathway); and
- ▲ pathways associated with boreholes intersecting other transmissive features (it being assumed that no boreholes will penetrate from the surface into the footprint of the facility, so that only shallower monitoring boreholes, which have depths of up to c. 300 m, could potentially form part of a pathway).

The assessment considers the following kinds of potential pathways during the post-closure period:

- ▲ shafts with impaired (degraded) seals which could allow contaminants to be transported in aqueous form to rock formations above the Chandler Formation;
- ▲ pathways linking the caverns to aquifers in the overburden:
 - transmissive fractures or faults (noting that no faults have been identified within the footprint of the facility);
 - collapse columns that would be created should the roof of a cavern fail;
- ▲ aquifers in the overburden (in combination with other kinds of pathway); and

- ▲ pathways associated with boreholes intersecting other transmissive features (it being assumed that no boreholes will penetrate from the surface into the footprint of the facility, so that only shallower monitoring boreholes, which have depths of up to c. 360 m, could potentially form part of a pathway).

Not all these kinds of pathway could on their own, provide a route from the waste to a receiving environment, but rather would need to act in combination with one or more other pathways. For example, all the aquifers are almost horizontal and isolated from the Chandler Formation by impermeable or poorly permeable rock formations. Hence, for an aquifer to form part of a pathway between the wastes and a receiving environment, it would need to be connected to the wastes by a different kind of pathway, such as a shaft with degraded seals. Furthermore, another pathway would be needed to connect the aquifer to a near-surface receiving environment. A borehole drilled into the aquifer in the future to obtain water for irrigation might provide such an additional pathway.

4.2.4 Receptors

In general terms a receptor is something that could be adversely affected by a contaminant, such as people, an ecological system, property, or a water body¹⁴. The IRA needs to consider both those receptors that occur at the present and also those that could potentially occur in the future. Given the very long time frame of the PCRA, the receptors that need to be considered could change considerably. Furthermore, any given receptor may not be present throughout this timeframe. For example, climate change may mean that farming can occur near the CF at some times, but not at others. Owing to this variability, it is inappropriate to give detailed descriptions of the receptors. Instead, general kinds of receptor are identified.

As noted above, most of the groundwater in the vicinity of the CF is too saline to be potable and the aquifer units discussed above are not used for drinking water. Some water is extracted for stock watering, usually from the Horseshoe Bend Shale Formation or the Upper Langra Formation.

The quantitative analysis undertaken as part of the post-closure assessment treats the aquifers as the primary receptors of concern. It is the concentration in each aquifer of contaminants that originate in the waste that is taken as the comparison point. However, it should be noted that the existing water in the aquifers may not meet the standards set out in the various groundwater regulations (Australian Drinking Water Guidelines, v6, 2011 (updated March 2015); World Health Organization (WHO) Drinking Water Guidelines, v4 (2011); Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)).

¹⁴ e.g. Environment Agency of England and Wales (2004); South Australian Environmental Protection Authority (2007).

Based on the quantitative assessment of the aquifers, potential impacts on the following additional receptors are then assessed:

- ▲ surface water bodies;
- ▲ groundwater aquifers;
- ▲ surface soils;
- ▲ air;
- ▲ humans (members of the wider public, since worker health and safety is not included in this assessment);
- ▲ flora (including crops);
- ▲ fauna (including livestock).

5 Geological Assessment

The Chandler facility is located in the eastern part of the Amadeus Basin, within a tectonically stable plate interior, thousands of kilometres from the nearest tectonic plate boundaries that are characterised by frequent seismicity and on-going intense deformation (Figure 5-1).

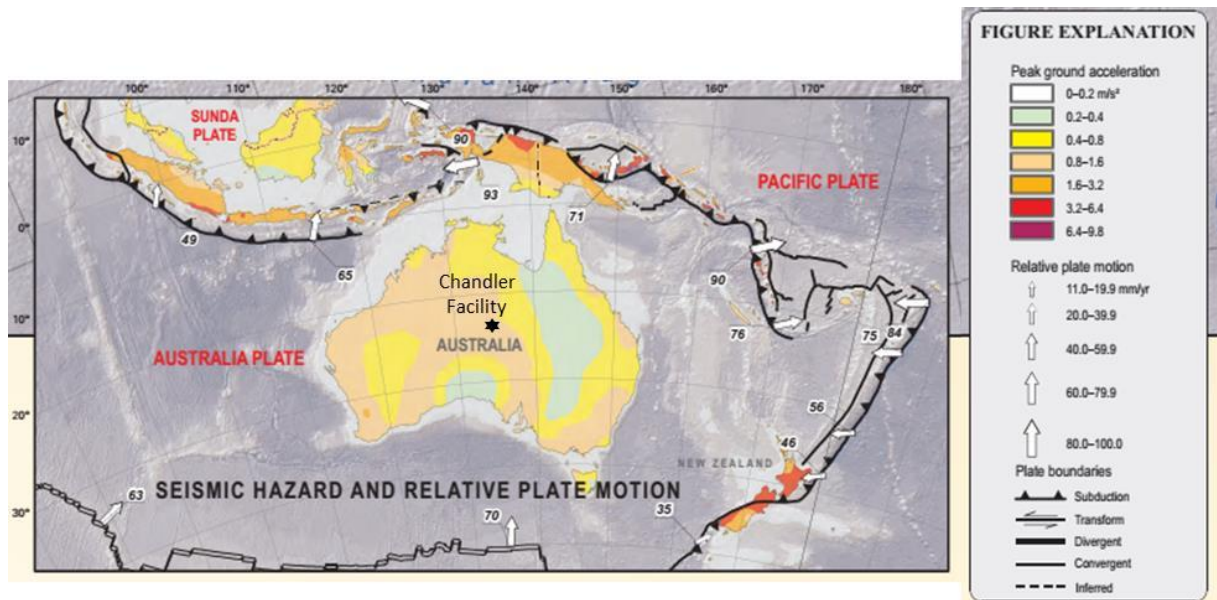
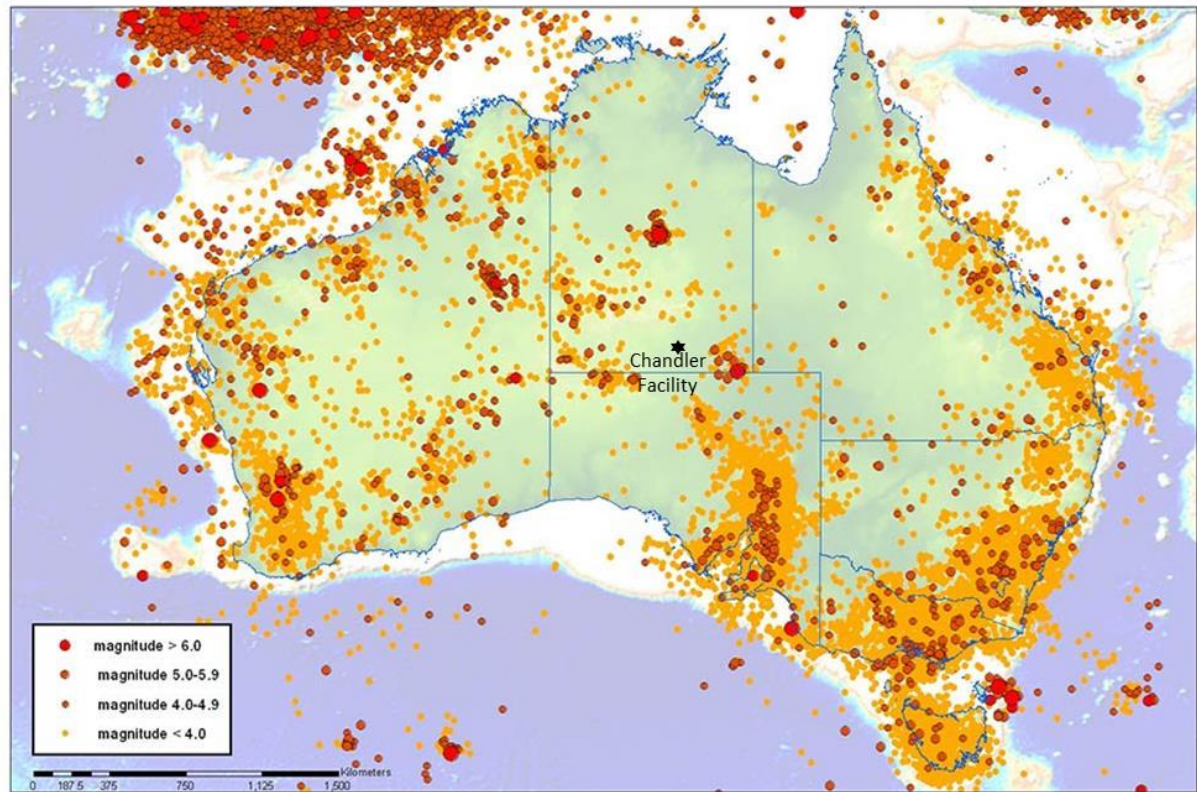


Figure 5-1: Location of the CF in the stable interior of the Australian tectonic plate (after Benz et al. (2011)).

Nevertheless, earthquakes do occur in stable continental interiors and indeed there have been several earthquakes of magnitude up to 6.6 (the largest recorded in Australia) within the area of Northern Territory (Figure 5-2). However, there have been no recorded large earthquakes within the vicinity of the CF.

Even were such earthquakes to occur, the underground facilities would not be affected significantly, since damaging vibrations (Rayleigh Waves and Love Waves) occur only at the earth's surface. Extensive research in Japan, a far more seismically active country than Australia, has established the feasibility of siting geological disposal facilities for high level radioactive waste (HLW) at depths comparable to those proposed for the CF, provided that active faults do not occur near the facility (JNC, 2000). Seismic vibrations are attenuated rapidly and would be very unlikely to be felt at the depth of the 800 m depth of the CF (see for example the dataset from Kamaishi Mine, Japan; JNC, 2000).



All Australian earthquakes located up to 2011

Figure 5-2: All recorded Australian earthquakes up to 2011. After Geoscience Australia (<http://www.ga.gov.au/scientific-topics/hazards/earthquake/basics/where>)

Earthquakes are caused by a sudden rupturing (faulting) of rocks under a prevailing stress regime, or a sudden movement (re-activation) of existing faults. The earthquakes would only be of concern to the safety of a deep underground facility if the moving fault that causes the earthquake were to intersect the facility. However, under the stress regime in central Australia new faults are not expected to form. Furthermore, seismic surveys have revealed no faulting within the footprint of the CF, or its surroundings (RPS, 2013) and it follows that any faults that do occur must be too small to be resolved (displacements likely <10 m). Since there is a well-established correlation between the sizes (displacements) of existing faults and the magnitude of earthquakes that are likely to occur along them (Wells and Coppersmith, 1994), it follows that the risk of movements of existing faults within the CF causing significant seismic events is not a concern.

Despite the complex history of the Amadeus Basin, the strata in the area of interest are be relatively flat lying and continuous. To the northeast of the CF, within the south eastern Amadeus Basin is the Camel Flat Syncline. The near surface formations within this syncline are a different sequence of formations than those that occur in the upper sequences at Chandler, but which occur in the northern Amadeus Basin, for example the Mereenie Sandstone. About 40 km to the south of the facility, the relatively flat lying Amadeus Basin formations present at the location of the CF plunge deep below the Pedirka Basin.

The geological structure in the area of interest has been sampled by four deep boreholes that reach the Cambrian Chandler formation, two drilled by Tellus (CH001A and CH003), and two pre-existing oil exploration wells (Mt Charlotte No. 1 and Magee). CH001A lies at the northern margin of the underground footprint of the facility, while the other boreholes are outside the facility's footprint. Boreholes CH001A and CH003¹⁵ were drilled to investigate the full thickness of the salt for site investigation purposes and were subsequently fully sealed with cement. CH001A was fully cored. Additionally 9 shallower boreholes, with depths of up to 300 m, were drilled within the footprint of the facility during 2015 for the purposes of obtaining hydrogeological information. These shallower boreholes will be left open during operations and potentially during the following institutional control period for the purposes of monitoring. There is also some 2D seismic coverage in the area, which has been reprocessed as part of the Tellus investigations.

According to Douglas Partners (2016), the basic stratigraphy at the proposed facility location is:

- ▲ surface to about 8m: recent deposits, including sand dunes;
- ▲ 8m - 343m: Horseshoe Bend Shale and Langra Formations (upper, middle and lower). The Langra Formation in this region consists of alternating thin bands of hard siltstone and very fine sandstone ;
- ▲ 343m – 390m: Parkes Siltstone;
- ▲ 390m – 503m: Stairway Sandstone, which comprises interbedded sandstone and siltstone;
- ▲ 502m – 772m: Jay Creek, which mainly comprises dolomitic siltstone;
- ▲ 772m – 1085m: Chandler Formation, which comprises anhydritic siltstone to 825m and halite below that. Core from boreholes CH001A and CH003 show the salt to be almost pure halite with very few marly beds or other impurities.

The facility will be located in the upper part of the Chandler salt formation. The upper halite bed in borehole CH001A is present in the depth interval 825m – 861m (Joint Ore Reserves Committee (JORC) report (ERCOSPLAN, 2014)). It is overlain by siltstone and underlain by a 10m thick bed of limestone/siltstone. Below this bed, the formation is dominantly halite with minor limestones and siltstones. Interpretation of the seismic data has identified the extent of the salt horizon and suggests that it is stable (i.e. in the CF are the salt does not appear to have been subject to any dissolution in the past it is not migrating as a diapir (RPS, 2013)).

The target horizon is 35m thick in borehole CH001A and 34m thick, and at a slightly shallower depth, in borehole CH003. The intention is that there should be 20m of intact salt

¹⁵ CH003 was stopped at 843m but the objectives for the exploration hole were achieved.

above the excavations, which implies that the facility would be at a depth of approximately 850 m and there would be 8-9m of salt between the facility and the underlying limestone bed.

It is anticipated in-seam seismic etc. will be used to identify faults/features of interest up to several hundred metres ahead of and prior to excavation. Therefore it can be assumed that the CF will not be intersected by any faults or features that are likely to be a pre-existing pathway to the overlying formations because the layout would be adjusted to ensure an appropriate standoff distance. Some minor concealed faults have been suggested but these do not appear to be within the footprint of the facility.

There are no known resources in the area of interest, apart from the Chandler salt formation and a much deeper salt horizon. The area has been investigated for hydrocarbons, which are found further to the west in the Amadeus Basin, but no significant hydrocarbons were found in the Chandler area and the seismic and other data indicate that there are no obvious structures within which significant accumulations would be trapped. Similarly, previous exploration for uranium and diamonds has been unsuccessful.

6 Geomechanical Assessment

Preliminary investigations of the geomechanical behaviour of the CF have been carried out by Douglas Partners (2015) and Atkins (2016). Since relevant data are not available for the Chandler Formation and overlying rocks within the footprint of the facility, the following information was used:

- ▲ the geometry of the planned mine layout (i.e. corresponding depth, dimensions and shape of the room and pillar layout);
- ▲ the local geology;
- ▲ the results of the analyses concerning the non-soluble material of the Chandler Halite (Terra Search, 2014);
- ▲ core photographs from the exploratory borehole CH001A (ERCOSPLAN, 2014);
- ▲ generic salt mechanics data and results from in situ measurements, derived from previous geomechanical studies carried out by Atkins.

Geomechanical modelling was undertaken using the finite difference method to analyse the geomechanical response of the Chandler Formation and overlying rocks to the excavation and operation of the CF over a period of 30 years. The studies employed engineering judgement to analyse the results of the geomechanical modelling. Established experience and knowledge enabled the use of appropriate parameters concerning the strength and the constitutive response of the Chandler Halite. The geometry and in-situ geostatic stresses and the boundary conditions that characterise the planned room and pillar mine layout were analysed.

The studies showed that, provided the CF is designed and operated appropriately, the excavated cavities will remain stable throughout the operational phase of the facility. In particular, roof spans are required to be sufficiently small to ensure that unacceptable creep convergence of the rooms can be avoided. A significant influence on the strain that will be undergone by the Chandler Halite is the c. 270 m thick Jay Creek Limestone, which overlies the Chandler formation. Provided that there are no major faults or discontinuities within it, the Jay Creek Limestone will act as thick plate that is expected to contribute significantly to the stability of the planned excavations.

However, the analyses had a number of practical limitations:

- ▲ the assumed mechanical and physical parameters of the modelled geological materials was based on ;
- ▲ the assumed simultaneous excavation of all the rooms in the modelled panel;
- ▲ the assumptions made in determining the geostatic components; and

- ▲ the introduced idealised configuration whereby a three-dimensional structure has been analysed by a two-dimensional model.

The longer-term (post-closure) geomechanical behaviour of the CF is more uncertain than that over the operational period. At the time of closure, there will be significant total voidage present within the facility, estimated to be in the range 20%-40%. This voidage consists of:

- ▲ pore space within solid wastes;
- ▲ pore space between the grains of the salt backfill that surrounds the solid wastes;
- ▲ pore space within the cured hydraulic backfill;
- ▲ voids between the solid wastes / backfill and the walls of the caverns (because 100% filling is unattainable);
- ▲ voids between hydraulic backfill and the walls of the caverns (because 100% filling is unattainable in practice).

Due to creep of the salt, much of this pore space will be reduced, until eventually the waste and backfill provide sufficient support to the salt that creep ceases. It is expected that most of the void space within the wastes and backfill will not be reduced by creep because the waste /backfill material will become grain-supported well before all the voids are lost.

Creep typically occurs in three stages: primary, or Stage I; secondary, or Stage II and tertiary, or Stage III (Figure 6-1).

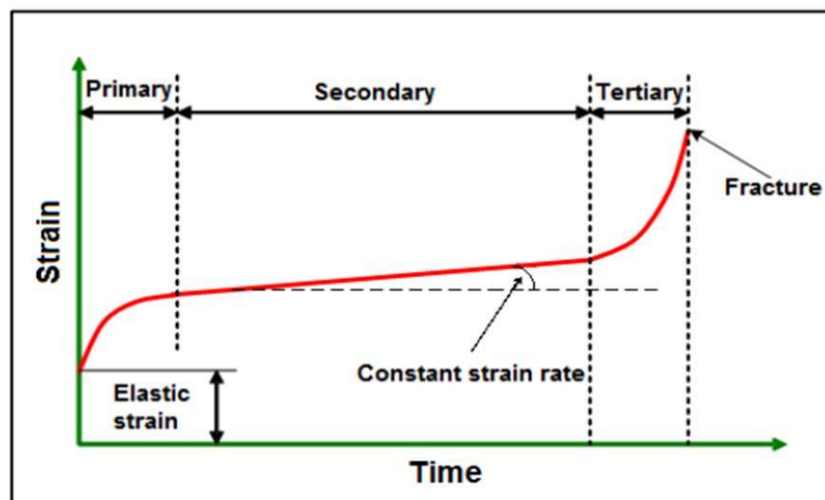


Figure 6-1: The idealised strain-time curve for a creep test. After Atkins (2016).

Initially, as load is applied there is virtually instantaneous elastic strain, but over time, under constant stress, the strain rate decreases. With increasing strain the strain rate continues to decrease. The time interval over which this decelerating strain-rate occurs is the period of primary creep. The secondary creep phase is reached when resistance to creep increases and the strain rate reaches a near-constant, minimum value. This stage is often termed a “steady state creep” period. At the end of Stage II, the strain rate exponentially increases with strain,

and the creep rate begins to accelerate, resulting in the initiation of a creep fracture process. This final stage of accelerating deformation that leads to a rapid material failure is called Stage III, or tertiary creep.

The rate of convergence of the excavated rooms will be decreased by the presence of waste and/ or backfill. Backfilling can be done to prevent long-term convergence, provided that the waste is suitably emplaced. The smaller the residual void volume after backfilling, the lower the convergence rate. The more rapid is the rate of waste emplacement and backfilling, following room excavation the better control there will be on the expected room convergence. When waste materials that flow are used (hydraulic backfill) they should be emplaced in a manner that minimises unfilled spaces at the level of the roof and improves significantly the support provided by the stored waste. For solid, packaged waste material and the surrounding salt backfill, the anticipated initial reduction in the closure rate of the excavated rooms is anticipated to be between 20% and 25%. Well-compacted hydraulically backfilled waste materials are expected to result in an initial reduction in the rate of closure between 35% and 40%.

Based on geomechanical analyses for other facilities (e.g. WIPP; Committee on the Waste Isolation Pilot Plant, National Research Council, 1996; USDOE, 2014), it is believed that if creep were to persist into Stage III (i.e. brittle failure occurs), the fractures developed would re-seal such that the halite would remain essentially impermeable.

7 Hydrogeological Assessment

Average annual rainfall in the region is about 280 mm per year. The BOM give an overall annual mean of 197.4 mm for the Maryvale station for the years 1948 to 2014, but the rainfall is not uniformly distributed between years. BOM state that annual rainfall ranges from 45.3 mm to 521.8 mm at the Maryvale Station during the years 1948 to 2014. Evaporation rates within the Mine Infrastructure Area (MIA) are approx. 3,100 mm / year and are consistent with semi-arid conditions.

Rainfall tends to be concentrated in large storm events that result in extensive surface flow and flash flooding. The area around the CF drains to the Finke River and the Hugh River, which are ephemeral and flow on average less than once per year; the last major flood flow of the Finke River is thought to have been about 15 years ago. Flooding events lead to recharge of local shallow alluvial water bodies that feed water holes and some local shallow bores. It appears that these are perched water bodies. The high temperatures mean that evapotranspiration rates are high so recharge to depth is limited (estimated at order 1mm/y to the water table by URS, 2012).

Several zones that are able to sustain some flow to a borehole have been identified in the various boreholes that have been drilled. Tellus has drilled six groundwater monitoring boreholes and two investigation production boreholes to depths of up to about 360 m to monitor the groundwater levels and compositions and installed monitoring equipment in two other pre-existing boreholes. The rest water level is usually about 80 m below ground surface.

The boreholes identified several permeable medium to coarse grained sandstone units. Douglas Partners (2016) identifies three “aquifer” units from the wireline logging and drilling information:

- ▲ The upper aquifer at depths of 90 m – 102 m seen at two drilling locations had a low yield and appears to be poorly connected. It is thought to be associated with the Horseshoe Bend formation;
- ▲ The middle aquifer at depths of 151 m – 185 m was identified in most of the boreholes but has a variable yield. It is thought to correspond to the Upper Langra Formation;
- ▲ The lower aquifer at depths of 222 m -320 m, which had the highest yield and was seen in most, but not all of the boreholes. It is thought to correspond to the Lower Langra Formation.

Below these units, the Stairway sandstone (390 m – 502 m) was identified as a potentially significant aquifer in oil exploration studies but is not thought to be regionally connected. Little is known about the Jay Creek Limestone, although the lithological description implies that it is unlikely to contain significant aquifer beds. The Idracowra Sandstone unit, also

known as the Santo Sandstone, was encountered in the easternmost borehole but is not present within the footprint of the CF and is a poor aquifer if below the water table. For the purposes of the assessment it is assumed that four aquifers of varying quality are present in the immediate vicinity of the CF.

Although the sandstone beds may have a primary porosity of 10-20%, the effective porosity is thought to be significantly lower and in many places the primary porosity has been infilled with calcite or silica. The aquifer units tend to correspond to areas where the infill is absent. Groundwater inflow to boreholes often appears to be from discrete fractures, probably bedding planes.

Preliminary results are available from the Tellus groundwater monitoring boreholes; the length of the recording period is currently a significant limitation and the results from the different boreholes are sometimes contradictory. The results suggest the following:

- ▲ the water table is at about 85-90 m below ground surface but there may be temporary perched water bodies above this;
- ▲ the groundwater resources are in general poorly connected and in some cases the “expected” aquifer was not encountered in a borehole;
- ▲ head (water level measured in the piezometer) tends to increase with depth but the gradients are small. The head difference between the upper part of the Stairway and the Lower Langra seems to be of the order of 0.5 m, the head difference between the Upper and lower Langra seems to be up to half a metre and the head difference between the Upper Langra and Horseshoe Bend seems to be up to 3 m.

For assessment purposes, it is conservative to assume that an upwards head gradient is present. There is no information about the head gradient between any aquifer in the Jay Creek Limestone and the Stairway sandstone but for assessment purposes a head of a metre or so could be assumed.

The regional direction of flow in the aquifers in the area is thought to be to the southeast. Flow rates are thought to be very low, for example a rate of $<0.01\text{m/y}$ has been suggested for the Langra Formation (Graham Ride, written communication, 29th February 2016).

The current interpretation is that the low yielding aquifers intersected in the Horseshoe Bend Shale Formation are in localized very fine poor porosity sandstone beds with links to recharge locations probably through minor fracture preferential flow paths from above and in some cases below and bedding planes. The chemical water quality is poor and there can be different types of water in the different aquifers. The chemical water analyses generally indicate relatively recent recharge.

The recharge locations for the deeper aquifers are not known but likely to be some distance (at least 50 km away) from the area of interest. The discharge locations are also unknown, but are hundreds of kilometres from the proposed site of the CF. The aquifers in the area of

the proposed CF pass underneath the Pedirka Basin and discharge at an unknown very distant location.

The nearest significant town to the facility is Alice Springs. Alice Springs obtains its drinking water from the Mereenie Sandstone. This aquifer has no direct hydrogeological connection to the formations overlying the Chandler facility and in regional terms is up-gradient of the facility. The community of Titjikala obtain their drinking water from a shallow aquifer to the east of the Hugh River which recharges this system with water that is of a standard appropriate for drinking.

Halite deposits such as that of the Chandler Formation are typically effectively impermeable. This can be illustrated by the fact that similar kinds of deposit form the caprocks to many hydrocarbon fields throughout the world (e.g. Capture Power and National Grid, 2016). Such caprocks have retained low-density hydrocarbons within the underlying reservoirs for many millions of years.

The porosity of such halite deposits is extremely low. Beauheim and Robert (2002) report that the undisturbed halite-dominated host rock of the WIPP, a deep (c.650 m) geological repository for defence-related transuranic (TRU) radioactive waste in New Mexico, USA, has connected porosity close to zero.

8 Geochemical Assessment

This section does not give a detailed interpretation of the groundwater chemistry within the vicinity of the CF and the wider area, but rather aims to evaluate what the geochemical data imply for the risks associated with the CF.

Analyses obtained for groundwater samples from the boreholes drilled by Tellus are given in Table 8-1. Groundwater compositions from across the wider Amadeus Basin are given in Table 8-2. There are a number of uncertainties about these water compositions. Not all the reported water compositions are assigned to a sampling depth. For the samples for which sampling depths are reported, the sampling intervals are not given. Therefore, the potential for mixing between waters of different types during sampling, which becomes more likely the wider the sampling interval, cannot be assessed. Information about the volumes of water pumped to obtain the samples, the degree of contamination with drilling fluids, and chemical perturbations during sampling (e.g. degassing, contamination with air) is also needed to interpret the data.

Several of the samples have reported Total Dissolved Solid (TDS) concentrations that are inconsistent with the reported concentrations of other dissolved constituents, calling into question the quality of the samples and / or analyse and/or reporting (transcription of data). Some of the samples obtained from the Langra Formation in the boreholes are reported to be very high in F concentrations (up to 876 mg/L; Table 8-1). These values seem potentially anomalous in view of the fact that most of the samples from the Langra Formation do not contain such high concentrations of F. The samples with high reported F concentrations also have very low SO₄ concentrations (<2 mg/L), which also seem anomalous in view of most samples having SO₄ concentrations in the range 1310 mg/L to 2200 mg/L.

Table 8-1: Groundwater quality data from boreholes drilled by Tellus (HSB = Horseshoe Bend Shale; UL = Upper Langra; LL = Lower Langra).

Station ID	Main Aquifer	X coordinate	Y coordinate	Elevation	Well Depth	Sample Depth	Water Type	TDS	Ca	Mg	Na	K	Cl	HCO3	CO3	SO4	F	NO ₂	NO ₃	B	Br	Fe	Mn_diss				
		m	m	m(asl)	m	m		mg/L																			
T0004	UL	392507	7258491	410	201	138	Na-Ca-Cl-SO4	8430	598	286	2300	69.6	3500	177	<1	1620	1.0	0.040	1.140	1.46	10.1000	0.2200	0.1400				
T0004	UL	392507	7258491	410	201	114	Na-Cl-SO4	8580	595	282	2260	70.6	3860	171	<1	1600	1.0	0.040	1.220	1.34	9.2400	0.0800	0.3350				
T0004	UL	392507	7258491	410	201	180	Na-Cl-SO4	12000	745	378	3170	66.4	5140	168	<1	1940	0.9	0.040	0.380	1.56	11.6000	0.1000	0.0650				
T0004	UL	392507	7258491	410	201		Na-Ca-Mg-SO4	13800	793	401	3280	73.2	0.015	164	<1	2070	1.0	<0.02	0.400	1.70	13.2000	0.0820	<0.0004				
T0004	UL	392507	7258491	410	201		Na-Ca-Mg-SO4	14600	836	418	3450	73.0	0.015	179	<1	2140	1.1	0.020	<0.02	1.68	14.4000	0.5100	<0.0004				
T0005	HSB	392519	7258476	410	120	90	Na-Cl-SO4	9030	562	288	2230	96.7	3710	123	<1	1610	1.6	0.060	1.700	1.12	9.8300	0.5600	1.2200				
T0005	HSB	392519	7258476	410	120	114	Na-Ca-Cl-SO4	9100	610	289	2330	67.7	3880	162	<1	1650	1.2	0.040	1.120	1.38	9.6500	0.3400	0.5400				
T0005	HSB	392519	7258476	410	120	120	Na-Cl-SO4	9320	676	340	2750	74.5	4230	178	<1	1860	1.0	0.040	0.660	1.58	10.2000	0.1400	0.3000				
T0006	UL & LL	392976	7255631	423	0	222	Na-Ca-Mg-SO4	14300	873	423	3380	77.5	0.01	173	<1	2200	1.1	<0.02	0.180	1.60	13.5000	0.2780	<0.0004				
T0006	UL & LL	392976	7255631	423	0	132	Na-Ca-Mg-SO4	11100	674	343	2470	74.1	0.035	163	<1	1870	1.2	0.020	2.800	1.48	12.4000	0.2320	<0.0002				
T0006	UL & LL	392976	7255631	423	0	192	Na-Ca-Mg-SO4	13600	845	401	3220	76.3	0.025	175	<1	2150	1.1	<0.02	0.280	1.61	13.9000	0.2000	<0.0004				
T0006	UL & LL	392976	7255631	423	0	366	Na-K-Cl	12400	414	32	2100	3340.0	7790	167	<1	<2	876.0	0.045	0.010	<0.002	<0.0004	<0.0004	<0.002				
T0007	UL & HSB	395943	7256291	443	0		Na-Ca-Mg-SO4	8820	590	278	1920	64.8	0.025	147	<1	1400	1.1	0.020	4.820	1.19	9.7000	0.1840	<0.0002				
T0008	HSB	394168	7256478	439	178		Na-Ca-Mg-SO4	9540	665	323	2010	69.3	0.015	155	<1	1600	1.2	<0.02	14.400	1.32	11.7000	0.5780	<0.0002				
T0009	UL & HSB	393690	7257551	426	0	192	Na-Ca-Cl-SO4	10000	685	333	2320	86.6	4530	133	<1	1730	1.0	<0.02	5.700	1.40	9.8500	<0.0004	0.2140				
T0009	UL & HSB	393690	7257551	426	0	228	Na-Ca-Cl-SO4	10200	690	330	2370	75.7	4490	151	<1	1750	1.2	<0.02	5.480	1.46	9.6500	<0.0004	0.1890				

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Station ID	Main Aquifer	X coordinate	Y coordinate	Elevation	Well Depth	Sample Depth	Water Type	TDS	Ca	Mg	Na	K	Cl	HCO3	CO3	SO4	F	NO ₂	NO ₃	B	Br	Fe	Mn_diss
		m	m	m(asl)	m	m		mg/L															
T0009	UL & HSB	393690	7257551	426	0	258	Na-Cl	15200	914	476	4100	82.7	7080	168	<1	2330	1.1	<0.02	0.580	1.75	12.2000	<0.0004	0.2060
T0009	UL & HSB	393690	7257551	426	0	306	Na-Cl	15500	910	469	4150	82.1	7210	156	<1	2300	1.0	<0.02	0.360	1.78	13.1000	<0.0004	0.2120
T0010	UL	392406	7258507	410	216	90	Na-K-Cl-F	8440	297	29	1630	2280.0	4150	165	2	<1	594.0	0.395	0.010	<0.001	<0.0002	<0.0002	0.0110
T0010	UL	392406	7258507	410	216	132	Na-K-Cl-F	8050	309	31	1720	2450.0	4580	158	<1	<1	650.0	0.285	0.010	<0.001	<0.0002	<0.0002	0.0031
T0010	UL	392406	7258507	410	216	186	Na-K-Cl	11500	416	33	2110	3460.0	6960	179	<1	<2	818.0	0.025	0.015	<0.002	<0.0004	<0.0004	<0.002
T0010	UL	392406	7258507	410	216	216	Na-K-Cl	12200	426	33	2150	3560.0	13500	181	<1	<2	828.0	0.020	0.010	<0.002	<0.0004	<0.0004	<0.002
T0011	LL	392958	7255638	423	330		Na-Cl-SO4	10600	683	356	2640	86.1	4890	148	<1	1950	1.1	<0.02	3.320	1.53	10.3000	<0.0004	0.1550
T0011	LL	392958	7255638	423	330	330	Na-Ca-Cl	10200	712	344	2060	86.9	4720	45	<1	1310	0.5	<0.02	0.040	1.08	9.0100	<0.0004	0.2420

Table 8-2: Groundwater Chemistry across the Amadeus Basin (after URS, 2012).

	Depth (m)	Stratigraphic Unit	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₃ ⁻	TDS
Mt Charlotte-1			1,674	666	5,996	179	7.7	1,944	12,756	2.8	23,221
Finke River			52.1	22.3	55.8	50.9	218.8	47.5	101	0.2	439
Magee-1	180	Finke Group	589	315	1,870	66	175	1,510	3,836	<0.1	8,273
	244		1,060	216	2,650	165	67.7	1,922	5,165	<0.1	11,212
	345		834	468	2,820	87	122.6	2,040	5,543	<0.1	11,855
	492	Stairway Sandstone	1,140	472	3,790	121	133.8	2,007	7,401	<0.1	14,998
	780	Chandler Formation	1,300	495	13,330	404	147.4	1,420	22,897	<0.1	39,919
	1513	Gillen Member	33,300	10,960	65,820	5,570	131.4	112	201,938	<0.1	317,766
	1529		30,200	7,220	70,370	4,100	211.3	159	190,947	<0.1	303,102
	1914		10,340	2,610	101,600	1,820	45.9	500	188,849	<0.1	305,742
James Range A-1	617	Hugh River Shale	592	119	2,325	52	167	3,430	2,180		
	829	Bitter Springs Formation	546	1	2,500	32	18	4,780	1,060		
	914		504	19	2,300	36	45	3,796	1,100		
Murphy-1	578	Carmichael Sandstone	771	372	6,070	77.4	159.6	2,880	10,763	0.7	21,014
Waterhouse-1			65	44	138	13	260	149	210	4	883
Orange-1		Arumbera Sandstone	7,650	420	23,600	9,400	104	260	57,200	<1	98,600

Note: all analytes recorded in mg/L

However, it is noteworthy that:

- ▲ All the aquifers (Horseshoe Bend Shale, Upper Langra, Lower Langra and Stairway Sandstone) contain water with salinity significantly in excess of the salinity of potable water. Were water from these aquifers to be used for human consumption it would need to be diluted to TDS of <1000 mg/L and more likely <<600 mg/L (e.g. WHO, 2011).
- ▲ The highest salinity groundwaters occur in the Stairway Sandstone (TDS = c. 15,000 mg/L; Table 8-2), the Chandler Formation (TDS = c. 40,000 mg/L; Table 8-2) and the underlying Gillen Member (TDS = 318,000 mg/L; Table 8-2).
- ▲ The highest salinities are all less than any water that is saturated with respect to (in equilibrium with) halite. Such a water at 25 °C would have a TDS of 360,000 mg/L.

If any of these groundwaters were to be used in future for human consumption or for agriculture, they would need to be diluted significantly on account of their high salinity. This dilution would also reduce the concentrations of any contaminants that were unexpectedly to enter them from the CF (which is assessed to be very unlikely – see Section 10.3.2, Section 10.4, Section 11.2.4 and Section 11.2.5).

The groundwater from the Chandler Formation that is substantially undersaturated with respect to halite presumably comes from the part of the Chandler Formation that overlies the halite. If this were not the case, the groundwater would be expected to have TDS around 10 times as great as that observed. The relatively low TDS of the groundwater within the upper part of the Chandler Formation is very unlikely to be due to dilution of halite-saturated water by rapidly flowing groundwater because:

- ▲ Such a process would be expected to result in dissolution of the halite, for which there is no evidence (e.g. RPS, 2012).
- ▲ On lithological grounds the upper part of the Chandler Formation is interpreted to have very low permeability.
- ▲ Groundwater fluxes are interpreted to be very slow, based on the low interpreted rates of recharge and low hydraulic gradients (see Section 4.2.1 and Section 7).

In view of these points, the steep salinity gradient that must exist between the top of the Chandler Halite and the upper part of the Chandler Formation where groundwater samples were obtained implies that any natural transport of solutes upwards from the Chandler Halite must be extremely small.

Similar arguments to these also support the conclusion that any natural fluxes of groundwater and solutes upwards from the Chandler Formation to the Stairway Sandstone Formation must be very small.

The density contrast between any deeper saline water near to the Chandler Halite and the shallower, less saline water within the overburden will also tend to act against upwards flow

of groundwater. For example, the salinity of the water in the Stairway Sandstone implies a density of c. 1015 kg/m³. In contrast water in the Chandler Formation that has dissolved halite to the point of saturation will have a salinity of c. 360,000 mg/L, equivalent to a density of c. 1,360 kg/m³.

The Chandler Formation has two lithological associations: the Chandler halite and the overlying Chandler carbonate (ERCOSPLAN, 2013). The former consists mainly of coarse, crystalline halite, with very rare occurrences of gypsum, anhydrite and native sulphur (ERCOSPLAN, 2013). Analytical data from recent boreholes indicate that the halite has a composition in the range of 62 – 98% halite, 0.02 – 17% anhydrite and 0.3 – 24% insoluble material.

As a result of the small mineralogical variations, bedding is hardly recognizable and hence the dip directions cannot be observed easily. However, across the wider region, outside the CF, the formation shows features (thickening etc.) that indicate past halotectonic processes, with the salt varying in thickness between 50m to more than 1,000m.

The Chandler carbonate occurs quite extensively although with a low thickness of 10 to 50m. The carbonate in fact comprises black calcareous mudstone with abundant chert, shale and siltstone. The chert has been described as to occur in beds on top of the formation and in single nodules at the bottom. In the East-central province, the carbonate is described as to be intensely modified by intraformational salt tectonics.

9 Biosphere Impact Assessment

The biosphere is that part of the environment normally inhabited by living organisms at sufficiently shallow depths that might typically be affected by basic human actions such as farming (e.g. see IAEA, 2007).

In the environment around the CF the biosphere has the following principal components:

- ▲ people;
- ▲ livestock, principally cattle;
- ▲ indigenous natural wildlife;
- ▲ indigenous natural vegetation.

However, the biosphere is subject to considerable short- and long-term temporal change, reflecting, changing human activities, weather events and changing climate. For this reason there is considerable uncertainty as to the nature of the biosphere that could be impacted by contaminants originating in the waste, should control over the waste (in the operational period) or containment of the waste (in the operational and post-closure period) ever be lost.

There is also considerable uncertainty over the actual biosphere impacts that would be caused by organisms being exposed to contaminants originating in the wastes. This is because the precise chemical forms of the wastes are presently unknown and because in any case there are uncertainties about the toxicological effects of many of the contaminants present in the wastes (see, for example WHO, 2011). While water quality standards and guideline values are available for the various contaminants, these are typically set cautiously at levels that would result in no significant impact to biota. It does not necessarily follow that exposure to some level of contamination in excess of a standard or guideline value would always be harmful in practice.

For these reasons, the approach adopted is to design and operate the facility in such a way that the biosphere will not be exposed to contaminants originating in the wastes, either in the operational phase or in the post-closure phase. There is a high degree of confidence that this goal can be achieved both in the operational phase and the post-closure phase, as assessed in detail in Section 10 and Section 11 respectively.

There are three main ways in which the biosphere could be exposed to the wastes to be emplaced in the CF, in the event that controls over the wastes or containment are inadequate:

- ▲ The biosphere could be exposed to water contaminated by contact with the wastes and then transported.
- ▲ The biosphere could be exposed to solid particulate matter (i.e. dust) originating in the wastes and that has been transported by air.

- ▲ The biosphere could come into direct contact with the wastes (e.g. vegetation growing on waste containers or animals coming into direct contact with waste containers).

Organisms that are exposed to contamination via one of these routes could become contaminated and enter the food chain, leading to contamination of other organisms. For example, vegetation could become contaminated and then be eaten by an animal that would then also become contaminated.

In the operational phase, all three exposure routes could potentially cause organisms to be exposed to contamination owing to failure of controls in either the underground workings or in the surface facility. The risks of such exposures are assessed in detail in Section 10.

The CF lies at the transition between erosion-resistant low hills to the northwest and a sandy ephemeral floodplain to the southwest. Although the area has low rainfall (max c. 280 mm annually), but there can be high rainfall / flash flood events. For example, even in low rainfall events (15 mm within 24 hours) is enough to charge ephemeral watercourses that exist on the surface of the proposed MIA. Precautions will be taken (e.g. siting on relatively higher ground, drainage channels to divert water) to prevent flooding of the facility. However, should these precautions fail, then potentially these ephemeral water flows could transport waste materials and cause the biosphere to be exposed to them.

Failure of containment of wastes in the surface facilities could lead to airborne disposal of waste materials, causing exposure of organisms within or around the footprint of the facility. Precautions will be taken to prevent such releases of material occurring.

During the operational phase, transport of contamination in groundwater could cause exposure of organisms only within the footprint of the CF, owing to the fact that groundwater flow is a very slow process and the nearest exploited groundwater resources to the facility are a considerable distance away e.g. c 25km to Titjikala.

The underground waste emplacement area site is a long way (>100 km) from the main groundwater aquifers that are exploited for drinking water supplies (in the Alice Springs area to the north and the Great Artesian Basin to the east) and there is not thought to be any direct connection with the aquifers that overlie the facility. There are local boreholes that penetrate the shallowest aquifer in the area around Titjikala located 25 km to the northeast. However, only the shallowest aquifer, the Idracowra Sandstone unit, is used as a source of drinking water for humans. The Horseshoe Bend Shale is also used in the vicinity of Titjikala to supply water for drinking by cattle. The Titjikala groundwater bore is hydrogeologically disconnected from aquifers that lie beneath the proposed MIA for Chandler. For example, water from the Titjikala bore is potable and recharged by the Hugh River.

In contrast, only the groundwater exposure route is relevant during the post-closure phase. However, this would require containment of the facility to be compromised, which is considered unlikely. In the event that containment was to be lost, then groundwater would

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need to transport contaminants from the wastes to the shallow biosphere via one or more pathways. The risks of this occurring are assessed in detail in Section 11.

10 Assessment of the Operational Phase

10.1 Functional Analysis of the CF System

10.1.1 Interactions Among System Components

An interaction matrix was used to identify systematically potential interactions among different components of the CF (Appendix A) and the surrounding geosphere. The matrix represents system components along the leading diagonal. Processes by which these components could potentially interact are then entered in off-diagonal elements. The approach is illustrated schematically in (Table 10-1). An interaction matrix for the CF is shown in Table 10-2. In this matrix, it is assumed that all engineered and natural systems features present (and many that could be present, such as unknown fractures) are present, and can potentially interact (noting that many can be discounted). The reason for this approach is to provide a way of auditing the systems evolution scenarios (Section 10.2) developed using a “top-down” approach, to ensure that system evolution scenarios or potential source-pathway-receptor connections have not been missed.

Table 10-1: Schematic illustration of a component interaction matrix.

Component 1	Processes by which Component 1 affects Component 2	No direct interaction between Component 1 and Component 3, so “greyed out” (-)
Processes by which Component 2 affects Component 1	Component 2	Processes by which Component 2 affects Component 3
Processes by which Component 3 affects Component 1	No direct interaction between Components 3 and Component 2 so “greyed out”(-)	Component 3

Table 10-2: Potential Interaction Matrix for CF (see text)

Salt extraction shaft and seals	-	-	-	-	-	-	-	-	-	potential pathway	potential pathway	-	-	creep	-	potential pathway	-	-	pathway for contamination of surface air/soil	exposure to contaminants (if pathway intact) - workers and public
-	Waste emplacement shaft and seals	ventilation	ventilation	ventilation	ventilation	-	-	-	-	potential pathway	potential pathway	-	-	creep	-	potential pathway	-	-	pathway for contamination of surface air/soil	exposure to contaminants (if pathway intact) - workers and public
-	-	Rooms	-	-	-	unloading	-	-	-	contamination (loss of containment)	contamination (loss of containment)	unloading (geometry change)	possible destabilisation/r oof collapse	creep	-	potential pathway	-	-	cavern collapse	falling material (workers)
-	-	Tunnels	-	-	-	-	-	-	-	potential pathway	potential pathway	unloading (geometry change)	possible destabilisation/r oof collapse	creep	potential pathway	potential pathway	-	-	cavern collapse	falling material (workers)
vehicle fire	vehicle fire	vehicle fire	vehicle fire	Moveable/fixed infrastructure	-	Impact/destabilisation	-	-	-	-	-	-	-	-	-	-	-	-	-	vehicle accidents (workers)
-	-	-	-	-	Head space	-	-	-	-	-	contamination (loss of containment)	-	possible destabilisation/r oof collapse	creep	-	-	-	-	-	-
-	-	structural support	-	-	-	Pillars	structural support	structural support	-	sorption of contaminants	sorption of contaminants	loading	structural support	-	-	-	-	-	-	-
-	-	-	contamination if pipe fails	contamination if emplacement pipe fails	-	loading	HBF Waste	-	-	-	-	loading	exert pressure (overfill/salt creep)	exert pressure (overfill/salt creep)	-	-	-	-	-	worker exposure (leak)
-	-	-	-	-	backfill reduced head space	loading	-	Loose salt backfill	-	sorption substrate	sorption substrate	-	-	-	-	-	-	-	-	worker exposure (dust)/collapse impact
-	-	contamination (loss of containment)	-	-	-	-	-	-	-	Solid waste+container	-	mixing of waste materials	loading	-	loading	-	-	-	-	worker exposure
-	contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	possible damage to vehicles	-	possible dissolution	-	possible dissolution	waste interaction (loss of containment)	Liquid waste+container	-	possible dissolution if released	-	possible dissolution if released	contamination (loss of containment)	contamination (loss of containment)	-	-	contamination if pathway intact	worker/public exposure if pathway intact
contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	contamination (loss of containment)	possible damage to vehicles	contamination (loss of containment)	salt deliquescence	-	salt deliquescence	mixing of waste materials	possible gas dissolution into liquid	Aerosol/ gas from waste release/accidents I mixing	salt deliquescence	salt deliquescence	salt deliquescence	potential pathway	contamination (loss of containment)	-	-	contamination if pathway intact	worker/public exposure if pathway intact
-	-	-	-	-	-	structural support	structural support	-	-	sorption substrate/diffusive transport medium	-	Underlying salt	-	-	potential pathway	potential pathway	-	-	-	-
loading of shaft seal materials	loading of shaft seal materials	-	-	-	-	loading	possible loading (creep)	-	sorption substrate	sorption substrate	-	-	Overlying salt	-	-	potential pathway	-	-	-	-
potential pathway	potential pathway	potential pathway	-	-	-	-	possible emplacement water leakage	-	-	potential pathway	potential pathway	-	-	Confining salt	change in geometry due to creep (closure)	change in geometry due to creep (closure)	-	-	-	-
potential pathway	potential pathway	potential pathway	-	-	-	-	possible emplacement water leakage	-	-	potential pathway	potential pathway	potential pathway	potential pathway	creep	Boreholes	combined potential pathway	possible contamination	possible pathway	No impact if boreholes not in use	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	creep	combined potential pathway	Fractures	possible contamination	possible pathway	possible containment of surface soil	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Aquifers	-	impact on water quality	drinking water contamination (public)
flooding	flooding	flooding	flooding	flooding	flooding	flooding	flooding	mobilisation	mobilisation	mobilisation	mobilisation	dissolution	dissolution	-	-	-	pathway if breached	Aquicludes	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	flooding	flooding	contamination	-	Biosphere Receptors (incl. surface waters)	contamination of environmental media (soil, water, air, flora and fauna)
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Human Receptors

10.1.2 Scenario-Defining Events and Processes

In general, any event or process that influences the behaviour of the CF will not operate in isolation, but will be coupled to other events and processes. Consequently, the identification of an event or process as the cause of a loss of control over the hazard and activation of one or more pathways is to some extent one of convenience for the purposes of analysis. Furthermore, a given process could cause such loss of control and pathway activation in some cases, but may in other circumstances be caused by some other process. For example, a roof collapse may potentially damage the electrical and fuel systems of a vehicle leading to a fire. On the other hand the heat generated by a vehicle fire caused by an electrical system failure might cause a roof collapse. The goal here is therefore to identify a set of events and processes that lead naturally to the definition of a set of scenarios that cover all plausible states / evolutions of the system.

Based on the assessment of interactions among components of the system, the phenomena listed in Table 10-3 have been identified as possible causes of loss of control over the hazard during the operational phase.

Table 10-3: Phenomena that could initiate loss of control over the hazard and activation of one or more pathways between the hazard and one or more potential receptors.

Cause of Loss of Control	Description	Treatment
Rockfall in partially-filled room/tunnel	Roof failure in partially filled room or rockfall could also potentially connect the rooms to conductive features within the overburden (considered in the PCRA)	Covered explicitly by a scenario. Qualitative evaluation.
Conductive feature of the rock (fault or aquifer) encountered unexpectedly	During the excavation of the facility a conductive feature (fault or aquifer) is encountered unexpectedly and connects the facility to shallower conductive features in the overburden.	Not explored explicitly by a scenario. Given the self-sealing characteristics of halite and the fact that conductive features are highly likely to be identified based on seismic data and hence avoided, if they occur, this process is highly unlikely. The effects would be similar to those of a rockfall that leads to the facility being connected to conductive features higher in the overburden. This process is therefore considered together with rockfalls in the analysis.
Vehicle fire	Vehicle fire at the surface or in tunnels/disposal rooms/shaft, leading to waste packaging being compromised. Depending upon where the fire occurs, there could be release of contaminants to the atmosphere within the facility, from where it can be circulated by the ventilation system, or contamination of the atmosphere at the surface. Also depending upon where the fire occurs, possibly there could be contamination of groundwater.	Covered explicitly by a scenario. Qualitative evaluation.

Cause of Loss of Control	Description	Treatment
Fire in fixed facilities	Fire in fixed facilities underground or in buildings at the surface, leading to waste packaging being compromised. Depending upon where the fire occurs, there could be release of contaminants to the atmosphere within the facility, from where it can be circulated by the ventilation system, or contamination of the atmosphere at the surface. Also depending upon where the fire occurs, possibly there could be contamination of groundwater.	Covered explicitly by a scenario. Qualitative evaluation.
Ventilation and other services fail	Inadequate ventilation/lighting, leading to a build-up of contaminated air in the facility. It should be noted that this process in itself would not lead to loss of control over the hazard unless a lack of ventilation resulted in actions being taken that would diminish proper supervision and management of the wastes within the facility.	Not considered explicitly within a scenario. Implications for workers and general excavation/emplacement operations, not considered further in this OPRA. Ventilation failure, would not itself lead to release of contamination from wastes. Similarly, failure of other services, such as electrical failures, would not cause releases of contaminants from wastes directly. Indirect releases of contaminants from wastes that might result from the failure of such services are considered by other scenarios. If it were to occur in combination with a process leading to contaminant release, ventilation failure could result in decreased potential for air-borne contamination to reach surface. On the other hand, ventilation failure could also produce higher peak levels of contamination within

Cause of Loss of Control	Description	Treatment
		underground parts of the facility and / or result in contamination remaining in the underground atmosphere for longer than would be the case should the ventilation function.
Waste degradation and gas generation	Corrosion of metals (H_2) generation and build-up of gases (e.g. methane) due to organic waste degradation, possible pressurisation in vaults	Not considered explicitly within a scenario. Waste degradation and gas generation during the operational phase unlikely to be significant. Most degradation processes that can be envisaged require a source of water, but conditions within the CF will be dry. The only source of water will be any residual moisture within the wastes themselves. Such moisture will be present in limited quantities, with the result that any waste degradation and gas generation in the operational phase will be limited.
Waste package failure	Release of solids (or derived dust) due to: ▲ package drops/breach (vehicle accidents etc.), either at the surface or within the facility; ▲ a container drop in the access shaft; ▲ degradation of canisters within a panel.	Covered explicitly by a scenario. Consider potential for contaminant release (effect on workers not included in this OPRA) and transport via potential pathways to biosphere. Qualitative assessment.
Hydraulic backfill emplacement system failure	Failure of the backfill emplacement system may take three general forms: ▲ emplacement pipe bursts during emplacement, ▲ failure of pumping system; or	Covered explicitly by a scenario. Operational: prevent continued normal operations. There is potential for infrastructure to be contaminated, depending upon where the burst occurs. However, the backfill will

Cause of Loss of Control	Description	Treatment
	▲ failure of hydraulic backfill supply. Any of these circumstances may lead to hydraulic backfill present within the pipe system solidifying, causing a blockage that prevents further use of the system.	solidify and cure once it is has leaked, thereby limiting the potential for receptors to come into contact with it.
Impaired shaft lining performance	Water ingress during operations, leading to potential for flooding of underground facility and mobilization of contaminants (if containers leak/hydraulic backfill can be leached).	Covered explicitly by a scenario. Minor leaks will be identified and can be grouted. Major water ingress potentially more of an issue, both considered.
Sabotage / criminal acts	Conceivably sabotage or criminal acts could lead to loss of control over the hazard, for example by causing spills. However, the effects of such sabotage or criminal acts would	Not considered in detail. Sabotage or criminal acts are unlikely owing to operating procedures designed to prevent them. Were they to occur, then the environmental effects would be similar to those of other initiating processes that are considered (e.g. vehicle fires, spillages etc.)
Seismic activity	Earthquakes lead to package breaks/hydraulic backfill emplacement failure, leakages of waste, leakage of fuel/oil from vehicles, major infrastructure damage, risk to workforce etc.	Not considered in detail. Qualitative arguments that seismic activity is unlikely to impact upon the facility and, if it occurs during the operational period, such impacts are unlikely to be significant. Significant seismicity is not expected, because the Chandler facility is located in the stable interior of a tectonic plate. It should be noted that, even if it occurs, seismic activity would likely only affect shallower operations, to depths of a few tens of metres owing to the attenuation of ground displacements

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Cause of Loss of Control	Description	Treatment
		with increasing depth; mines are generally unaffected adversely by seismic activities, even in highly seismically active regions such as Japan.

These initiating events can be mapped to events that were identified to potentially cause releases of waste materials to sensitive receptors during the successful OPRA for the Minosus facility in Cheshire, UK (Hooker et al., 2002). This mapping is made in Table 10-4.

Table 10-4: Correspondence between events considered by the Minosus assessment (Hooker et al., 2002) to potentially cause releases of waste materials and initiating events considered in the CF OPRA.

Minosus Assessment (Hooker et al., 2002)		Corresponding Initiating Event From Table 10-3
Event No.	Event Description	
1	HGV accident at surface	Vehicle fire Waste package failure
2	Container damage during unloading at surface	Waste package failure
3	Container damage during handling / storage at surface	Waste package failure
4	Failure of lift resulting in container damage	Waste package failure
5	Container damage at base of shaft	Waste package failure
6	Vehicle accident underground	Vehicle fire Waste package failure Hydraulic backfill emplacement system failure
7	Container damage during handling at panel	Waste package failure
8	Degradation of canisters in panel	Waste package failure
9	HGV fire at surface	Vehicle fire
10	Fire in surface buildings	Fire in fixed facilities
11	Fire in lift	Vehicle fire Fire in fixed facilities
12	Vehicle fire on waste route	Vehicle fire
13	Flooding of mine	Impaired shaft lining performance Rockfall in partially-filled room/tunnel Conductive feature of the rock (fault or aquifer) encountered unexpectedly
14	Earthquake of highest magnitude recorded in last 500 years	Seismic activity
15	Release of methane / hydrogen	Waste degradation and

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Minosus Assessment (Hooker et al., 2002)		Corresponding Initiating Event From Table 10-3
Event No.	Event Description	
		gas generation
16	Failure of extractor fan	Ventilation and other services fail

It should be noted that the initiating process “Hydraulic backfill emplacement system failure” was identified for the CF system, but is not relevant for the Minosus facility where hydraulic backfilling was not employed.

The assessment for the Minosus facility did not explicitly consider “Sabotage / criminal acts”. These are noted in the CF OPRA for completeness, but are not considered in detail, owing to their effects being similar to other initiating processes that are considered.

10.2 Scenario Development

10.2.1 Nature of Scenarios

Scenarios are commonly developed and analysed during risk assessments for a wide range of sub-surface storage and waste disposal projects (e.g. NEA, 2001; Robinson and Hooker, 2002; Watson et al., 2008; Capture Power and National Grid, 2016). There are several slightly different definitions, but broadly a “scenario” is *a plausible description of the potential behaviour or evolution of a system according to the nature of the features, events and processes that might act within and upon it*. In the present OPRA, the “system” of concern consists of the wastes, the surrounding engineered structures (e.g. backfill and shaft seals), the surrounding geosphere (rock sequences, including geological structures such as faults and fractures that may occur within them, and the groundwater) and the potential receptors that could be affected.

Here, two types of scenario are distinguished:

- ▲ An Expected Evolution Scenario (EES), which is a statement of how the CF and its surroundings are expected to behave if development and operational plans are implemented properly.
- ▲ Six Alternative Evolution Scenarios (AES), which are statements of how the CF system would behave under alternative sets of circumstances, different to those of the EES.

It is important to note that an AES is *not a prediction* of the future behaviour of the system, but rather a representation of the status of the system under a specified set of conditions.

Any impact arising should the system not behave as planned, would be no greater than the greatest impact arising from the assessed scenarios.

10.2.2 Approach

A “top-down” approach to developing scenarios was undertaken, involving the following steps:

1. Firstly, the system was described to identify important components of the system and spatial and temporal relationships among them.
2. The hazard of concern to the assessment was described.

3. Potential¹⁶ pathways for contaminants to come into contact with potential¹⁷ sensitive receptors were identified. These pathways would become relevant should control over the hazard be lost.
4. Potential sensitive receptors were identified. These receptors are entities that could plausibly be harmed should they come into contact with contaminants as a consequence of control being lost over the hazards identified in 1. and one or more pathways identified in 3. becoming active.
5. Possible interactions between the different components of the system were determined systematically to identify possible processes by which:
 - control over the hazard could be lost;
 - pathways between the hazard and potential receptors could become active.
6. Processes that could cause a combination of loss of control over the hazard and one or more pathways to become active were then identified.
7. Scenario descriptions were then developed consisting of:
 - an EES, which describes how the system is expected to behave, according to plans being followed;
 - a set of AES, describing how the system might behave in the event that one of the processes identified in 6. occurs, each one comprising:
 - i. a description of the initiating process; and
 - ii. the interactions among the components of the system that could arise as a result of the initiating process.

10.2.3 Expected Evolution Scenario (EES)

The EES is a statement of the evolution of the CF during the operational period, assuming that operations are carried out as planned and that the facility behaves as designed.

- ▲ There are no significant changes to the presently planned operational regime (e.g. types of waste accepted, changes in facility concept).
- ▲ Rooms and pillars behave in accord with the design intent.
- ▲ No rockfall/roof collapses occur that are sufficient to threaten the integrity of waste containers.

¹⁶ These are pathways that are not proven to exist, but which could plausibly exist under appropriate circumstances. Therefore, the likelihood for these pathways occurring and the consequences should they occur, need to be assessed.

¹⁷ These receptors are not necessarily certain to occur at the time of any contaminant release, but could plausibly occur.

- ▲ Vehicles operate as planned, such that there are no collisions or fires that would cause release of contamination.
- ▲ Some minor change in room geometry possible due to creep, but this is not significant during the operational phase and can be managed.
- ▲ Ventilation and other services work as planned.
- ▲ Hydraulic backfill emplacement occurs as planned, without any pipe blockages or leakages of hydraulic backfill.
- ▲ Degradation of wastes in containers and hydraulic backfill is very slow and does not result in any significant changes to the properties of the wastes during the operational phase. For example, large volumes of gas are not expected to be produced by metal corrosion or waste degradation.
- ▲ There are no spills of waste material from package drops / breaches.
- ▲ The salt provides an effective barrier against contaminant transport in the event of minor spills
- ▲ Creep begins, causing a tendency to seal voids associated with shafts and boreholes.
- ▲ Shaft linings prevent sufficient water ingress to the facility to compromise the integrity of waste packages, mobilize contaminants from hydraulic backfill or adversely affect operations. A monitoring system is established, which will be used until the end of institutional control.
- ▲ No significant seismic activity occurs (i.e. seismic activity that would compromise the integrity of any structures or operations).
- ▲ Wastes that include explosive /clinical waste etc. are not permitted and excluded under Waste Acceptance Criteria (WAC), which are consistent with European legislation (specifically Appendix A of Council Decision (EC) 2003/33/EC and Article 5(3) of the Landfill Directive, Council Directive (EC) 1999/31/EC).

10.2.4 Alternative Evolution Scenarios (AES)

The AES in the operational phase proposed to be taken forward for further risk assessment are:

1. AES 1: Rockfall (in an unfilled or partially-filled room, tunnels);
2. AES 2: Vehicle fire;
3. AES 3: Fixed infrastructure fire;
4. AES 4: Waste package (ISO-container or bulka-bag) failure;

5. AES 5: Hydraulic backfill emplacement system failure; and
6. AES 6: Impaired shaft lining performance.

The initiating processes that are outlined in Section 10.1.2 which are not used to define an AES are discussed as variants of these scenarios.

10.3 Qualitative Assessment of AES

10.3.1 Approach

A qualitative assessment of AES during the operational phase of the CF has been undertaken. For each scenario (1-6), a description of the scenario and sub-scenarios are presented, along with a consideration of likelihood of “causing event(s) and / or process(es)” to occur, possible mitigating/managing actions and likely impacts.

The combination of likelihood (over the timescale of operation) and impact give the overall risk as shown in the matrix given in **Error! Reference source not found.** The likelihood of a scenario occurring on a linguistic scale is considered qualitatively to range from “improbable” to “probable”. Similarly, the impact of each scenario is considered qualitatively on a scale “none” to “very high”.

The approach taken is that each scenario has been described given plausible initiating events that are likely to result in the system evolving in a different manner to that assumed in the expected evolution scenario.

Table 10-5: Risk Matrix Approach (red = high risk; yellow = moderate risk; blue = low risk; green = effectively no risk).

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable	Green	Blue	Yellow	Red	Red	Red
Likely	Green	Blue	Yellow	Yellow	Red	Red
Possible	Green	Blue	Blue	Yellow	Yellow	Red
Unlikely	Green	Blue	Blue	Blue	Yellow	Yellow
Highly Improbable	Green	Blue	Blue	Blue	Blue	Yellow

Bowtie representations are also presented to show and communicate risks from the qualitative assessment (Section 10.3.3).

Risks can be placed into two categories:

1. Risks resulting from threats to ongoing operation of the CF (socio-economic impacts, hereafter terms); and

2. Risks posed by threats to environmental receptors, due to intact source-pathway-receptor linkages (exposure to materials release from wastes or substances released due to accidents, such as products of combustion from vehicle fires).

For each category considered, the terminology used to describe likelihood is given in Table 10-6. The terminology used to describe impacts is given in Table 10-7.

Table 10-6: Description of terms used to describe the likelihood of a scenario occurring.

Highly Improbable	Unlikely	Possible	Likely	Highly Probable
Virtually certain <i>not</i> to occur. The evidence base ¹ is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur and <u>none of the available evidence</u> indicates that the phenomenon / scenario will occur.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u>will not</u> occur than there is that it will occur. It is judged <u>clearly that the phenomenon / scenario will probably not occur</u> .	The evidence base is substantial, but some evidence indicates that the phenomenon / scenario will occur, whereas other evidence indicates that it will not occur. However, the evidence that the phenomenon / scenario will occur has about the same weight as the evidence that the phenomenon / scenario will not occur. In other words there is <u>no clear balance of evidence</u> that the phenomenon / scenario will occur as opposed to it not occurring.	The evidence base is sufficient to reach a clear conclusion about whether the phenomenon / scenario will / will not occur. There is much more evidence that the phenomenon / scenario <u>will occur</u> than there is that it will not occur. <u>It is judged clearly that the phenomenon / scenario will probably occur</u> .	Virtually certain <i>to</i> occur. The evidence base is sufficient to reach a clear conclusion about whether a phenomenon / scenario will / will not occur and <u>all available evidence</u> points to the phenomenon / scenario occurring.

Notes: 1. Application of this scale is predicated on there being sufficient evidence (in terms of “quantity” and “quality”) to make a judgement of likelihood. That is, aleatory uncertainties (related to the inherent variability of a phenomenon) are encompassed by the scale, but epistemic uncertainties (arising from lacking knowledge) are not.

Table 10-7: Description of terms used to scale impact.

Assessment	None	Very Low	Low	Medium	High	Very High
Operability	None	Trivial disruption and associated costs.	Minor disruption to ongoing operations, short term (<1 day), minor additional cost to Facility for remedial action (if needed)	Significant disruption to ongoing operation (days-weeks), significant additional cost to Facility for remedial action (if needed)	Major disruption to ongoing operation (month-years), high additional cost to Facility for remedial action (if needed), viability of ongoing operations brought into question	Facility permanently unable to function in any capacity. Major socio-economic impact incurred due to loss of operations (very high costs for remedial activity).
Environmental	None	Negligible contamination of environmental receptors Negligible ecological impact Negligible / immeasurable public exposure to contaminants and no significant public health implications Negligible livestock exposure to contaminants	Minor contamination of environmental receptors (measurable) Minor potential for ecological impact (possibly short-term/reversible) Very low level of public exposure, theoretical possibility of health effects (acute/chronic) Possible minor livestock (e.g. cattle) exposure	Low-level contamination of environmental receptors (potential exceedances of environmental quality indicators) Potential for ecological impact (possibly short-term/reversible) Low level public exposure, possibility of increased risks to health, possible observation of related acute health effects in susceptible individuals Livestock exposed to contaminants need to consider potential tainting of animal products Overall impacts result in regulatory observations	Significant contamination of environmental receptors Ecological impact (possibly irreversible) Significant public exposure, expected increased risks to health and/or observation of acute health effects in population Livestock exposed to contaminants, possible detrimental health effects, animal products deemed unfit for human consumption Overall impacts result in regulatory intervention	Catastrophic contamination of environmental receptors (including loss of any local vegetation) Major potentially irreversible ecological damage Major widespread public exposures resulting in significant observable adverse health effects, and/or loss of life) Complete loss of livestock and need for disposal of animal products as unfit for human consumption

10.3.2 AES Descriptions and Qualitative Analyses

Brief descriptions of AES, associated-source-pathway-receptor linkages, mitigating measures, likelihood, degree of impact and overall risk with regard to operability and the environment are given in Table 10-8 and Table 10-9 respectively. Summaries of overall risks relating to operability and the environment are given in Table 10-10 and Table 10-11, respectively. The risks assume that appropriate plans are in place to prevent these scenarios from arising, and for mitigating their effects should they do so.

The Tables include overall assessments of potential impacts, made on a qualitative basis considering the key information inputs and expert judgements described in previous sections.

To provide context for the assessment, key elements of the AES are listed below.

The **rockfall in partially-filled room / tunnel scenario (AES 1)** assumes that there is a significant mass of material falling from the roofs (more than minor dust, or a few small fragments) in either:

- a. a tunnel; or
- b. a room that is being excavated or into which waste is being emplaced.

This scenario reflects a degree of failure in rockfall mitigation measures that are expected to be in place (e.g. rock bolting and design). Multiple simultaneous rockfalls in different parts of the facility are considered to be implausible.

This scenario could result in three kinds of risk to the environment or operability of the facility:

- i. restricted access to all or part of the facility;
- ii. damage to waste containers; or
- iii. water ingress to the CF.

Were damage to containers to occur, the potential for contaminant release would be similar to that covered by the waste package failure scenario (AES 4).

If a significant volume of water were to ingress into the facility as a result of roof collapse (more than minor seepages that could be easily avoided by waste emplacement activities and readily stopped by grouting), then the potential for contaminant release and risks to operations would be broadly similar to the impaired shaft lining scenario (AES6).

The **vehicle fire scenario (AES 2)** assumes that at least one vehicle fire event could occur during the operation of the facility, even if fire prevention measures and vehicle maintenance procedures are in place. The fire could occur anywhere between the

ground surface and the site of waste emplacement underground. There are two main variants:

- a. a fire underground (likely worst case within or at the base of a shaft); or
- b. a fire at the ground surface.

The chief differences between a vehicle fire at the surface and underground will be:

- ▲ Compared to vehicle fires at the surface, vehicle fires underground may result in higher peak concentrations of any contaminants that are released, owing to the confined space within which release occurs.
- ▲ Compared to vehicle fires underground, vehicle fires at the surface will have a higher probability of contaminating the wider environment owing to atmospheric dispersal.
- ▲ Compared to vehicle fires underground, those at the surface will pose less risk to the operations of the facility since any damage will likely be more readily rectified.

The **Fixed infrastructure fire (AES 3)** considers the potential for a fire in fixed infrastructure, at the ground surface or underground. The effects of such a scenario being realized at any particular locality would largely be similar to those for a vehicle fire at a similar locality, except in so far as an item of fixed infrastructure could be larger than a single vehicle. Scenario AES 2 and AES 3 could be closely related in that a vehicle fire could cause a fixed infrastructure fire, or vice versa.

The **waste package failure scenario (AES 4)** considers the potential for release of containerised waste underground due to:

- a. containment being breached (for example, containers being dropped in rooms/tunnels or damaged by vehicles);
- b. the drop of an ISO-container down the disposal shaft resulting in rupture of waste container and ISO-container.

The **hydraulic backfill emplacement failure scenario (AES 5)** considers the potential for failure of hydraulic backfill emplacement system, leading to blockage and need to remove the pipe and repair/replace. There are two variants:

- a. failure to maintain a flow of backfill mix, due either to pump failure or failure to introduce backfill mix to the system; or
- b. a pipe burst

In either case, there would be consequences at the ground surface and underground. Were a pipe burst to occur, then slurry would be spilled either in the sub-surface environment or at the ground surface. It is assumed that such a spill would be recognized quickly and the system shut down, so that the spill, whether at the surface or underground would be restricted in volume. The spilled backfill mix would solidify

and could then be broken into pieces if necessary and treated as solid waste. Backfill in the remaining pipe would also solidify, once pumping had stopped. A consequence would be a requirement to replace the pipe before resuming hydraulic backfilling operations.

The **impaired shaft lining scenario (AES 6)** assumes that there has been either a failure in the QA/QC associated with lining materials or their emplacement and that this results in either:

- a. minor water seepage; or
- b. major water ingress via permeable horizons.

The latter situation would occur only if the failure of the shaft lining grout occurred at a location adjacent to an aquifer which could sustain prolonged inflows. Many of the more permeable horizons within the overburden have been found in boreholes to be incapable of supporting such sustained flow.

Table 10-8: Description of alternative evolution scenarios: operability impacts.

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
1	Rockfall	Failure of engineering measures to mitigate against significant rockfall in (a) a tunnel (b) a room In each case, two variants: (ai) Rockfall only (aai) Rockfall accompanied by water influx (bi) Rockfall only (bii) Rockfall accompanied by water influx Multiple simultaneous rockfalls in different parts of facility deemed implausible	(a) (i) vehicles, possible disruption to transport of containers (ii) access to all or part of the facility prevented, possible mobilization of contaminants (b) (i) vehicles, possible loss of a room for disposal (ii) access to all or part of the facility prevented, possible mobilization of contaminants Results in impeding of transport in tunnels or rooms	Standard monitoring and inspection of working Use of mitigating procedures (e.g. rock bolting) and appropriate excavation design geometry Remedial measures if rockfalls occurred may include re-excavation, or disposing to different rooms If water ingress would need to physically isolate the part of the facility affected, which may not be possible	(ai) Likely (aai) Highly improbable (bi) Likely (bii) Highly improbable	(ai) Medium Loss of accessibility, need to clear material/re-excavate resulting in disruption (aai) Medium-High Depending on extent of flooding, possible long-term remediation required/facility ceasing to function. Relatively low permeability of aquifer limits inflow. (bi) Low Possible loss of room for waste emplacement, or shift emplacement to different room until remedial actions complete (bii) Medium-High Depending on extent of flooding, possible long-term remediation required/facility ceasing to function. Relatively low permeability of aquifer limits inflow.

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
2	Vehicle Fire	Fire in underground tunnels/room, or at the ground surface causes disruption to emplacement activities, potential releases of combustion products (gases and particulates)	Damage to underground infrastructure and disruption of operations if occurring underground, contamination of the atmosphere underground and potentially contamination of the atmosphere at the surface, if smoke / fumes vented via the shafts Damage to surface infrastructure and disruption of operations if occurring at the surface, potentially contamination of the atmosphere around the facility	Standard fire prevention practices and vehicle maintenance Emergency response arrangements Remedial measures (e.g. decontamination if required)	Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility	Medium Significant disruption to ongoing operations, need for remedial activities
3	Fixed infrastructure fire	Fire in fixed equipment in underground tunnels/rooms, or in facilities at ground surface causes disruption to emplacement activities, potential releases of productions of combustion (gases and particulates)	Damage to underground infrastructure and disruption of operations if occurring underground, contamination of the atmosphere underground and potentially contamination of the atmosphere at the surface, if smoke / fumes vented via the shafts	Standard fire prevention practices and facility maintenance Emergency response arrangements Remedial measures (e.g. decontamination if required)	Unlikely - Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility. Lower probability corresponds to higher impact.	Medium - High Significant disruption to ongoing operations, need for remedial activities. The maximum plausible impact for a fixed facility is greater than for a single event involving a vehicle (except in so far as the vehicle fire could cause a larger fire in a fixed facility, especially at the surface).

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
			Damage to surface infrastructure and disruption of operations if occurring at the surface, potentially contamination of the atmosphere around the facility			Greater impacts correspond to lower probability events.
4	Waste package failure	Dry emplacement wastes (a) Discrete waste spill due to container drop or failure (e.g. vehicle accident, damage due to fire, rockfalls) (b) Container drop in shaft resulting in rupture of containers at base of shaft	(a) Tunnels/rooms/infrastructure (b) Shaft, tunnels connecting shaft to rooms	General minimisation of likelihood considered during facility design Maintenance of equipment (a) Standard health and safety procedures, worker training for underground operation of vehicles (b) Elevator safety mechanisms to prevent opening of doors when elevator at bottom of shaft and/or elevator drop. Standard health and safety procedures, worker training. Possible waste interaction due to spills resulting in exacerbated gas/aerosol production mitigated	(a) Likely Probability minimised via standard operating procedures, but considered that one event could occur over whole operational lifetime, in contrast to expected scenario (b) Highly Improbable Multiple safety protocols to prevent drop of containers in shaft	(a) Medium Significant disruption to operations, need for remediation of contaminated areas prior to ongoing working (b) High Major disruption, need for extensive remedial activities

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
				against by considering separation of wastes during acceptance and emplacement Emergency response protocols and actions		
5	Hydraulic backfill emplacement system failure	(a)Failure of hydraulic backfill emplacement system at the surface, or underground, leading to blockage (b)Leak of backfill pipe, either underground or at the surface	(a)Hydraulic backfill emplacement pipe must be replaced, the blocked pipe itself becoming solid waste (b)Tunnels/rooms/ infrastructure, shaft, tunnels connecting shaft to rooms, if at surface facilities close to the leak	QA/QC procedures for backfill manufacture and emplacement, design of facility. Maintenance of equipment. Standard procedures, worker training If a leak were to occur, emplacement of backfill would cease	(a) Likely (b) Possible Risk minimised by quality control procedures in place for backfilling system	(a),(b)Medium Disruption to operations, need for remediation prior to ongoing waste emplacement
6	Impaired shaft lining performance	Failure of shaft liner during operations and water ingress via permeable horizons/surface possibly exacerbated via high rainfall/recharge	Possible failure of shaft lining grout (possibly exacerbated by high rainfall/surface flooding) leading to water ingress resulting in: (a)minor water ingress into tunnels and disruption to salt excavation/waste	QA/QC procedures for shaft liner manufacture and emplacement Site design to minimise potential for build-up of surface water and run-off in vicinity of shafts Inspection of facility,	(a)Possible Risk minimised by facility design and mitigating procedures (e.g. grouting) (b)Highly Improbable-Unlikely Risk minimised by facility design and mitigating procedures (e.g. grouting)	(a)Very low Minor disruption whilst minor leaks are repaired (b) Medium-Very High Depending on extent of flooding, possible long-term remediation required/facility ceasing to

Nº	Name	Description	Receptors and Implications for operability	Mitigating measures in place	Likelihood of Event	Possible Impact
			emplacement operations (b)major water ingress minor water ingress into tunnels and disruption to salt excavation/waste emplacement operations	identification of minor leaks and mitigation via grouting Major ingress of water to rooms reduced by closure of bulkhead doors. Potential to pump out water from shaft to minimize extent of flooding of rooms/tunnels	prior to significant failure Lower probability corresponds to higher impact.	function Greater impacts correspond to lower probability events.

Table 10-9: Description of alternative evolution scenarios: environmental impacts during the operational phase.

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
1	Rockfall	Occurring in either: (a) a tunnel (b) a room In each case, two variants: (ai) Rockfall only (aii) Rockfall accompanied by water influx (bi) Rockfall only (bii) Rockfall accompanied by water influx Multiple simultaneous rockfalls in different parts of facility deemed implausible (ai) and (bi) leading to release of contaminants, with similar effects to those considered in Scenario 4 (aii) and (bii) leading to mobilization in a similar way to considered in Scenario 6	(ai) and (bi) Considered in Scenario 3 (aii) and (bii), similar pathways to those in Scenario 6 plus escape through collapsed overburden to the Stairway Formation aquifer.	Standard monitoring and inspection of working Use of mitigating procedures (e.g. rock bolting) Remedial measures if rockfalls occurred may include re-excavation, or disposing to different rooms If flooding occurs may prove impossible to mitigate	(ai) and (bi) Environmental impacts considered in Scenario 3 (aii) Highly Improbable (bii) Highly Improbable	(ai) and (bi) Environmental impacts considered in Scenario 4 (aii) Very low (bii) Very low Potentially the lowest aquifer (the Stairway) formation would be contaminated. However, this aquifer contains dense, saline water and there are probably no natural conduits through which contaminated water could be transported to shallower levels. Within the operational time frame environmental impacts would be very low. The implications of this scenario for longer-term impacts are considered further in the PCRA.

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
2	Vehicle Fire	Vehicle fire in tunnels/room, disruption to operational activities, potential releases of productions of combustion (gases and particulates)	Products of combustion underground– (a)shaft air -members of public at surface (b)shaft air-local livestock/ecosphere Products of combustion at the surface– (c)members of public at surface (d)local livestock/ecosphere	Standard fire prevention practices and vehicle maintenance Emergency response arrangements	(a)-(d)Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility	(a)-(d)Very Low (a),(c) Potential for members of public being exposed very low due to distance of local population to the facility (b), (d) Potential exposure of nearby livestock, depending on atmospheric conditions, livestock could be moved if considered at risk until fire put out
3	Fixed infrastructure fire	Fire in underground tunnels/room, or at the ground surface causes disruption to emplacement activities, potential releases of combustion products (gases and particulates)	Products of combustion underground– (a)shaft air -members of public at surface (b)shaft air-local livestock/ecosphere Products of combustion at the surface– (c)members of public at surface (d)local livestock/ecosphere	Standard fire prevention practices and vehicle maintenance Emergency response arrangements	(a)-(d)Unlikely-Likely Probability minimised due to mitigating measures, one event may be considered to occur during overall operational lifetime of facility. Lower probability corresponds to higher impact.	(a)-(d)Very Low to Low (a),(c) Potential for members of public being exposed very low due to distance of local population to the facility, but if fire occurred in a large waste store at the surface, the potential impact is possibly higher than for a vehicle fire at the surface. (b),(d) Potential exposure of nearby livestock, depending on atmospheric conditions, livestock could be moved if considered at risk until

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
						fire put out, but if fire occurred in a large waste store at the surface, the potential impact is possibly higher than for a vehicle fire at the surface. Greater impacts correspond to lower probability events.
4	Waste package failure	(a) Discrete waste spill due to container drop or breach (e.g. vehicle accident) (b) Container drop in shaft resulting in rupture of containers at base of shaft	(i) Dust –Shaft-Local air+deposition on surface soil/vegetation (including local cattle grazing areas) (ii) Dust –shaft-surface water/biota (iii) Dust –shaft-surface air-members of public	General minimisation of likelihood considered during facility design Maintenance of equipment (a) Standard health and safety procedures, worker training for underground operation of vehicles (b) Elevator safety mechanisms to prevent opening of doors when elevator at bottom of shaft and/or elevator drop. Standard health and safety procedures, worker training Emergency response protocols and actions	(ai-aiii) Likely Probability minimised via standard operating procedures, but considered that one event could occur over whole operational lifetime, in contrast to expected system evolution scenario (bi-biii) Highly Improbable Multiple safety protocols to prevent drop of containers in shaft, “double” containerisation (bags/barrels in ISO-containers)	(ai) Very Low Considering length of pathway (aii) Very Low Considering length of pathway distance to receptor (aiii) Very Low Considering length of pathway and distance to nearest population centre (bi) Low Considering length of pathway (bii) Low Considering length of pathway (biii) Low

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
				Possible waste interaction due to spills resulting in exacerbated dust production mitigated against by considering separation of wastes during acceptance and emplacement		Considering length of pathway Note that release at shaft base is more likely to enable movement of contamination to the surface, hence classification of (b) pathways as “low” rather than “very low”.
5	Hydraulic Backfill emplacement system failure	(a)Failure of hydraulic backfill emplacement system at the surface, or pipe underground, leading to blockage (b)Leak of backfill pipe, either underground or at the surface	Hydraulic backfill emplacement pipe	QA/QC procedures for backfill manufacture and emplacement, design of facility. Maintenance of equipment. Standard procedures, worker training	(a),(b)Possible Risk minimised by quality control procedures in place for backfilling system	(a)None It is likely that any failure of the injection system would result in at least some of the pipe needing to be replaced, but there would be no direct environmental impacts; the pipe itself, and the solidified waste that it contains, would need to be treated as solid waste. (b)Very Low It is likely that any leak would be stopped quickly owing to the system being continuously monitored. Whether the leak occurs at the surface or underground, the small

Nº	Name	Description	Source-Pathway-Receptor	Mitigating measures	Likelihood of Event	Possible Impact
						volume of leaking material would solidify before it could migrate significantly.
6	Impaired shaft lining performance	Failure of shaft liner during operations and water ingress via permeable horizons/surface possibly exacerbated via high rainfall/recharge	Possible failure of shaft liner grout (exacerbated by high rainfall/surface flooding) leading to water ingress resulting in: (a)minor water ingress and disruption to salt extraction/waste emplacement operations (b)major water ingress and disruption to salt extraction/waste emplacement operations and mobilization of contaminants via leaching of backfill or disruption of dry emplaced wastes (assume container leakage)	QA/QC procedures for shaft liner manufacture and emplacement Site design to minimise potential for build-up of surface water and run-off in vicinity of shafts Inspection of facility, identification of minor leaks and mitigation via grouting Major ingress of water to rooms reduced by closure of bulkhead doors. Potential to pump out water from shaft to minimize extent of flooding of rooms/tunnels	(a)Possible Risk minimised by facility design and mitigating procedures (e.g. grouting) (b)Highly improbable Risk minimised by facility design and mitigating procedures (e.g. grouting) prior to significant failure	(a)None Minor water ingress unlikely to result in flooding of rooms/tunnels, high capacity for water to be soaked up into salt (deliquescence) (b)Very low Lack of conductive features, therefore lack of pathways for contaminant transport to aquifers

None of the (plausible, yet cautious) alternative scenarios or their subsets poses a “high” overall risk on operability. There are five of the scenarios/subsets that have a “moderate risk” and three that have a “low risk”. Also, it should be noted that numerous mitigating measures can be taken for each of the alternative evolution scenarios. None of the alternative scenarios were considered to be “highly probable”. Only one possible subset (AES 5b) was considered to potentially have a very high associated impact, however that scenario was considered to be “highly improbable”, leading to a “moderate” overall risk.

None of the alternative scenarios pose a “high” overall risk to environmental receptors. Four source-pathway-receptor linkages have a “moderate” overall risk (associated with AES2, AES3 and AES4) and six have source-pathway-receptor linkages that are “low” overall risk (associated with AES1, AES4, AES5 and AES6). Also, it should be noted that numerous mitigating measures can be taken for each of the alternative evolution scenarios. None of the source-pathway-receptor linkages considered in the scenarios were considered to result in a “medium”, “high” or “very high” impact.

Table 10-10: Summary of risks related to operability for each AES. Colour coding as in Table 10-5.

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely			1bi	1ai, 2, 3, 4a, 5a		
Possible		6a		5b		
Unlikely				6b	3	
Highly Improbable					1aii, 1bii, 4b	6b

Table 10-11: Summary of risks related to environmental receptors for each AES.
Colour coding as in Table 10-5.

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely	5a	2a, 2b, 2c, 2d 3a, 3b, 3c, 3d, 4ai, 4aii, 4aiii				
Possible	6a	5b				
Unlikely						
Highly Improbable		1aii, 1bii, 6b	4bi, 4bii, 4biii			

It can be seen from comparing Table 10-10 and Table 10-11 that the risks are generally higher with respect to operability of the facility, than they are with respect to the environment. That is, should one of the AES be realized, its implications for operating the facility are likely to be more significant than its implications for environmental safety.

10.3.3 Bowtie Analysis

For each alternative evolution scenario, a BowTie has been constructed. This approach is a structured methodology for visualising and communicating risks and the steps taken to manage them (e.g. as implemented in BowTieXP™, Governors, 2012). A schematic diagram of showing the components of a BowTie are given in Figure 10-1. Each BowTie illustrates:

- ▲ The hazard – with the potential to cause harm.
- ▲ A top event – that could cause the hazard to be actually harmful (reflecting loss of control).
- ▲ Threats (left hand side) that could realize the top event; and consequences (right hand side) that could be caused by the top event.
- ▲ Barriers on both sides of the BowTie, reflecting measures that could prevent (left hand side) or mitigate (right hand side) the effects of the top event.

Thus each BowTie provides an overview of the key risks and potential measures associated with the system for each of the scenarios. It does not provide an assessment

of those risks and associated overall likelihood / impact associated with them; the BowTies can be seen as complementing, not duplicating, the above risk matrices.

BowTies for each alternative evolution scenario that encompass both operability and environment aspects are presented in Figure 10-2 to Figure 10-6. Outcomes are discussed in context in Section 10.4 and Section 12.

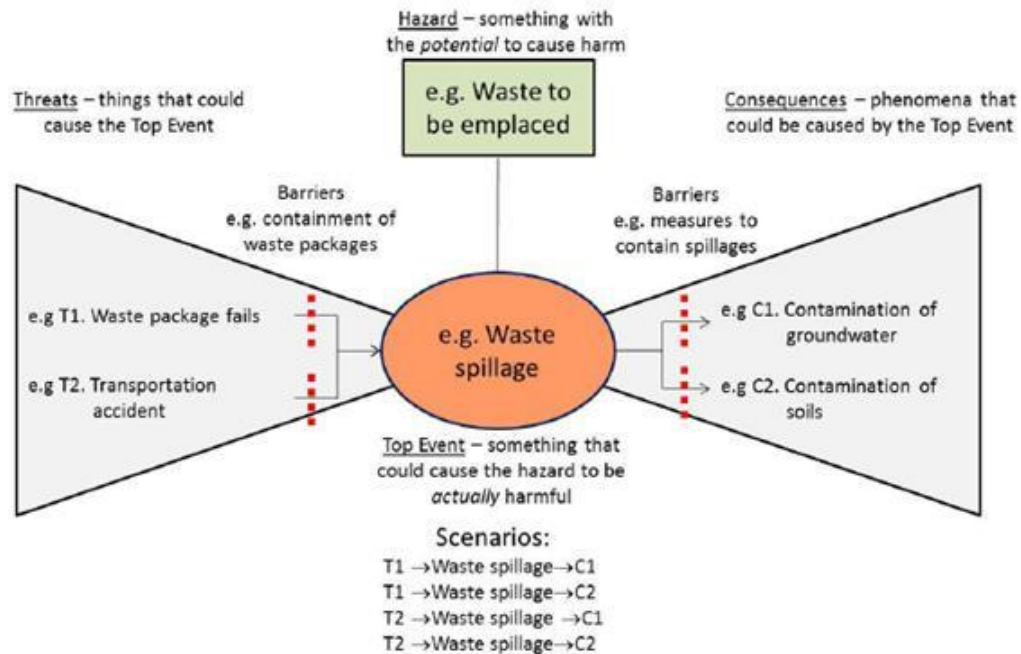


Figure 10-1: Schematic illustration of BowTie analysis.

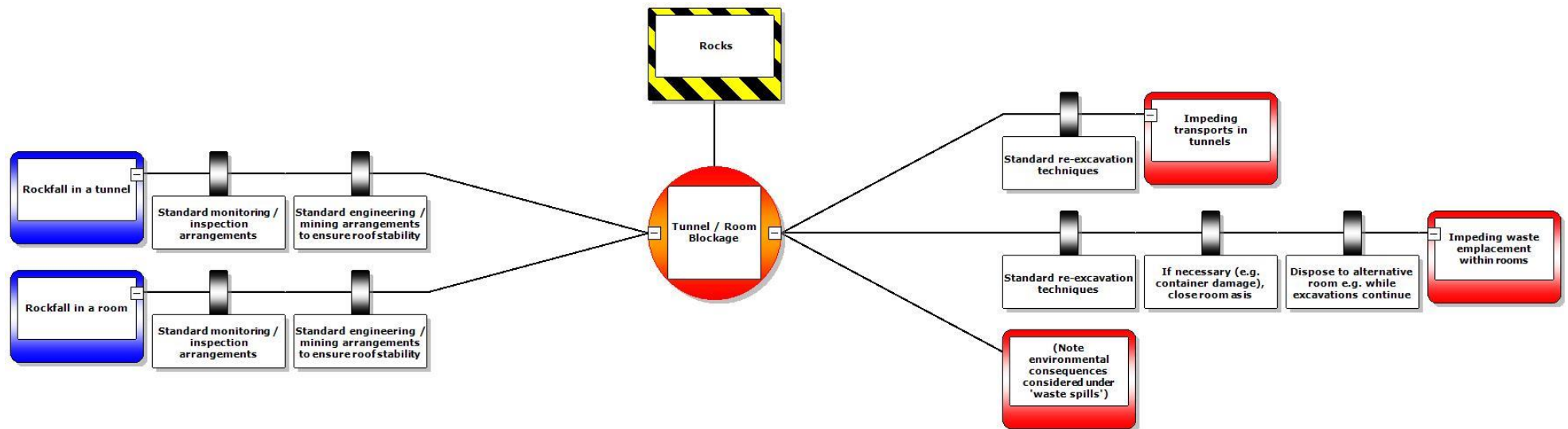


Figure 10-2: BowTie for Rockfall alternative evolution scenario.

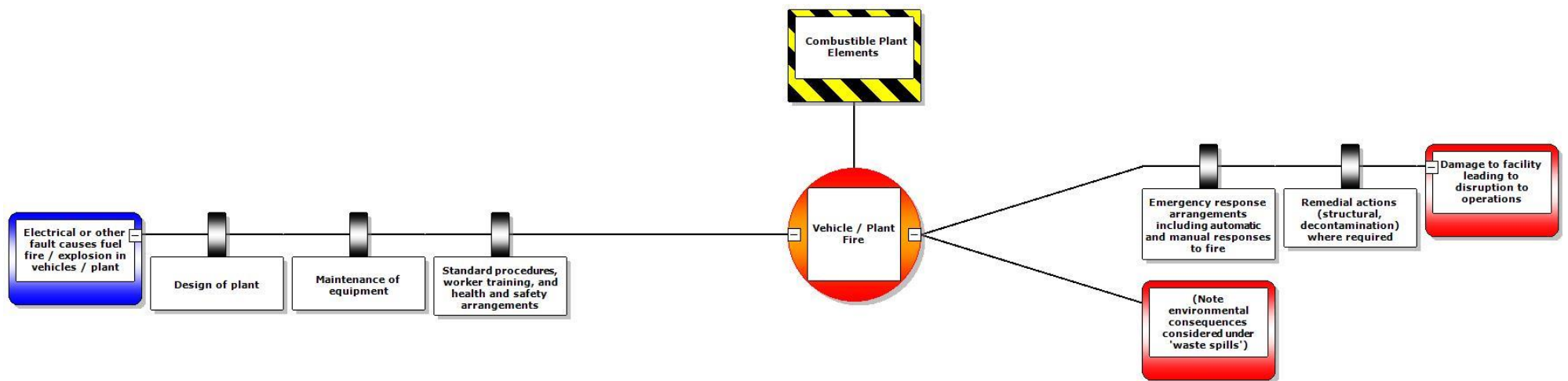


Figure 10-3: BowTie for Vehicle/Plant Fire alternative evolution scenario.

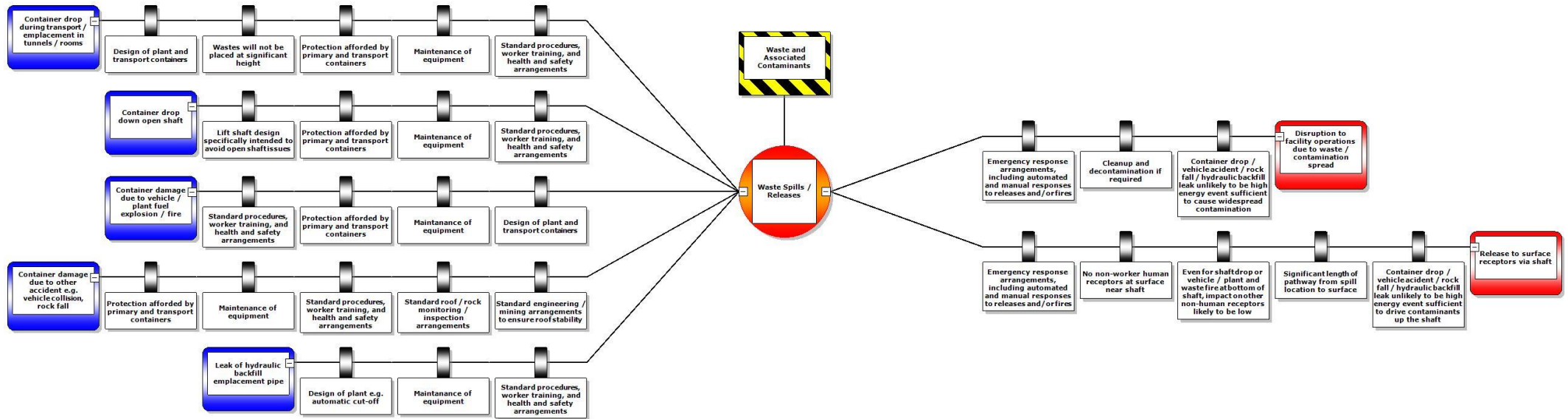


Figure 10-4: BowTie for Waste Spill/Release alternative evolution scenario.

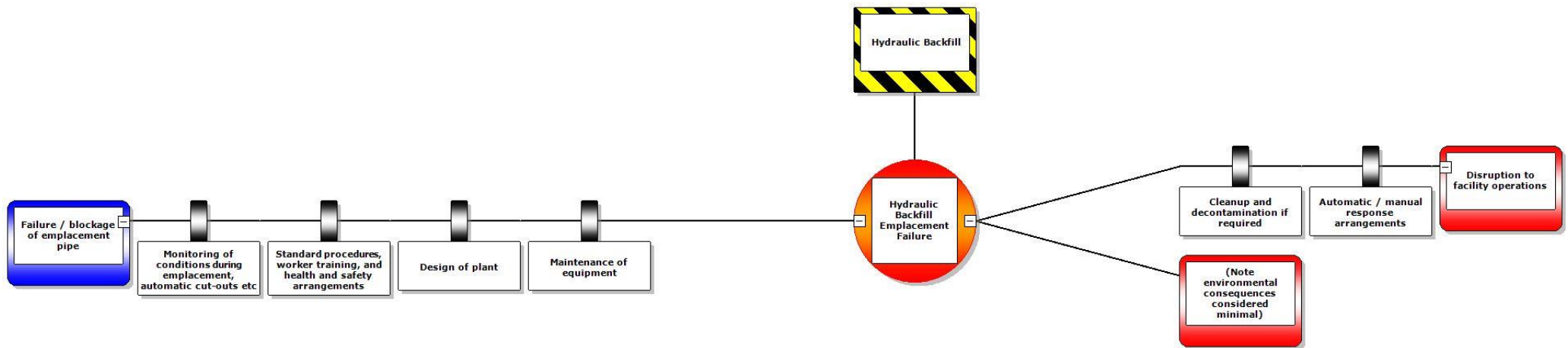


Figure 10-5: BowTie for Hydraulic backfill emplacement failure alternative evolution scenario.

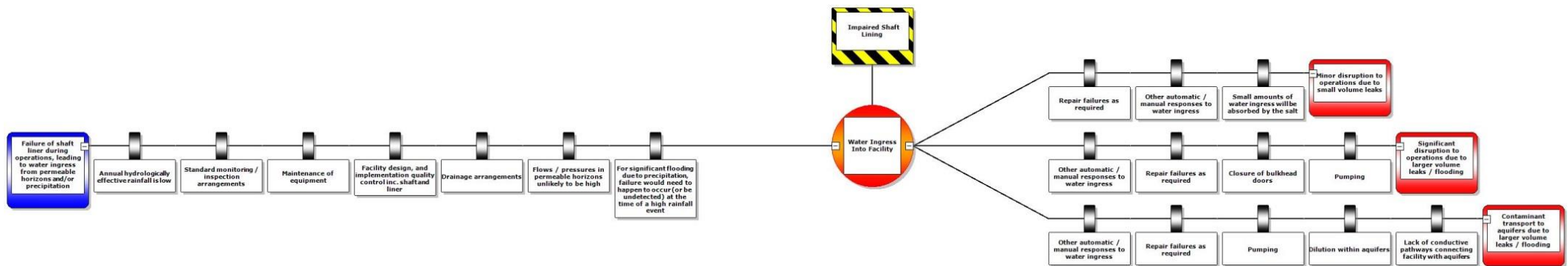


Figure 10-6: BowTie for Impaired shaft lining performance alternative evolution scenario.

10.4 Summary of the OPRA Outcomes

10.4.1 Overview of Potentials Risks and Mitigation

As would be expected at the outset, the OPRA has concluded that the EES, where operation and environmental performance of the facility is as planned with no significant deviations, is the only “probable” scenario.

The outcomes of the AES assessments can be summarized as follows.

Risks to Operability

- ▲ None of the AES were assessed as representing a “high” risk.
- ▲ Scenarios cautiously assessed as having a potential “moderate” risk, in that they could impair operations for a few days or weeks and require remedial action if they occur, included rockfall, vehicle plant/fire, waste spill/release, hydraulic backfill emplacement failure and impaired shaft lining performance scenarios. However all but a “highly improbable” scenario of shaft lining failure leading to significant flooding could cause significant impacts, but not ones that could not be mitigated or call into question the effective operation of the facility. That is, even the cautious assessment undertaken provides confidence that none of these risks are sufficient to compromise the overall business case for the effective running of the facility.
- ▲ The BowTies indicate various preventative and mitigation measures that may be employed. At present these have been taken into account in the assessment, but cautiously. That is, it has been assumed that no preventative “barrier” can be completely effective. Further analysis of the mitigation methods described in the BowTies could provide additional confidence in performance that could, should a further iteration of assessment be undertaken, help reduce both the assessed likelihoods of the AES occurring and of the plausible impacts that could arise if they were to be realized. “Barriers” that might be employed and / or modified to prevent the AES or mitigate their impact, depending upon the scenario considered, include: plant and facility design and maintenance; waste packaging; operational methods, including emplacement methods; monitoring approaches to identify the potential for incidents to occur and allow preventative actions to be taken; emergency responses; and subsequent remedial actions that could reduce the impacts of an AES that occurs.

Risks to Environmental Receptors

- ▲ None of the AES were assessed as representing a “high” risk.

- ▲ The highest impact scenarios were assessed as having potential “low” impacts, but those scenarios were all considered “improbable” to “unlikely”, the latter corresponding to larger fires involving fixed infrastructure at the surface.
- ▲ Scenarios involving vehicle plant/fires and waste spills/releases could potentially lead to a “very low” impact whilst being considered cautiously as “likely” to occur. However, these impacts would not be sufficient to lead to impacts to receptors above regulatory targets.
- ▲ Essentially, the lack of clear “source-pathway-receptor” linkages between the underground facility and its environs, given the nature of the facility, means there is confidence that the risks involved are manageable. For example, underground accident events would be unlikely to cause a release of a high enough energy to lead to significant impacts at the surface via releases of contaminants being transported through excavated tunnels or shafts. Furthermore contaminant transport through the salt host rock of the facility could not occur on the timescale of the operational phase, given the impermeable nature of the salt and its very low water content, combined with the fact that containerized wastes will be essentially dry, while the hydraulic backfill will be formulated to contain minimal free water following curing. Further consideration of the various barriers involved may serve to further reduce assessed risks should any future iteration of assessment be undertaken.

10.4.2 Comparison to other Facilities

Assessments for the Minosus facility in Cheshire, northwest England (Robinson and Hooker, 2002), and a proposed salt cavern stabilisation programme at Hengelo in the eastern Netherlands (Metcalf et al., 2013), were reviewed as part of the assessment development process. Scenarios and key FEPs for these other facilities were reviewed and compared / audited with those adopted for the present assessment. It is notable that the focus of these other assessments was different to the focus of the assessment for the CF, in particular in terms of operational assessments. Nevertheless, the confidence in operability and operational environmental safety provided for the Minosus facility and the Dutch salt cavern stabilisation programme by the relevant assessments helps provide confidence in the OPRA of the proposed CF presented here. In particular it is notable that the current proposed CF facility is much deeper (c. 800 m) than the Minosus one (c. 175 m) and the Dutch salt caverns (c. 500 m). Also, there are fewer present local potential environmental receptors in the vicinity of the CF, which, unlike the Minosus facility and eastern Netherlands’ salt caverns, is located in a desert environment remote from large population centres. Consequently, it could be

expected that for similar wastes and care in design and operations, potential risks for the CF should be even lower.

11 Long-term Assessment of the Post-closure Phase

11.1 Expected Evolution Scenario (EES)

11.1.1 EES Scenario Description

The EES is a statement of the evolution of the CF during the post-closure phase, assuming the facility behaves as designed (Figure 11-1).

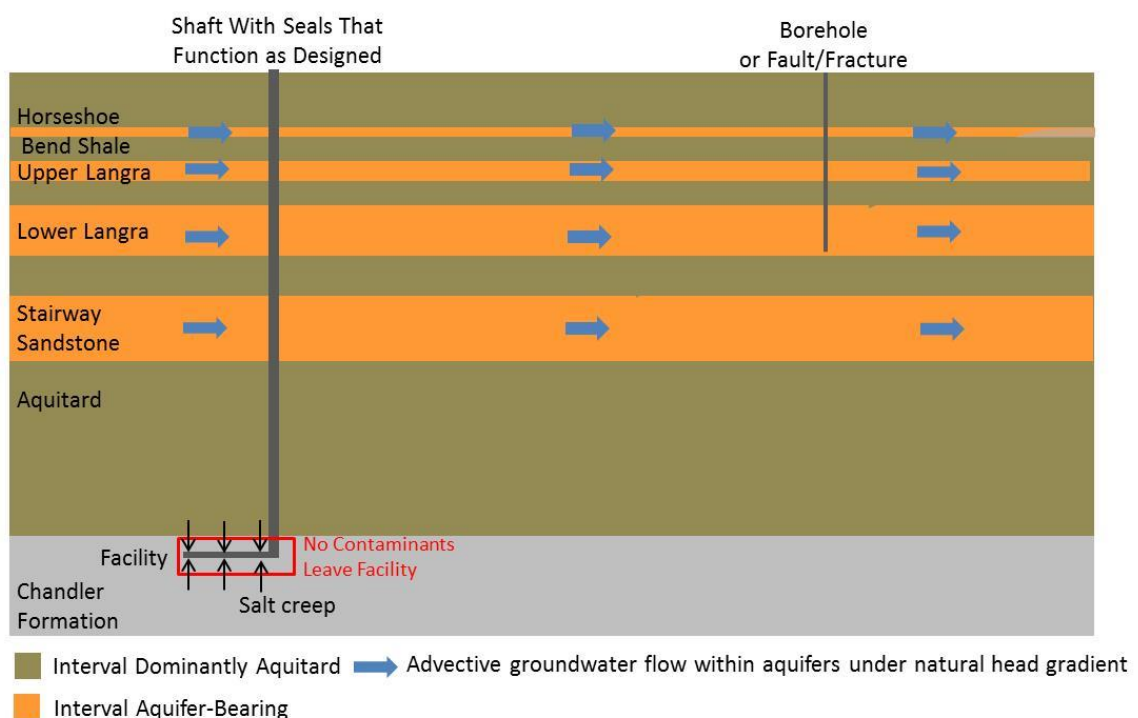


Figure 11-1: Schematic illustration of the EES. No contaminants leave the facility. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. The fault / fracture is a feature that has not yet been detected, but which may occur, potentially some distance downstream.

In the EES nothing has occurred in the operational period that could compromise the long-term evolution of the facility (e.g. there has been no cavern roof failure during the operational period that might have produced pathways for contaminant migration post-closure). That is, the facility has been operated as planned, all of the closure engineering (backfilling and seals) has been emplaced to the design specification and the different system components (host rock, overburden etc.) have the expected properties.

The wastes will be emplaced with very little or no free water present. In this scenario the hydraulic backfill will be formulated so that after curing there will be essentially no free water. The limited supply of water means that very little gas is produced by from the wastes, by organic matter degradation or corrosion. The high salinities will also tend to limit the activity of micro-organisms that could participate in gas-generating reactions.

At closure, the disposal rooms and access tunnels will contain significant voidage (estimated to be 20-40%, Section 4.14.1 and Section 4.2). This voidage is the result of porosity in the waste and backfill and the fact that 100% filling of cavities may not be achieved. However, while the excavations will be designed to remain stable during operations, it is expected that the salt host rock will creep after closure and compact and fully encapsulate the waste and backfill, eliminating most of the voidage. However, some voidage will remain within the waste, for example between grains that may compose certain wastes, or in the hydraulic backfill, that are sufficiently strong to support the imposed stress. Some voids will also remain as a result of a small proportion of water or gas that may be present; pressurisation of these fluids during creep will result eventually in no further creep being possible (the performance assessment for the WIPP estimated that as much as 20% porosity could be maintained throughout the performance period in that case (USDOE, 2014)). In the EES, the properties of the salt are such that this process does not breach the salt roof of the facility and the impacts of any minor roof falls are eliminated by creep and consolidation of the salt. The timescale on which this creep closure will occur is uncertain as the creep rate for the halite has not been determined. Based on analyses of halite formations that have been considered as hosts for radioactive waste repositories in a number of countries the timescale is likely to be at least several hundred years and possibly several thousand years (NEA, 2007). It is noted that the temperature at disposal depth will increase to about 45°C, from the lower temperature that will have been maintained by ventilation during operations, and this may serve to accelerate the creep process. For this scenario it is assumed that this creep process takes between a few hundred and a thousand years to completion.

The materials used to construct the shaft seals will similarly not be fully compacted at the time of closure and their properties will evolve over a period of time to some degree. Depending on the exact design of the seals, this evolution will involve a combination of compaction and saturation by groundwater. At the end of the process, the seals will achieve their long-term properties. In this scenario the seals have attained their long-term properties on a timescale of a few hundred years.

The CF will be located in a bedded massive halite which does not contain permeable interbeds (ERCOSPLAN, 2013). Such a halite formation is essentially impermeable.

Once the salt has crept to encapsulate the waste and the seals have attained their design properties, the disposal facility has reached its long term stable state. It is not expected to evolve further on the timescales of interest. The seals will be designed to have permeabilities as low as that of the salt and to maintain their integrity for geologically significant periods of time (>1Ma).

The salt formation remains stable, as it has for many millions of years, and no groundwater penetrates the facility. The fact that the Cambrian salt is apparently undisturbed, in spite of c. 520 million years elapsing since it was deposited shows that the CF system would be robust with respect to the climate changes and geological processes that will influence the area of the CF over timescales of millions of years.

The geological setting of the CF within the geologically stable interior of a tectonic plate, far from present dynamic tectonic plate boundaries where there is active deformation, provides further confidence that the CF will not be disturbed by geological processes within any timescale of concern to humans.

In the EES human activities (borehole drilling or mining) do not intrude into the facility in the future.

11.1.2 EES Scenario Analysis

In order for contaminants to leave the CF three conditions would need to be met:

1. There would need to be a potentially mobile phase (water or gas) that could transport the contaminants.
2. There would need to be a driving force to cause this phase to move.
3. There would need to be a physical pathway from the facility, such as a permeable fault, failed shaft seal, or imperfectly sealed borehole, via which the contaminants, in the mobile carrier phase, could be transported.

In the EES, all these conditions are never met simultaneously during the assessment time frame. Hence there is no way by which the contaminants can be transported out of the facility.

Arguments to support this statement are as follows:

- ▲ **Potential for a mobile phase:** In the EES, the WAC will ensure that at the time of closure the wastes themselves are essentially dry. The hydraulic backfill used in parts of the facility will be designed to ensure that immediately after curing there is very little, if any, free water. The halite itself is not entirely anhydrous, with small quantities of water being trapped in isolated fluid inclusions and potentially brine pockets. However, even though no analyses of water content in the halite exist, data from other halite formations indicates that probably the water content will be <<1 wt% (see, for example, Weber et al.,

2013). Therefore, the quantities of free water that will be contributed to the facility by the salt will be minimal. The paucity of water will severely limit any inorganic or microbially mediated gas-producing reactions, which require water to proceed. In addition, the highly saline character of any small quantity of water that does exist (owing to the presence of soluble halite) will limit the activity of micro-organisms. Following closure there is no way for water to enter the facility, since the halite of the Chandler Formation is impermeable and the shaft seals will maintain their integrity. Over time, creep of the halite will cause the original walls and roof to converge and reduce the residual voidage in the facility that could be occupied by a mobile phase.

- ▲ **Potential for a driving force:** The halite of the Chandler Formation is impermeable and will therefore effectively isolate the emplaced wastes from natural groundwater head gradients in the more permeable rock formations within the rock sequences above and below the halite. Thus, natural head gradients cannot provide a driving force to move contaminants from the CF. Even if there was a pathway between the CF and the rock formations above the halite (see below for further discussion), the relatively high density of the water within the CF, compared to shallower water, would tend to oppose upwards movement of water. Any free water present in the CF will be saturated with halite, which is highly soluble, and therefore will be substantially denser than the water present within the rocks above the CF. For example, according to URS (2012) the Stairway Sandstone contains water with TDS content of 14,998 mg/L, which implies a density of c. 1015 kg/m³. In contrast water in the Chandler Formation that has dissolved halite to the point of saturation will have a salinity of c. 360,000 mg/L, equivalent to a density of c. 1,360 kg/m³. Creep of the halite will provide a driving force, but this will cease once the residual voidage in the facility has decreased to a level that the wastes and backfill can support the halite. The timescale over which there will be a driving force caused by creep is presently unknown. However, based on analyses for radioactive waste facilities in halite formations elsewhere in the world, this period is likely to be at least several hundred years and may be several 1000 years (NEA, 2007). The very limited ability of the wastes to generate gas (for the reasons explained above) will ensure that any gas pressurisation that occurs will be minimal. The gas pressure will increase in response to creep of the salt, but the residual pore space will be sufficient to accommodate the small amount of gas.
- ▲ **Potential for pathways:** In the EES, the roof, walls and floor of the CF are undisturbed at the time of closure (i.e. no rock-falls in the operational period have compromised the integrity of the roof and walls). The halite will provide an excellent seal, which is of extremely low permeability owing to the lack of

connected porosity and its capability for self-sealing through creep over time following any brittle failure. The ability of halite to maintain its integrity over very many millions of years is indicated by the fact that halite forms the caprock to many hydrocarbon reservoirs throughout the world (e.g. in the North Sea, offshore Europe; Capture Power and National Grid, 2016). Had halite not been impermeable in these areas, hydrocarbons, which are less dense than formation water, would have been able to leak from the reservoirs and the hydrocarbon resource would not have been preserved. None of the available data, both from boreholes (Endeavour Geophysics, 2016; Douglas Partners, 2016) and seismic surveys (RPS, 2012) show evidence for faults through the halite. Even if undetected faults occur, the self-sealing properties of the halite would mean that they would not conduct water or gas. The only engineered structures that penetrate the Chandler Formation in the EES are the shafts. However, these will be sealed using a combination of materials that are proven to be capable of maintaining their integrity in the long-term. While the designs of the shaft seals have yet to be finalized, detailed analyses of shaft seals in similar kinds of facilities in other countries, supported by extensive research programmes, provides confidence that shaft seals can be designed to have properties similar to or better than the rocks in which they are emplaced and to maintain their integrity effectively indefinitely (e.g. USDOE, 2009; Quintessa Limited, 2011). Hence, in the EES the shafts will not form a pathway via which contaminants can leave the CF.

11.1.3 EES Assessed Risks

The EES is by far the most likely scenario to occur. It is highly improbable that natural processes would compromise the integrity of the facility even over timescales of many millions of years. This conclusion follows from the very stable geological setting of the CF, the abundant evidence from analogous settings (e.g. hydrocarbon reservoirs with halite caprocks that have not been breached even over many tens or hundreds of millions of years) and results from research into engineered materials throughout the world.

As the facility will maintain its integrity in this scenario, no contaminants can reach and interact with any of the identified receptors. Hence, the environmental impacts from the EES will be essentially zero.

Since the EES will result in no impacts to identified receptors this scenario results in no significant risk.

11.2 Alternative Evolution Scenarios (AES)

11.2.1 Nature of AES

It is emphasized that the AES are not expected to occur; they are low-probability scenarios which are presented as a basis for analysing the consequences of the CF system not behaving as designed. Very generally, the more extreme (higher impact) is a scenario, the lower its probability. Certain scenarios that would have very extreme impacts are not credible, but their impacts are nevertheless assessed as they provide a basis against which to judge the impacts of more plausible scenarios.

11.2.2 Summary of AES

Transport of contaminated groundwater to the biosphere would require penetration of, or damage to, the host rock and overburden, consisting of the upper part of the Chandler Formation and the rock formations above it.

There are three ways in which pathways from the CF and into the overburden might develop:

1. the halite above the facility might have a small volume of connected porosity, for example due to the slight disturbance to the halite during excavation;
2. a roof collapse that allows a pathway to develop between the waste and the part of the Chandler formation above the halite in which the CF is constructed and the overlying Jay Creek limestone;
3. failure of seals in one or both shafts.

These different possibilities have been represented by a set of AES that are summarized in Table 11-1. These scenarios are described in more detail in subsequent sub-sections of the report.

Table 11-1: Summary of scenarios considered.

Scenario	Variant	Title	Description	How Assessed
AES1	None	Connected porosity through the halite roof of the facility	This scenario is the same as the EES, except that: • There is 1-2% connected porosity through the halite in the roof of the CF, providing a pathway to the formations above the halite.	Numerical calculation with supporting qualitative arguments

Scenario	Variant	Title	Description	How Assessed
			The facility is water-saturated.	
AES2	a	Collapsed roof in the operational phase, combined with contaminant transport through borehole and aquifer pathways	The roof of the CF has collapsed during the operational phase (and no wastes have been retrieved) and subsequently the CF has saturated with groundwater. The collapsed roof provides a pathway for the migration of contaminated water from the CF to the overlying Jay Creek Limestone through which the water migrates by diffusion to the Stairway Sandstone Aquifer. From there, contaminated water can migrate to the biosphere via aquifer pathways operating in concert with borehole and / or fault pathways.	Qualitative arguments
	b	Collapsed roof in the post-closure phase, combined with contaminant transport through borehole and aquifer pathways	The same as for AES2a, except that roof collapses following closure of the facility.	Numerical calculation with supporting qualitative arguments
AES3	None	Impaired shaft seal	The shaft seal does not perform as well as intended and is more permeable than the aquicludes in the rock sequence it seals. Water inflows to the CF down the shaft and then transports contaminants via the impaired shaft seals, to the overburden aquifers. Transport of contaminated water is driven initially by creep of the salt and, once creep is finished, contaminants continue to migrate by diffusion.	Numerical calculation with supporting qualitative arguments
AES4	None	Accidental human intrusion	Humans unintentionally drill into the CF.	Qualitative arguments

The groundwater in the aquifers that overlie the CF is thought to discharge several hundred kilometres away, such that lateral transport rates are of the order of a

centimetre per year (Graham Ride, written communication, 29th February 2016). Consequently, the time for water to be transported between the CF and a natural discharge location via these aquifers would be millions of years, which is beyond the timescale of interest. Furthermore, over these extremely long timescales and transport pathways, there would be substantial dispersion of any contaminants that would progressively lower their concentrations with increasing distance from the CF (see Section 11.2.4 for analysis). For these reasons, none of the scenarios consider exposure of potential receptors at natural discharge locations.

11.2.3 AES Descriptions

AES1 Connected Porosity Through the Halite

This scenario is the same as the EES, except that:

- ▲ there is a very small volume of connected porosity through the halite in the roof of the CF, which allows transport of contaminants by diffusion in water;
- ▲ the CF contains free water which may mobilize contaminants from the waste and transport them through the connected porosity in the halite roof.

This scenario is illustrated schematically in Figure 11-2.

Beauheim and Robert (2002) report that the undisturbed halite-dominated host rock of the WIPP has connected porosity close to zero, which implies diffusive fluxes would be close to zero. Weber et al. (2013) report that a deep halite deposit at Gorleben in Germany has a water content of <0.02 wt%, which implies porosity of <0.03 (taking into account the density of the halite and water). However, this water is predominantly in unconnected porosity (fluid inclusions) within the halite and therefore is not mobile. Cardenas et al. (1999) report that at the WIPP the porosity of halite remote from excavations is up to 0.027, whereas the damaged zone around the excavations has a porosity of up to 0.04. Their evidence supports the conclusion that connected porosity in the halite would self-seal due to creep following closure. Hence, the highest porosity of 0.04 would not be sustained in the long-term. Consequently, this scenario considers connected porosity through the roof of the facility of no more than 0.02. Diffusion through such a small degree of connected porosity would be extremely slow (e.g. Winterle et al., 2012; see Section 11.2.4 for quantitative analysis).

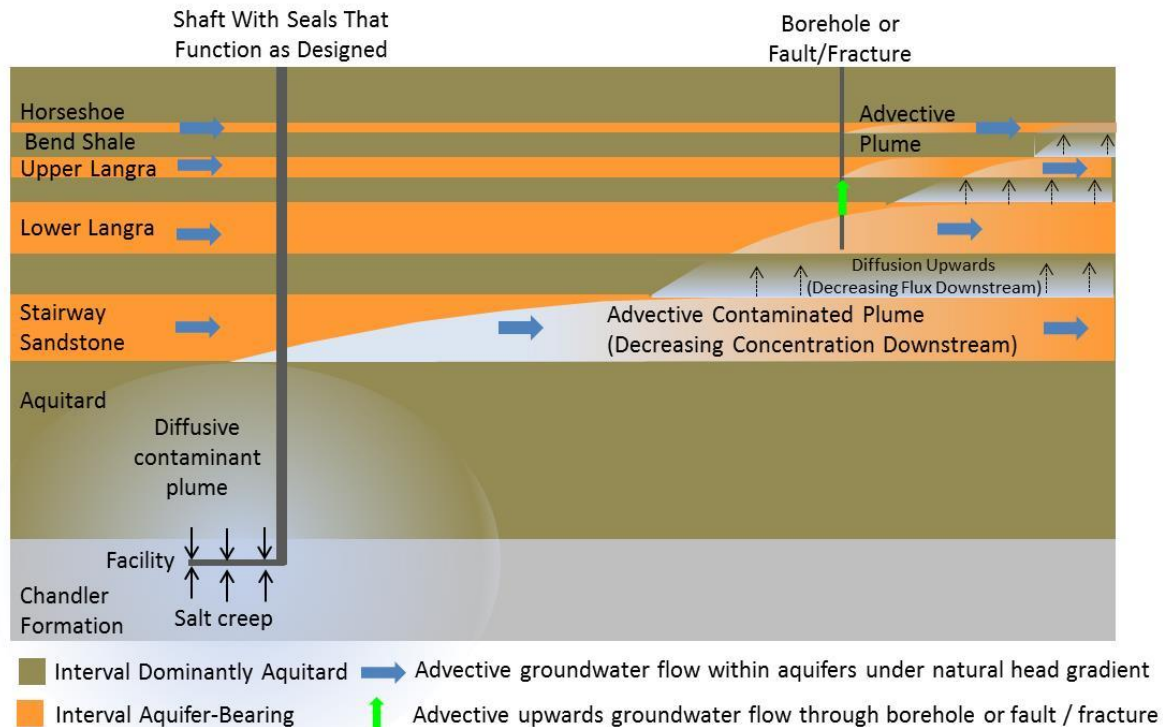


Figure 11-2: Schematic illustration of AES1. Contaminants leave the facility via the small (1-2%) amount of connected porosity in the roof. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. Alternatively this pathway could be a fault / fracture that has not yet been detected, but which may occur, potentially some distance downstream. Note that there would also be downwards diffusion of contaminants from any contaminated aquifer downstream, but this is not shown as upwards diffusion is the primary risk concern.

In this scenario the CF is water-saturated because of creep reducing the void space in combination with one or more of:

- ▲ emplaced wastes containing more free water than planned (for example because drying processes are less effective than planned);
- ▲ the hydraulic backfill contains more water than planned, such that it contains free water after curing;
- ▲ water entering the facility through the connected pore space in the halite that forms the roof;
- ▲ the halite containing undetected brine pockets.

Contaminated water travels through the connected porosity in the halite and then through the shallower parts of the Chandler Formation and the overlying Jay Creek Limestone until it encounters an aquifer within the Stairway Sandstone Formation (Figure 11-2). There, the contaminants are diluted by the groundwater that is flowing slowly and almost horizontally within the aquifer under the influence of the natural

head gradient. This flow transports the contaminants laterally, accompanied by further dilution due to dispersion within the aquifer. Thus, the concentrations of contaminants within the aquifer decrease progressively with increasing distance from the facility (Figure 11-2).

In this scenario, the only way in which the contaminants that are released from the CF can impact upon shallower aquifers and other receptors is if they encounter a pathway that can transport them upwards from the Stairway Sandstone. The only plausible pathways are:

- ▲ direct abstraction of water from the Stairway Sandstone via a borehole;
- ▲ upwards migration of contaminants through such a borehole that is no longer actively exploited, but that has been left in an imperfectly sealed state between the Stairway Sandstone and a shallower receptor;
- ▲ upwards migration of contaminants from the Stairway Sandstone to a receptor via a transmissive fault;
- ▲ upwards migration of contaminants through a combination of boreholes (including ones that are actively exploited and ones that are no longer exploited, but have been left in an imperfectly sealed state) and aquifers shallower than the Stairway Sandstone;
- ▲ upwards migration of contaminants through a combination of faults and aquifers shallower than the Stairway Sandstone;
- ▲ diffusion upwards through aquitards.

It should be noted that no boreholes presently penetrate the Stairway Sandstone within the footprint of the CF, but the scenario considers:

- ▲ the possibility that contaminated water flowing in the Stairway Sandstone may encounter a borehole at some distance away from the CF in the future; and
- ▲ the possibility that new boreholes may be drilled, whether in the vicinity of the facility or remote from it, downstream, at some point in the future.

Similarly, it should be noted that no potentially transmissive fault pathways have been identified within the vicinity of the CF. Also there is no reported natural discharge of deep water to the ground surface via faults outside the facility or downgradient from the facility. However, the scenario considers the possibility that presently unidentified transmissive faults may occur at some point downstream, remote from the facility. As in the EES (Section 11.1), the higher density of the saline groundwater at depth, compared to the lower density of the shallower, fresher groundwater, would tend to act against upwards movement of deep water.

AES2a Collapsed Roof in Operational Phase

In this AES there has been an unexpected roof fall during the operational phase, which has produced a pathway through the halite roof of the facility to shallower formations (Figure 11-3).

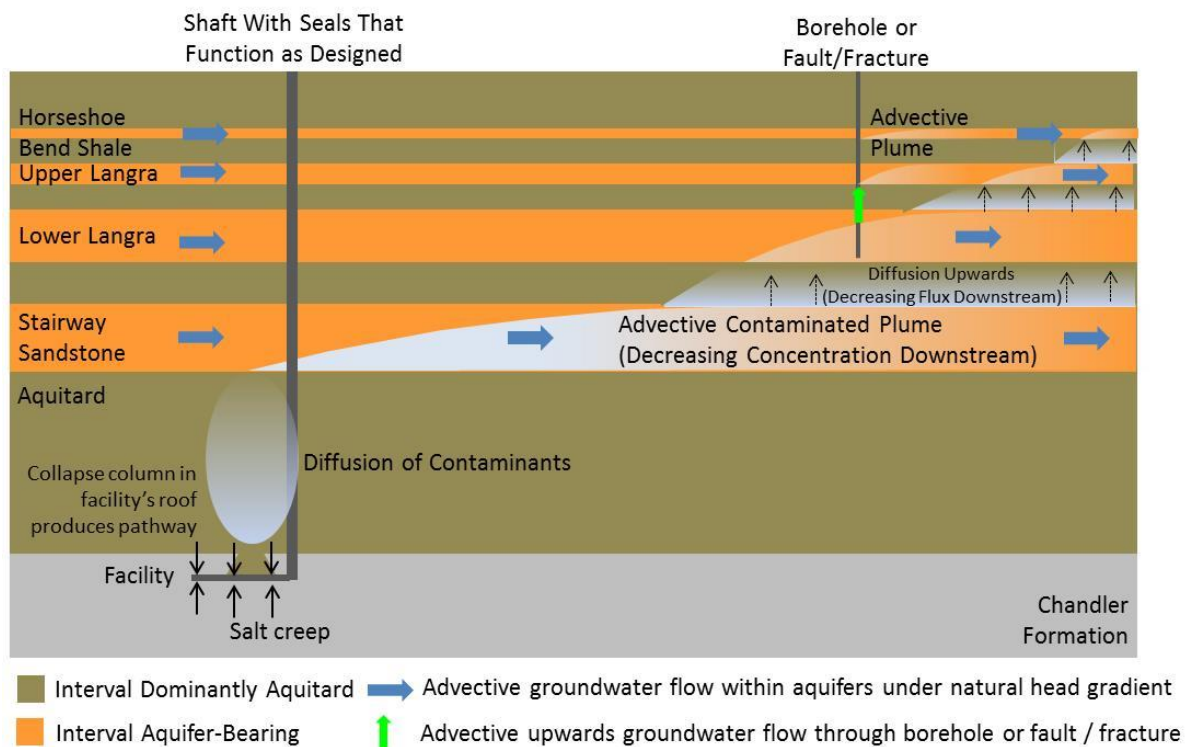


Figure 11-3: Schematic illustration of AES2. Contaminants leave the facility via a collapsed roof. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and / or that may be drilled at some time in the future. Alternatively this pathway could be a fault / fracture that has not yet been detected, but which may occur, potentially some distance downstream.

The size of the pathway produced would depend on the degree to which the cavern had been filled at the time of rock failure. The greater the void space in the cavern into which the collapse occurs, the further will the collapse column would extend upwards from the roof. A collapse into an unfilled cavern would be most likely to produce a pathway through the halite and into the overlying rock formations.

In this scenario, the roof collapse is not mitigated during the operational phase and therefore the pathway produced by collapse persists into the post-closure period. At some point following the collapse, in the post-closure period, the scenario envisages that the facility saturates with groundwater. It is extremely unlikely that any significant water inflow would occur during the Operational Phase (see the operational phase assessment, Metcalfe et al., 2016). Sudden, rapid inflows are implausible and

small inflows would be recognized and mitigating actions taken before significant water volumes had entered the facility.

Water would need to enter the CF through the pathway produced by the collapse, or else via an imperfect shaft seal. After flowing into the CF, the water becomes contaminated by contact with the waste. Subsequent creep of the salt provides a driving force that causes the water to leave the CF via the collapsed roof. The length of time over which contaminated water can be expelled by creep is the minimum of:

- ▲ the time between the ingress of water and the cessation of creep; and
- ▲ the time between the ingress of water and the pathway through the halite self-sealing through creep (assuming that the collapse is not of such a large magnitude as to effectively prevent self-sealing).

Assuming that the pathway formed by the collapse column does not seal by creep first, after cessation of creep contaminated water would be able to leave the CF only by diffusion through the collapse zone.

Were this scenario to occur, then after leaving the CF contaminants would migrate through the shallower formations through the same kinds of pathways as those described for AES1.

AES2b Collapsed Roof in Post-closure Phase

This scenario is essentially the same as AES2a, except that the roof collapse occurs in the post-closure phase. For any such collapse to occur the waste and / or backfill would need to be compressible and / or filling of the cavern by waste and backfill would need to be incomplete. If these conditions are not met, then the roof of the cavern would be supported by the cavern's contents and collapse could not occur. In any case, in AES2b there is a lower degree of void space into which roof collapse could occur than in any partially filled cavern in AES2a.

AES3 Impaired Shaft Seal Scenario

In AES3 the shaft sealing system does not function as designed owing to:

- ▲ seals being improperly implemented; and / or
- ▲ because seals degrade over time.

This scenario is illustrated schematically in Figure 11-4.

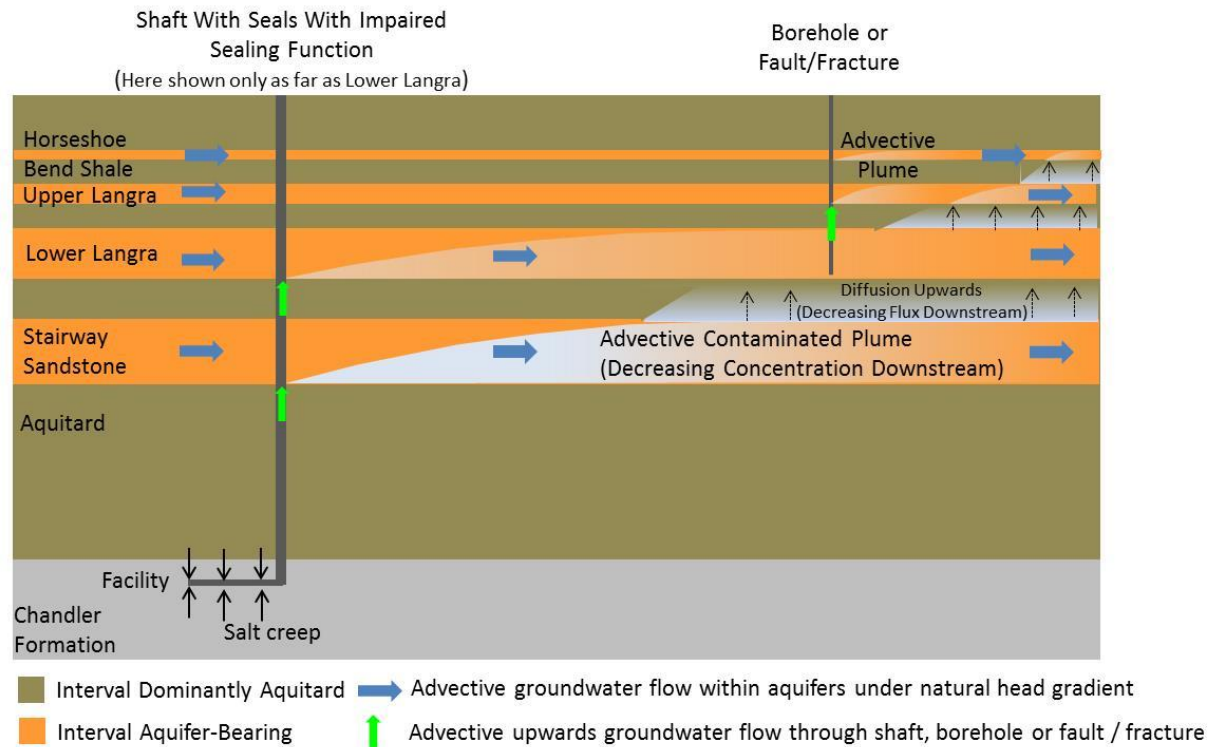


Figure 11-4: Schematic illustration of AES3. Contaminants leave the facility via a shaft with impaired seals. The indicated “borehole or fault / fracture” represents a borehole that may exist some distance downstream from the facility and/ or that may be drilled at some time in the future. Alternatively this pathway could be a fault / fracture that has not yet been detected, but which may occur, potentially some distance downstream.

The impaired function of the sealing system allows groundwater to flow from the aquifers in the rock sequence above the Chandler Formation into the CF before creep can effectively remove the reducible residual voidage within the facility. Thereafter, the water becomes contaminated by interacting with the waste and is driven back up the shaft, through the impaired seals, by the progressive creep of the halite.

In the most extreme situation, the shaft sealing system has higher permeability than designed throughout the length of the shaft, thereby allowing the contaminated water to be transported along the shaft from the CF to the ground surface. The upper limit on transport flux for any given driving force would be one where the shaft seals offer no resistance to water and contaminant transport. However, this situation is not credible because the materials used in the shaft sealing system will contain a number of highly durable materials and it is inconceivable that these could be completely removed by any natural process that would not also remove the surrounding rocks (which will not occur on relevant timescales owing to the very stable geological setting of the CF). While the shaft seal design has not been finalized, detailed assessments of other underground waste facilities (e.g. the WIPP in New Mexico, U.S.A (USDOE, 2009) and the DGR planned for construction at Bruce in Ontario, Canada (Quintessa et al., 2011))

have demonstrated that it is possible to construct shaft seals that will maintain their functions for geologically significant periods of time ($>>1$ Ma).

Some of the contaminants would be lost from the impaired shaft seals where they cross aquifers through which groundwater is flowing sub-horizontally under the natural groundwater head gradient. This naturally flowing groundwater would tend to transport some of the contaminated water from the shaft seals, downstream along the aquifer. Additionally, groundwater that enters the shaft seals from an aquifer would tend to dilute the contaminants that remain in the shaft seals. For these reasons, the concentrations of contaminants will decrease as they are transported upwards in the impaired shaft seals (Figure 11-3).

A less extreme (and more plausible) situation is one in which the shaft sealing system is impaired for only part of its length, upwards from the CF to the level of the Stairway Sandstone. In this case, all the contaminated water would be transported downstream in the Stairway Sandstone aquifer by groundwater flowing naturally within it.

If the impaired shaft sealing system were to extend to shallower depths than the Stairway Sandstone, but not all the way to the ground surface, only a proportion of the contaminated water would be transported to shallower levels past each aquifer that is intersected by the shaft (Figure 11-3). Where an impaired shaft seal crosses an aquifer some of the contaminated water would be diluted by groundwater flowing naturally within the aquifer. Additionally, such naturally flowing groundwater would tend to mobilize the contaminated water downstream along the aquifer.

Any contaminated water that enters an aquifer in this scenario would only be able to reach shallower levels via:

- ▲ direct abstraction of water from the aquifer via a borehole;
- ▲ upwards migration of contaminants through such a borehole that is no longer actively exploited, but that has been left in an imperfectly sealed state between the aquifer and a shallower receptor;
- ▲ upwards migration of contaminants from the aquifer to a receptor via a transmissive fault;
- ▲ upwards migration of contaminants through a combination of boreholes (including ones that are actively exploited and ones that are no longer exploited, but have been left in an imperfectly sealed state) and other aquifers at shallower depths;
- ▲ upwards migration of contaminants through a combination of faults and aquifers at shallower depths; and
- ▲ diffusion upwards through aquitards.

It should be noted that the scenario considers:

- ▲ the possibility that contaminated water flowing in an aquifer may encounter a borehole at some distance away from the CF in the future; and
- ▲ the possibility that new boreholes may be drilled, whether in the vicinity of the facility or remote from it, downstream, at some point in the future.

Similarly, it should be noted that no potentially transmissive fault pathways have been identified within the vicinity of the CF. Also there is no reported natural discharge of deep water to the ground surface via faults outside the facility or downgradient from the facility. However, the scenario considers the possibility that presently unidentified transmissive faults may occur at some point downstream, remote from the facility.

AES4 Accidental Human Intrusion Scenario

This scenario considers inadvertent human intrusion at some time in the future, after knowledge of the location and / or dimensions of the CF have been lost. Deliberate human intrusion it is not considered, as is common practice with such assessments (NEA, 2001), because the people undertaking the intrusion would be responsible for assessing the associated risks.

This scenario is illustrated schematically in Figure 11-5.

It is impossible to predict the evolution of society into the future and therefore regulators typically require the assessment of the consequences of accidental human intrusion to consider a scenario based on current day practices and technology. Given this basis, inadvertent human intrusion would consist of drilling a borehole into the CF. The scenario does not consider excavating a mine into the facility on the basis that exploratory boreholes would have previously identified contaminated material leading to any mining plans being abandoned. Were a decision to be taken to excavate a mine even if exploratory boreholes had identified the CF, then mine excavation would constitute deliberate intrusion, which is outside the scope of the this AES.

In the course of inadvertent penetration of the facility by boreholes, material from the CF would be brought surface. This material could include core/cuttings from boreholes, contaminated groundwater samples, and contaminated drilling fluid. Such material would be handled and, although personal protective equipment (PPE) would be used, there is the potential for contamination of surfaces by dust etc., which could

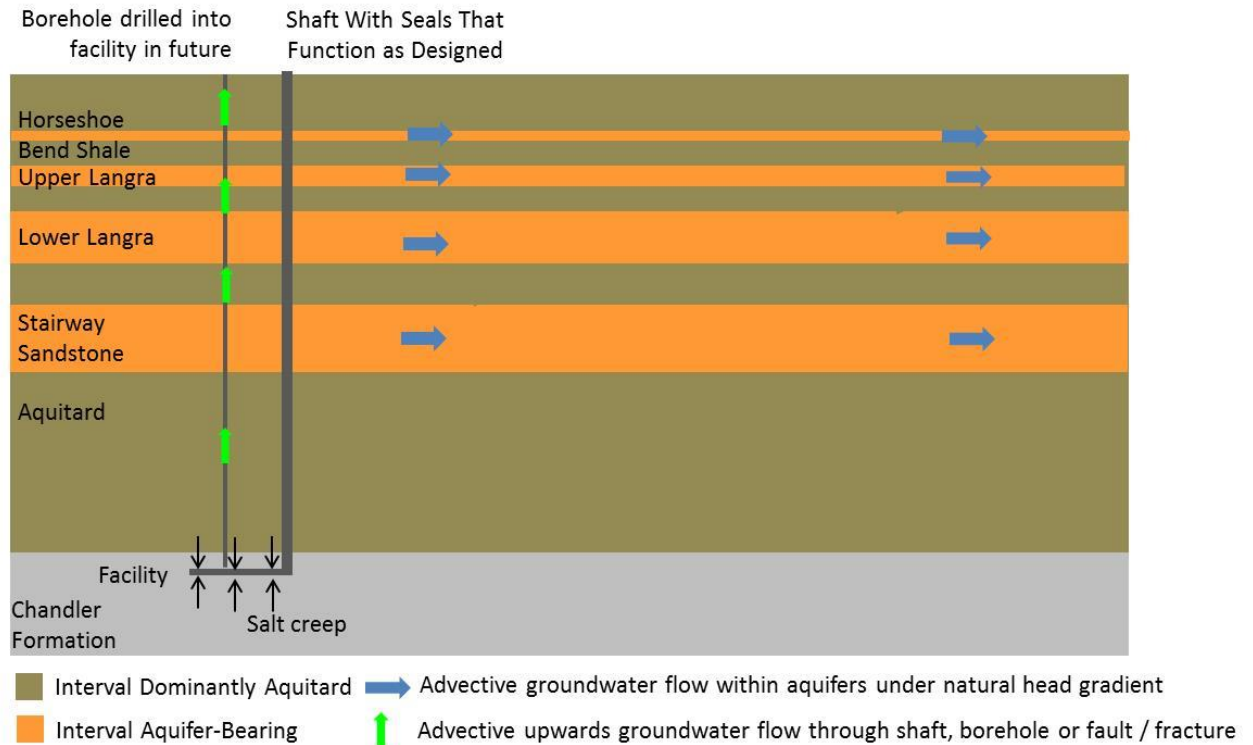


Figure 11-5: Schematic illustration of AES4, the accidental human intrusion scenario
Contaminants leave the facility via a borehole drilled accidentally at some time in the future.

result in ingestion of contaminants. Drilling fluid would be treated before discharge, but there is the potential that the treatment process would not remove the contaminants from the waste prior to discharge as they were not expected or that other equipment becomes contaminated. The scenario envisages that, once a contaminated sample had been recovered, additional precautions would be put in place to prevent contamination of workers and adverse environmental impacts.

If the core penetrated NORM waste, it would also be necessary to calculate the dose that the workers could be exposed to prior to realizing that the core was radioactive and taking appropriate precautions. The likely doses would be bounded by the operational doses incurred when processing and emplacing the NORM wastes so can be taken directly from that assessment.

11.2.4 Quantitative Assessment of AES

Nature of Assessment Models

Mathematical models have been constructed to analyse the AES. These models are “assessment level” models, which means that they are designed to represent the key

aspects of the various scenarios that influence impacts. Such models are commonly developed in safety assessments (e.g. Robinson and Hooker, 2002; Quintessa et al., 2011; USDOE, 2009). An important goal of assessment models is to place limits (bounds) on impacts for a given set of assumptions. These models are not, therefore, predictive models. They are not intended to represent *all* the processes within an analysed system and all the couplings between these processes.

AMBER Quantitative Assessment Tool

Quantitative assessments of the AES described in Section 11.2.3 were undertaken using the mathematical modelling software AMBER 6.0, supported by separate scoping calculations. This software allows users to build their own dynamic compartment models to simulate the migration, degradation and fate of contaminants in environmental and engineered systems (Quintessa, 2015).

The software package is able to represent the four key hydrogeological parameters that control contaminant migration that are highlighted in the NT EPA's siting guideline for solid waste disposal sites (NT EPA, 2013):

- ▲ hydraulic conductivity, K
- ▲ effective porosity;
- ▲ hydraulic gradient; and
- ▲ soil/rock/leachate species interaction as given by the Distribution Coefficient, K_d .

AMBER has been widely used in over 30 countries for safety assessments concerned with the management of a variety of wastes. It was employed in the long-term safety assessment of the presently operating Minosus underground disposal facility for hazardous waste, which is constructed in a halite formation in Cheshire, England (Robinson and Hooker, 2002).

The quantitative models are designed to inform judgements about risks in Section 11.2.5, rather than to output risk estimates directly. This approach is appropriate, given the uncertainties in the nature of the wastes, the fact that the design of the CF is not finalized and uncertainties about the hydrogeology of the area around the CF.

Assessment Model Descriptions

Representation of Scenarios

The assessment models are designed to represent important aspects of the AES described in Section 11.2.3 in order to gain insights into the potential magnitudes of the impacts from these scenarios, in the unexpected even that they are realized. However, within each scenario a great many variants can be envisaged, representing alternative conceptualisations and parameterizations of the different scenario components. It is not feasible, or necessary, for the assessment models to simulate all these different conceptualisations and parameterizations. Instead, the goal is to help place bounds on the impacts that could arise from the different scenarios. In other words the aim is to determine the highest contaminant concentrations that are plausible in any given location for a given set of assumptions. To achieve this goal a small number of model realizations have been run to calculate concentrations of contaminants in different locations for specified pessimistic assumptions. Where outputs from a model representing one scenario can be used to estimate limits on concentrations for another scenario, then a separate model realization has not been run for this second scenario. For example, if a borehole were to be drilled into the facility in the distant future and then imperfectly abandoned, the resulting effect would not be worse than the case where the shaft has an impaired seal (AES3). Thus, the calculation for the impaired seal also gives insights into the impact that might result from such an imperfectly sealed borehole.

System Representation

The model represents the following system components are:

- ▲ the facility, represented by a single compartment;
- ▲ salt above and below the facility;
- ▲ the aquitards between the salt and a specified aquifer;
- ▲ an aquifer, having 5 compartments corresponding to a Peclet number of 10, which can have a specified:
 - depth to represent an aquifer in the Stairway Sandstone, Lower Langra, Upper Langra or Horseshoe Bend Shale; and
 - length to allow sampling of concentration at a chosen point downstream of the shaft;
- ▲ a shaft connecting the facility to a specified aquifer, which has 5 compartments corresponding to dispersion associated with a Peclet number of 10;

- ▲ connection between the facility and a specified aquifer, via salt of fixed thickness and an aquitard of variable thickness (depending upon which aquifer is modelled), within which transport is via diffusion only.
- ▲ connection between the facility and a specified aquifer via the shaft, where transport is all via advection during the period when creep occurs, and by diffusion thereafter, the length of the pathway depending on which aquifer has been selected.

The user selectable options/parameter values that are relevant for the facility are:

- ▲ contaminated water travel lengths, depending upon which aquifer is modelled;
- ▲ diffusion or advection, according to which leakage path is used;
- ▲ distribution coefficient (K_d) representing sorption;
- ▲ porosities of the different rock formations;
- ▲ release model (solubility-controlled or instantaneous release of a notional 1t of inventory).

The compartmental representation of the scenarios AES1, AES2 and AES3 is shown in Figure 11-6 and Figure 11-7.

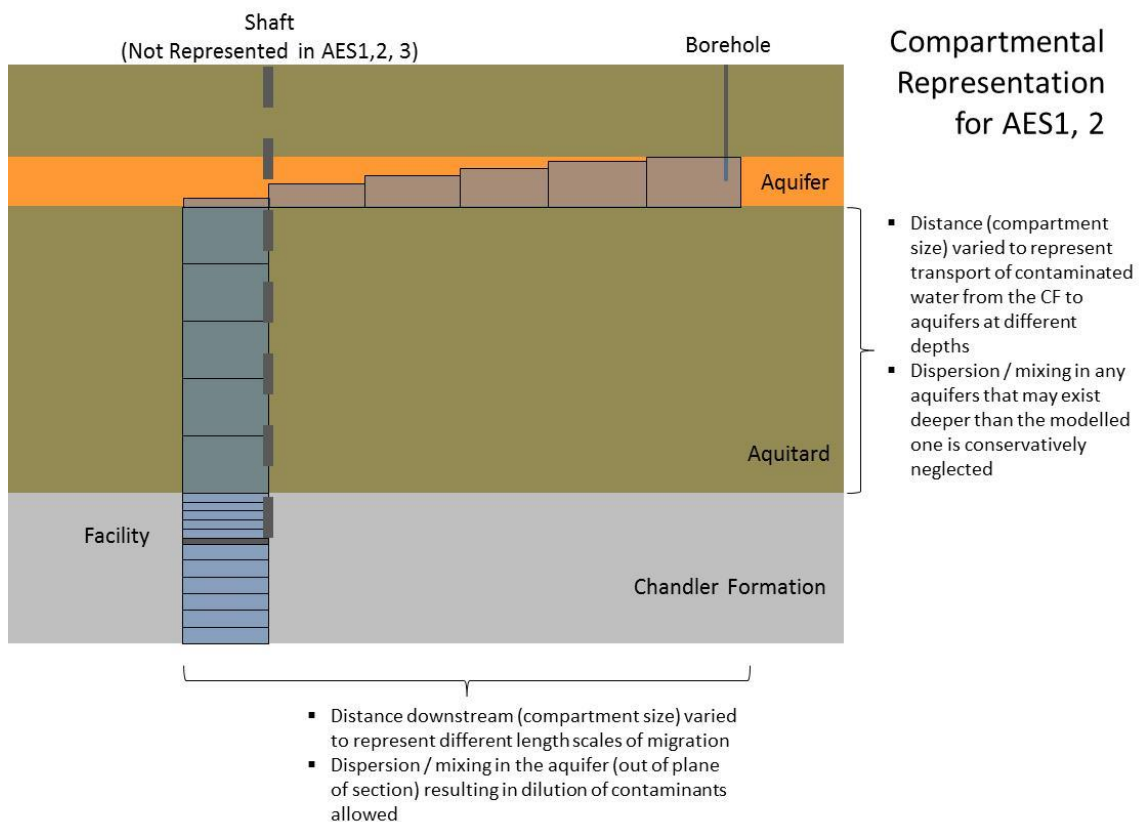


Figure 11-6: Schematic illustration of the compartmental representation in AMBER of the scenarios AES1 and AES2.

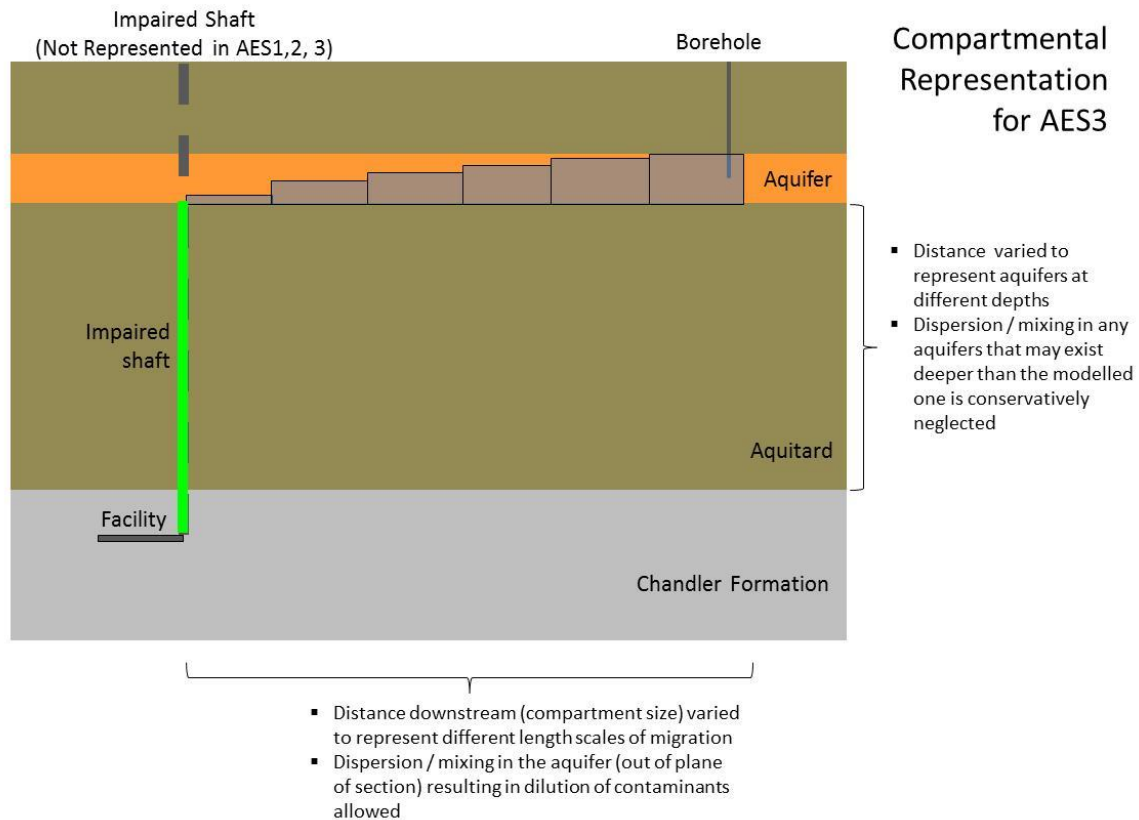


Figure 11-7: Schematic illustration of the compartmental representation in AMBER of the scenario AES3.

Stratigraphy

In the model contaminants are specified to discharge into the lowermost 10 m thickness of the aquifer. That is, at the location of discharge, each modelled aquifer is thinner than the formation within which it occurs (Stairway Sandstone, Lower Langra, Upper Langra or Horseshoe Bend Shale). Thereafter, vertical dispersion occurs along the flow path until the contaminant plume reaches the full thickness of the aquifer. This approach is pessimistic with respect to contaminants reaching an aquifer from the CF, because the transport distance is minimized. However, the approach is not conservative with respect to lateral transport since the vertical dispersion within a given formation (and hence dilution) is maximized. In practice, each formation is known to be heterogeneous and aquifers within them are heterogeneously distributed (Graham Ride, written communication, 29th February 2016). The nature and significance of this heterogeneity are presently areas of uncertainty.

Representation of the CF

The CF is represented as a single homogeneous compartment that has an average porosity, at closure, of 30% (assuming the wastes are half solid wastes with 40% porosity and half hydraulically emplaced wastes with porosity of 20%).

The volume of the wastes is calculated assuming that there are 128 rooms containing wastes emplaced in solid form and 128 rooms containing wastes emplaced in hydraulic backfill. Half the 256 rooms are of width 15 m and half of width 10 m. All are 250 m long and 6 m high.

Over a defined period, t_{Creep} (specified to be 1000 y) creep is specified to close half of the porosity in the rooms. However, the creep is modelled so that 50% of the lost void is closed after 100 years, 75% (cumulative) after 250 years and the remaining 25% between 300 and 1,000 years. For the case that considers the release via the shaft, this defines the volumetric flow rate through the shaft (Q_{Creep} m³/y). For the geometrical assumptions described above this corresponds to an average flow rate of 360 m³/y if the shaft does not restrict flow. However, given that even in the impaired shaft seal scenario (AES3) there is always some shaft seal material present (albeit with impaired performance), in practice the shaft would resist upwards flow along it. Consequently, this average flow rate is likely to be very pessimistic. As an illustration, if the impaired shaft seals actually had a hydraulic conductivity of 1×10^{-9} m/s flow would be severely restricted and < 1 m/y would flow up the shaft. In this case it would take 800,000 years to expel all the water from the facility.

Specific contaminants are not modelled explicitly because, while a plausible waste inventory has been specified (Section 4.2.2) the chemical composition of each kind of waste that might be emplaced in the facility is unknown. Hence an inventory of each contaminant present cannot be calculated reliably. Additionally, the chemical forms of the various contaminants are uncertain. For these reasons, the assessment models used two approaches to calculate concentrations of contaminants in the facility:

- ▲ concentrations of contaminants in different parts of the CF / overburden system when the concentrations of contaminants in the facility are assumed to be limited by solubility; and
- ▲ concentrations of contaminants in different parts of the CF/overburden system when a notional 10^6 g (1 tonne) inventory of a contaminant in the facility is specified.

In the first approach the inventory is unlimited. Hence, if there is a continuous aqueous phase, and if the flow regime is specified to be constant in the model, then given long enough a contaminant will leave the CF and attain a constant concentration at any location in the overburden. This concentration will be lower than the initial concentration in the CF. The precise decrease in concentration will be a function of:

- ▲ the distance between the CF and the particular location of interest; and
- ▲ dispersion and dilution of the contaminant as water originating in the CF mixes with uncontaminated groundwater along the flow path.

In the model the eventual constant concentration attained at any location will be determined by a dynamic equilibrium between the rates at which contaminants are supplied to and removed from the location by the flowing groundwater.

Generally, the concentration of a contaminant will decrease with increasing distance from the CF along a flow path.

A difficulty in applying this approach is that the solubilities of the different contaminants are highly uncertain because:

- ▲ potential solubility-controlling phases are uncertain; and
- ▲ thermodynamic data appropriate for calculating solubilities in the very high-salinity (halite-saturated) solutions that will occur are unavailable for relevant contaminants.

However, scoping calculations using Geochemist's Workbench (Bethke, 1996) and the "thermoddem" database (gwb_thermoddem_lvl2_no-org_11dec14.dat, <http://thermoddem.brgm.fr/>) suggest that solubilities would likely lie within the range 10^{-2} mol/L to 10^{-5} mol/L, depending upon the contaminant. Therefore, for each conceptual model and set of specified transport properties, AMBER calculations were undertaken for solubilities of 10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L.

In the second approach to specifying concentrations of contaminants in the facility, the entire inventory of any contaminant is pessimistically assumed to enter the aqueous phase, and hence be mobile, instantaneously. In this case, only the barrier functions of the geosphere and engineered barriers in the shaft, combined with the dilution effect of groundwater flowing through the shallower geosphere, limit the concentrations of contaminants in the overburden. However, because the inventory is finite, given long enough, ultimately it will be exhausted. Thus, unlike the outputs from AMBER simulations in which concentrations are solubility-controlled, the outputs from AMBER simulations with a specified 10^6 g inventory have a peak in contaminant concentrations in the overburden. The time at which this peak is calculated to occur informs an assessment of the time of peak risk.

The specified nominal inventory of 1×10^6 g for each contaminant allows easy scaling of the results to any actual contaminant inventory that it is proposed to emplace in the CF. The approach therefore can be used to help support the specification of WAC.

Diffusive Release Through Salt

In the AMBER model diffusion occurs through the halite, both upwards and downwards. The processes and characteristics of the rock are assumed to be isotropic within the salt, so only the upwards path is described below. The model incorporates a mirror image of the compartments and transport processes in the downward direction.

The geometry of the system is such that there will be much less diffusion through the sides of the CF so this aspect is not represented in order to simplify the model.

Releases from the waste and through the salt are represented with a compartment-model representation of diffusion. This involves both forwards and backwards transfers between each compartment that simulate diffusion by “mixing” between the compartments at a defined rate.

The transfer rate between each compartment λ_{diff} (y^{-1}) is given by:

$$\lambda_{diff} = \frac{d_{eff} A_x}{V \theta R \Delta} \quad (1)$$

where:

d_{eff} is the effective diffusion coefficient in the material (m^2 / s);

A_x is the interface area between the two compartments (m^2);

V is the volume of the compartment from which the transfer originates, the “donor” (m^3);

θ is the porosity of the donor compartment (-)

R is a retardation factor to simulate the sorption of contaminants to solid phases (-)

Δ is the distance between the mid-points of the two compartments (m).

The retardation factor is related to the contaminant-specific sorption coefficient for the material, K_d (m^3/kg):

$$R = 1 + \frac{\rho K_d}{\theta} \quad (2)$$

where:

$$K_d = \frac{\text{Sorbed concentration of the element of the sorbate of interest in mol kg}^{-1}}{\text{Aqueous concentration of the sorbate in mol m}^{-3}} \quad (3)$$

and ρ (kg/m^3) is the dry bulk density of the material.

In the model, a reference value of K_d is taken to be $0 m^3/kg$, corresponding to no sorption. In order to test the sensitivity of the calculated concentrations in overburden to K_d a range of values are also considered, between $10^{-6} m^3/kg$ and $100 m^3/kg$.

The region of salt through which diffusion occurs is represented with five compartments above the CF and five below. Discretisation in this way is necessary to adequately represent the diffusive process. It is necessary to increase the thickness of each compartment progressively; sufficient numerical accuracy is obtained if each

compartment is a factor of three larger than the preceding compartment. Thus, for a system of N compartments, the m -th compartment has a thickness of:

$$L_m = \frac{L_T}{\sum_{i=0}^{N-1} 3^i} 3^{m-1} \quad (4)$$

where L_T (m) is the total thickness of the salt above the CF.

Above the salt lies the Jay Creek Limestone. The groundwater in this formation is assumed to continue to diffuse until an aquifer is met (assumed to be in the Stairway Sandstone). Transport in the aquifer is represented with an advective transfer λ_{adv} (y^{-1}) from the compartment representing the initial layer of limestone:

$$\lambda_{adv} = \frac{Q_{adv}}{V \theta R} \quad (5)$$

where Q_{adv} (m^3/y) is the volumetric flow of groundwater through the compartment. The compartment corresponds to the footprint of the CF or to the shaft width, depending upon the model. In the former case it is specified to be 1000 m wide, and the plume is assumed to have a maximum depth that is the same as the aquifer thickness, namely 10 m. The groundwater velocity is assumed to be 0.01 m/y. The parameters used in calculations of diffusive release are given in Table 11-2.

Table 11-2: Parameter Assumptions for the Diffusion Release.

Description	Parameter	Value
Cross-sectional excavated disposal area of the rooms of the CF	A_X	$8 \times 10^5 \text{ m}^2$
Height of the CF	L	6 m
Effective diffusion coefficient of salt	d_{eff}	$4.2 \times 10^{-13} \text{ m}^2/\text{s}$
Thickness of salt above the CF	L_{salt}	20 m
Thickness of salt compartments 1 – 5	L	See Eq (4)
Density of salt	ρ	2220 kg/m^3
Density of Jay Creek Limestone	ρ	2500 kg/m^3
Porosity of salt	θ	0.02
Porosity of Jay Creek Limestone	θ	0.05
Sorption coefficient	K_d	0 (10^{-6} – 100) m^3/kg

Note: The reference value for K_d is 0 m^3/kg , but the indicated range is also considered.

Advective Release via a Shaft with Impaired / Failed Seal

Implicit in the advective release calculations is the assumption that the shaft has not been backfilled and sealed sufficiently and therefore permits release of contaminants from the CF. The pore space in the CF is pessimistically taken to be 75% water-

saturated at closure. In reality, this the degree of water saturation could be less than this, since the wastes are either emplaced dry, or else in a hydraulic backfill which will be designed to contain little free water after curing, and since there is no way, in the absence of the shaft lining failing for water to inflow.

It is assumed that creep will lead to a reduction in connected void space in the facility by a factor of two at most. As the pore space decreases, the water present is squeezed out through a shaft with impaired or failed seals. It is assumed that the only the smaller shaft has failed (6m in diameter) and conducts water. This leads to the most rapid transport toward overlying aquifers and hence is the most pessimistic situation.

Advection of contaminants up the shaft is then modelled using Equation (4), with the flow rate being:

$$Q_{creep} = \frac{V_{waste}(\theta_{waste}^i - \theta_{waste}^f)}{t_{creep}} \quad (6)$$

It should be noted that the parameters in this equation that are subscripted “waste” do not refer to the wastes per se, but to the properties of the disposal rooms containing waste, plus backfill or hydraulic backfill.

There is no flow up the shaft until all the unsaturated pore space is closed. T_{creep} for this process is determined by an unrestricted creep curve elicited by Tellus and takes 70 years. Creep and upflow is then controlled by the permeability of the shaft seals, with the driving force being the difference between lithostatic and hydrostatic pressure. Accordingly, there is unrestricted creep as porosity decreases from 0.3 to 0.225 and no flow. As porosity decreases further to 0.15 the flow and creep rate is controlled by the permeability of the shaft seals. At this latter porosity there is no more creep or flow.

The shaft is assumed to provide a pathway vertically upwards for expelled water to leak into an aquifer. The model is configured so that the point of release can be selected from an aquifer in:

- ▲ the Horseshoe Bend Shale;
- ▲ the Upper Langra Formation;
- ▲ the Lower Langra Formation; or
- ▲ the Stairway Sandstone.

The properties of each aquifer can be defined, but given the uncertainties and the scoping nature of the model, each is assigned a nominal flow rate of 0.01 m/y, an initial plume thickness of 10 m, a density of 2100 kg/m³ and a porosity of 0.2. The maximum contaminant concentration to which a receptor such as humans or livestock could be exposed would be the concentration in an aquifer that is sampled directly by a borehole.

The downstream width of the plume can be approximated by:

$$W_{Downstream} = \sqrt{(W_{Initial})^2 + \frac{L_{downstream} \alpha_{trans}}{4}} \quad (7)$$

Where $L_{downstream}$ (m) is the distance between the point of release from the shaft and the borehole, and α_{trans} is the transverse dispersion length (m).

Additional material-specific parameters used in the modelling of advective release via a shaft with failed or impaired seals are given in Table 11-3. Corresponding dimensions used in these models are given in Table 11-4.

Table 11-3: Material-specific parameter values for the advection case.

Material	Density (kg/m ³)	Porosity (-)	Notes
Waste-filled emplacement rooms	2000	0.3	Initial porosity given - reduces by 50% due to creep during model (density not varied since has no effect on contaminant concentrations)
Shaft	2000	0.15	Assume like concrete
Salt	2220	0.02	Half the maximum value reported for the disturbed zone around excavations at the WIPP (Cardenas et al., 1999), variant with 0.01 also run
Stairway Sandstone	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Lower Langra	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Upper Langra	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra
Horseshoe Bend Shale	2100	0.2	Porosity, upper estimate reported by oil geologists for the Upper Langra

Table 11-4: Dimensions assumed for the advection case.

Description	Parameter	Value
Cross-sectional excavated disposal area of the rooms of the CF	A_X	$8 \times 10^5 \text{ m}^2$
Height of CF	L	6 m
Timescale for creep to close porosity	t_{Creep}	1000 y unless shaft content restricts water flow in which case calculated
Diameter of Shaft	W_{Shaft}	6 m
Distance contaminants travel in Shaft (to Stairway)	L_{Shaft}	355 m
Distance contaminants travel in Shaft (to Lower Langra)	L_{Shaft}	530 m
Distance contaminants travel in Shaft (to Upper Langra)	L_{Shaft}	665 m
Distance contaminants travel in Shaft (to Horseshoe Bend)	L_{Shaft}	750 m
Distance travelled between shaft/boreholes in aquifer	$L_{\text{downstream}}$	10 km and 20 km
Transverse dispersion in aquifers	α_{Trans}	1% of pathlength

Performance Metrics

Over the long time period covered by the assessment (quantitative calculations are undertaken to 1 Ma), the surface environment, and consequently potential receptors, will change considerably. While scenarios can be specified for the nature and evolution of these receptors (e.g. nature and evolution of ecosystems) and impacts on them could be calculated, such a detailed approach is inappropriate given the uncertainties about the site. Instead, the approach is to calculate contaminant levels at different locations as a function of time and compare these with a number of groundwater quality standard and guideline values.

It should be noted that, even if a concentration does exceed a groundwater quality standard or guideline concentration, this does not necessarily mean that there will be any adverse environmental impact. This is because these standard and guideline values are typically set conservatively by organisations such as the World Health Organisation (WHO).

As described above, the contaminant concentrations output by the AMBER models may be subdivided into two groups:

- ▲ those obtained when concentrations of contaminants in the facility are assumed to be limited by solubility; and
- ▲ those obtained when a notional 10^6 g (1 tonne) inventory of a contaminant in the facility is specified.

Outputs of the second kind cannot be meaningfully compared with groundwater quality standards and guideline values because, for any given contaminant, the inventory may be lower or higher than the notional 10^6 g specified in the models. However, these outputs are useful because they illustrate the general variation in concentration over time (i.e. an increase to a peak and then a decrease). These outputs also provide a general indication of the plausible timescales over which the inventory would be lost from the facility in the unexpected AES.

Comparing the outputs of the solubility limited calculations with groundwater quality standards and guidelines is necessary. In principle, the concentration of any contaminant in the facility should be equal to or lower than a limit at which some solid phase that contains the contaminant would precipitate. While the actual phases that might form and their solubilities are uncertain, the calculations were undertaken for a wide range of plausible solubilities.

The outputs of the AMBER models given in the remainder of this section can be compared with permissible concentrations of contaminants in groundwater quality standards and guidelines. Relevant concentrations are tabulated in Table 11-5.

Table 11-5: Groundwater standard and guideline values for priority contaminants given in Section 4.2.2.

Substance	Australian Drinking Water Guidelines, v6, 2011 (updated March 2015) (mg/L)		World Health Organization Drinking Water Guidelines, v4 (2011) (mg/L)		Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) (mg/L)	
	mg/L	mol/L	mg/L	mol/L	mg/L	mol/L
Beryllium (Be)	0.06	6.66E-06	-		-	
Lead (Pb)	0.01	4.83E-08	0.01 (Provisional)	4.83E-08	0.001	4.83E-09
Chromium (Cr)	0.05 (Cr(VI))	9.62E-07	0.05 (Total)	9.62E-07	0.00001	1.92E-10
Mercury (Hg)	0.001	4.99E-09	0.006 (Inorganic)	2.99E-08	0.00006	2.99E-10
Benzene	0.001	1.28E-08	0.01	1.42E-07	0.6	7.68E-06

AES1 Assessment - Connected Porosity Through Halite

In calculations analysing this AES, the halite has connected porosity of either 0.01 or 0.02, allowing contaminants to diffuse out of the facility through the halite. After leaving the halite, contaminants then diffuse further through the rock before encountering an aquifer. Diffusion is represented as being directly up and directly down. There is no broadening of the plume in the horizontal direction.

Example outputs from these simulations are shown in Figure 11-8 and Figure 11-9. These figures show that even in the Stairway Sandstone, where the closest known aquifer to the facility occurs, groundwater standards / guidelines would not be exceeded for at least 100,000 years for any contaminant, given the specified solubility ranges. These figures also show that, for contaminants with solubilities towards the lower end of the considered range, even after 1 Ma, groundwater standard / guideline values are unlikely to be exceeded.

The calculated concentrations for the case with porosity 0.01 (Figure 11-8) are slightly greater at any given time than for the case with porosity 0.02 (Figure 11-9). While counter-intuitive, this result is a consequence of both cases having the same diffusion coefficient. Thus, effectively in the case with porosity of 0.01, the flux of contaminants is actually slightly higher than in the case with porosity 0.02

In fact, the diffusion coefficient would vary as a function of porosity, such that the lower the porosity, generally the lower the diffusion coefficient. However, there are no data available with which to judge this relationship for the halite of the Chandler formation.

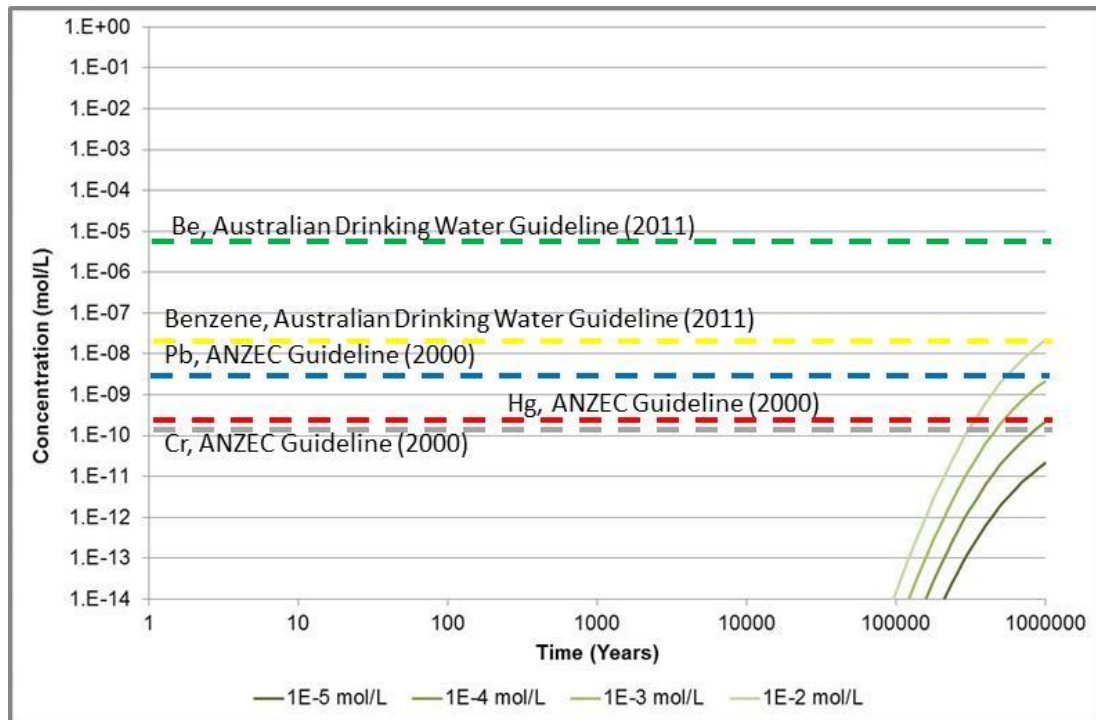


Figure 11-8: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES1. Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport to the Stairway Sandstone is by diffusion. Connected porosity in the halite roof is 0.01. There is no sorption.

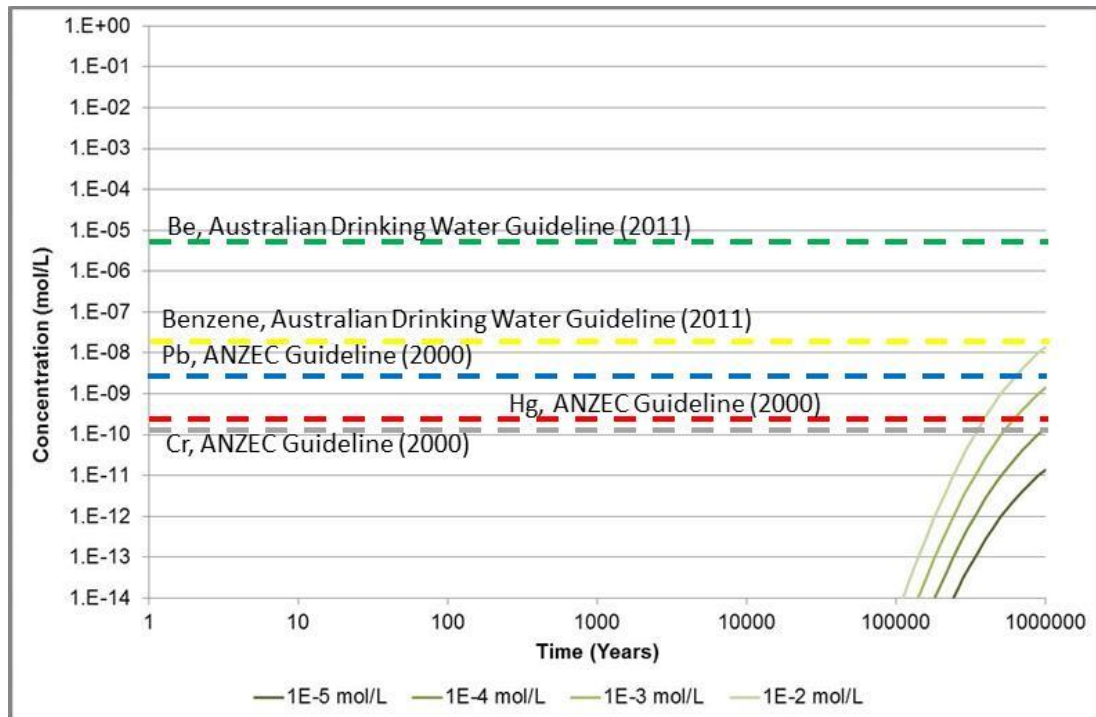


Figure 11-9: As for Figure 11-8, but the connected porosity of the halite is 0.02.

The results shown in Figure 11-8 and Figure 11-9 were obtained while neglecting sorption. The effects of sorption can be appreciated by comparing these figures with Figure 11-10.

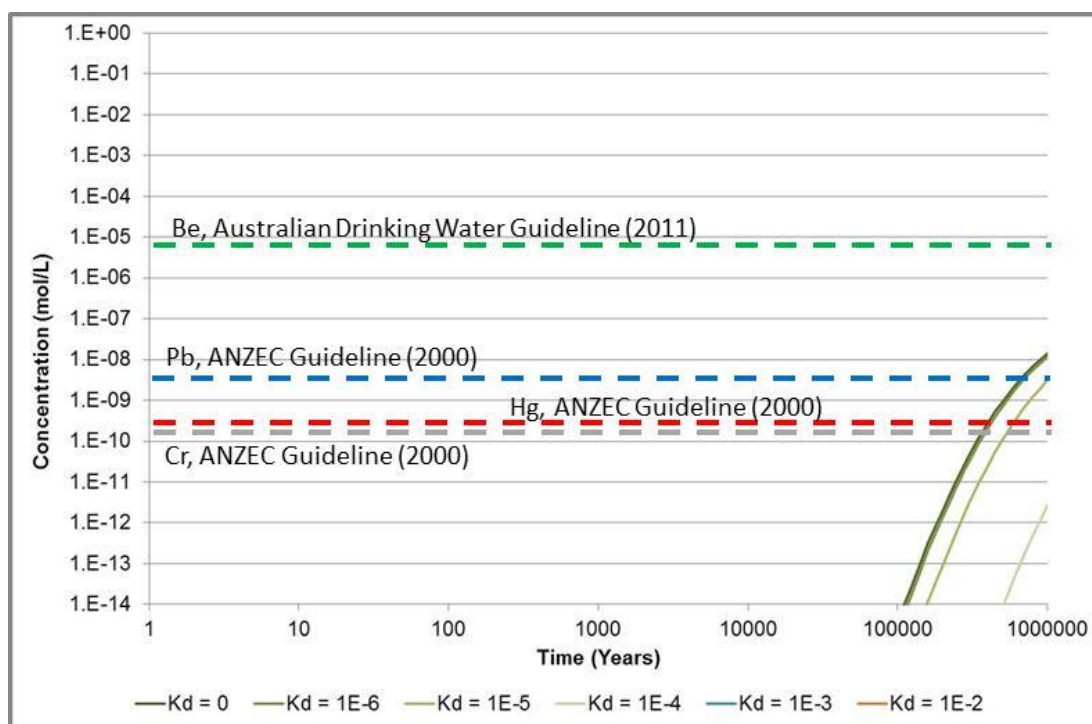


Figure 11-10: As for Figure 11-8, the connected porosity of the halite is 0.02, but with the effects of various sorption coefficients (K_d) being taken into account; the larger the sorption coefficient, the greater is the partitioning of a contaminant onto the solid (immobile) phases present. The guideline value for Benzene has been removed because this constituent is unlikely to sorb to any significant degree.

It can be seen that sorption reduces significantly the concentration of each contaminant at any particular location and time. For K_d values $>10^{-5}$ the calculated contaminant concentrations are >2 orders of magnitude below the lowest considered groundwater contaminant guideline (the one for Cr) at 10,000 m from the facility, even after 1 Ma following closure.

It is also important to note that these concentrations are calculated for an aquifer in the Stairway Sandstone Formation. This formation contains saline water (TDS = 15000 mg/L according to Douglas Partners, 2013) and hence is unlikely to be exploited for water resources. Were the water to be used for human consumption it would need to be diluted (either during transport to shallower aquifers that contain less saline water or conceivably by the people extracting the resource) to TD of <1000 mg/L and more likely $<<600$ mg/L (e.g. WHO, 2011). Thus, the contaminant concentrations in the Stairway Sandstone would be decreased by well over an order of magnitude before human consumption would be considered.

In practice, as explained in Section 11.2.3, during transport upwards from the Stairway Sandstone by any plausible pathway other than via direct abstraction from an open borehole section within the Stairway Sandstone, there would be significant dispersion and dilution of the contaminants.

AES2a Assessment - Collapsed Roof in Operational Phase Assessment

The probability that roof collapse during the operational phase would lead to a pathway for contaminant transport out of the facility in the post-closure phase is very small. The facility will be designed to prevent such collapses and, in the even that such a collapse occurs, remedial action is likely to be taken. However, collapse in the operational phase, into an unfilled cavern, would produce a maximally adverse transport pathway. It is therefore appropriate here to estimate the magnitude of such collapses.

Rockfall into an excavation can occur until a self-supporting collapse column develops. The total void volume is unchanged but is distributed throughout the collapse column, i.e. the rock is not compressible so there is no change in voidage due to compression / relaxation of the matrix porosity (or minerals) in the rock.

The expansion of the rock volume upon collapse is described by a bulking factor that varies with rock type (Figure 11-11).

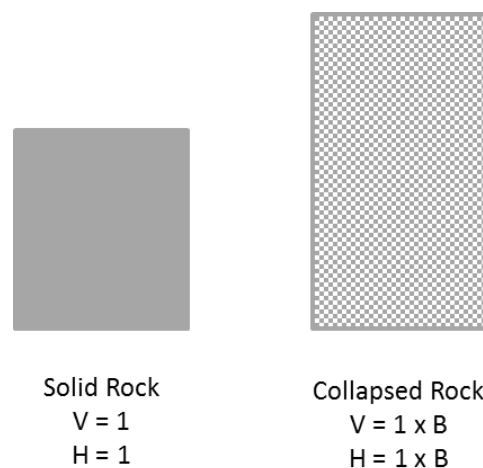


Figure 11-11: Definition of bulking factor: V = volume, H = height, (constant width and depth).

The bulking factor generally increases with rock quality and strength. The height of the collapse column depends on the void height, bulking factor and shape of the collapse column.

In its assessment of the planned DGR at Bruce in Ontario, Canada, NWMO used a bulking factor of 1.3 for crystalline limestone, a moderately strong rock (Quintessa Ltd,

2011). A bulking factor of 1.1 was used for salt caverns overlain by sedimentary formations in the Netherlands (Metcalf et al., 2013). However, the bulking factor of 1.1 assumed that “peeling” and collapse of individual beds (layers) of rock led to a layered collapse column and limited bulking.

The height of the collapse column can be calculated using a volume balance:

$$h_c v_r + h_{r0} v_{r0} = (h_c + h_{r0}) v_c \quad (8)$$

Where:

h_c is the height of the collapse zone above the original roof of the excavation (m)

v_r is the void fraction in the undamaged rock (effectively zero)

h_{r0} is the height of the tunnel/vault (m)

v_{r0} is the void fraction in the tunnel / vault (equals 1 if there is no waste or backfill)

v_c is the void fraction in the collapsed rock, which is equal to $(B-1)/B$

B is the bulking factor

These parameters are illustrated in Figure 11-12.

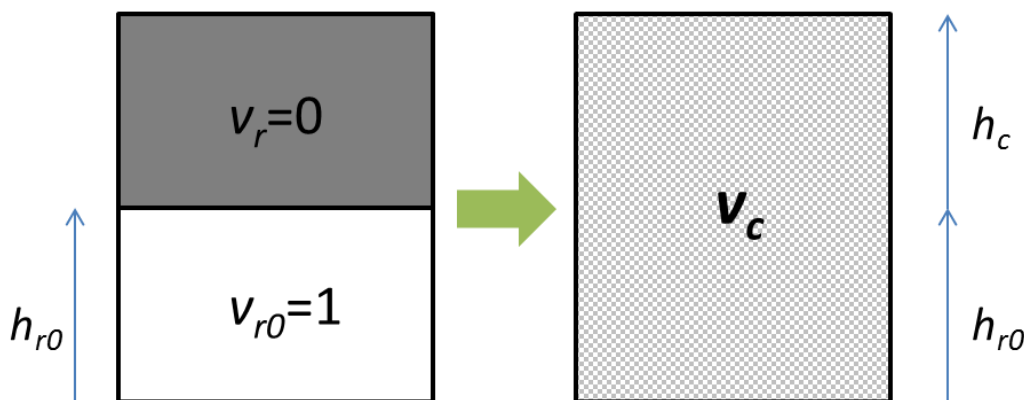


Figure 11-12: Volume balance for calculation of bulking factor.

The assumption of a rectangular collapse column does not take into account that voids would naturally evolve towards a more stable geometry, leading to an arch of rock above the collapse column. Therefore the collapse column could be higher than suggested assuming regular collapse. This is bounded by the assumption of a wedge collapse, where the height of the collapse column (h_c) is twice that for a rectangular collapse.

Solid wastes will be emplaced in the CF in large plastic sacks or in drums / boxes. A gap of about 0.5 m will be left between the waste stacks and the disposal room walls and ceiling. Ideally, these gaps will be filled with fine salt at the time of waste emplacement. However, some waste will initially be accepted for storage that ultimately becomes disposal. It will be very difficult to fill the gaps in these rooms. As

the dry waste packages may themselves contain significant porosity and be compactible to some degree, there is clearly the potential for significant porosity in the rooms. A scoping calculation assuming 25% porosity in the waste stacks suggests that the porosity of a closed room could be up to about 40%.

Calculated potential heights of the collapse column, based on these assumptions, are shown tabulated in Table 11-6.

Table 11-6: Potential height of collapse column

Form	Bulking factor	Height of collapse above original roof of the excavation (m)
Rectangular	1.1	24.0
Rectangular	1.3	8.0
Wedge	1.1	48.0
Wedge	1.3	16.0

A bulking factor of 1.3 is considered to be a realistic assumption. There is a degree of caution because the calculation assumes the waste packages will compact under the load from the rock to the extent that all voidage is “expressed” and is filled with collapsed rock.

The roof of the excavations will be 20 m below the top of the Chandler formation, so with a bulking factor of 1.3 the collapse column will not extend into the overlying Jay Creek Limestone. However, there would also be a zone of damaged (fractured) rock above the collapse column. For a wedge collapse, fractures could potentially extend to the Jay Creek Limestone.

With a bulking factor of 1.1, the collapse column could extent into the Jay Creek Limestone. However, a bulking factor of 1.1 is considered to be cautious, because there is no reason to assume a layered, well ordered collapse column in this instance. Again the calculation is also cautious because it assumes the waste packages will compact under the load from the rock to the extent that all voidage is “expressed” and is filled with collapsed rock.

Implications for contaminant transport in the post-closure phase of the maximal collapse that could occur in the operational phase were calculated using the AMBER model. The key results for the Stairway Sandstone are presented in Figure 11-13.

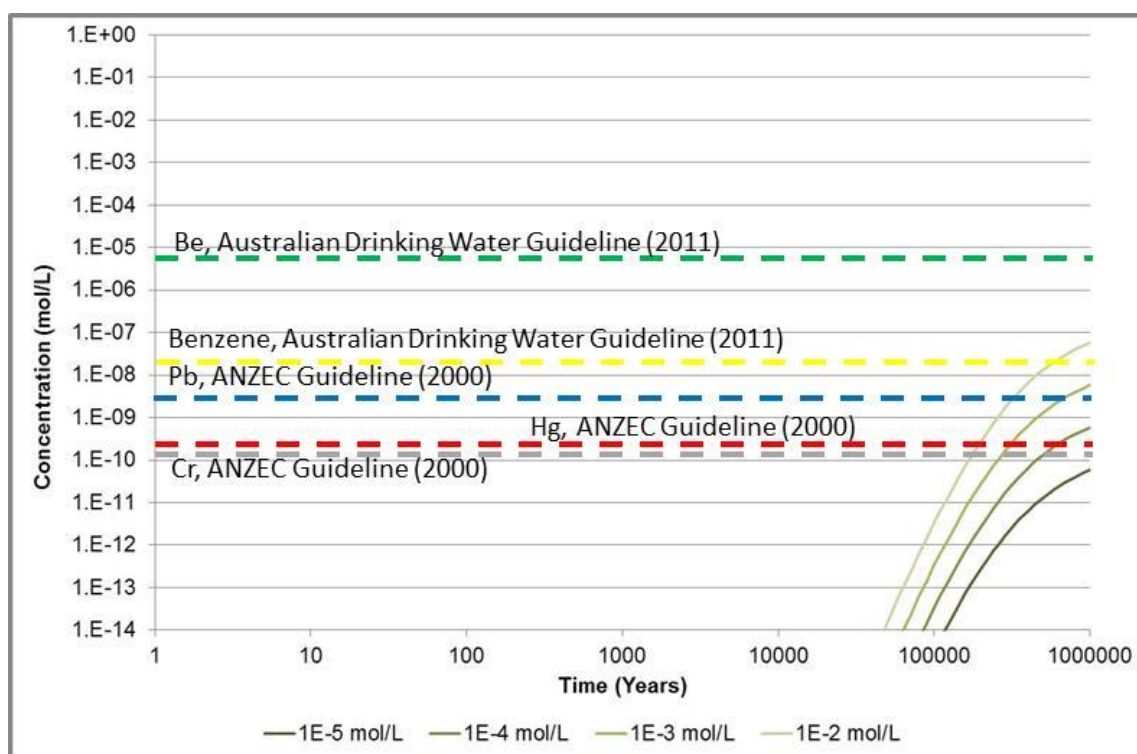


Figure 11-13: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES2a.

Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport through the Jay Creek Limestone to the Stairway Sandstone is by diffusion. There is no sorption.

In this calculation, the groundwater standard / guideline values are exceeded for most of the considered contaminants after a few hundred thousand years when all except the lowest solubility constraint is considered. However, a contaminant with the lowest considered solubility (10^{-5} mol/L) would not exceed any of the standard / guideline values considered after 1 Ma. Additionally, there are some contaminants (exemplified by Be) with standard / guideline values that are sufficiently high that they would not be exceeded after 1 Ma even for the highest solubilities considered.

As explained for AES1, maximum contaminant concentrations in the Stairway Sandstone will likely be much higher than in any shallower rock formation owing to the dispersion and dilution that will accompany upwards transport along any plausible transport path. Only if the Stairway Sandstone was sampled directly by a groundwater well could shallower receptors, including humans, be exposed to the maximum concentrations reached in the Stairway Sandstone.

AES2b Assessment – Collapsed Roof in Post-Closure Phase

Were roof collapse to occur in the post-closure phase, it would result in substantially less upwards propagation of a transport pathway than would be the case should collapse occur into an un-filled cavern in the operational phase. The effects of a roof collapse in the post-closure phase would therefore be less than those calculated by AMBER for AES2a.

Although the potential for a collapse column to extend into the overlying Jay Creek Limestone is low, the potential post-closure impacts if it did occur are:

- ▲ Any post-closure roof collapse would not provide a continuous pathway to the deepest known aquifer, the Stairway Sandstone. Instead in the most extreme case the collapse would affect directly only the Jay Creek Limestone, which is believed to have low permeability causing it to hydraulically isolate the Chandler Formation over geological timescales, thereby preventing salt dissolution.
- ▲ As a result of such roof collapse, there would be a smaller thickness of low-permeability Jay Creek Limestone between the top of the Chandler Formation and the aquifers of the Stairway Sandstone Formation than would be the case in the absence of roof collapse.
- ▲ Roof collapse post-closure would not cause a driving force for fluid movement out of the CF. The reason is that formation of a collapse column would not result in any volume changes, only a re-distribution of the macro-voidage. Except in the unlikely case that the facility has flooded during the operational phase and not been pumped dry subsequently, the facility will initially be at atmospheric pressure. Thus any collapse of the roof would result in water flowing into the facility in the short-term. In the longer term it would be salt creep that would provide a driving force for this water to be expelled from the CF, by closing macro-voids and compressing the wastes, thereby expelling any water into the Jay Creek Limestone¹⁸.

AES3 Assessment – Impaired Shaft Seal

The scenario of a leaking shaft is very cautious, since many studies have shown that it is possible to seal a shaft to be at least as effective a seal as natural aquitards (e.g.

¹⁸ This driving force is not included in the AMBER models of this scenario, which include only diffusion, but the effects would be similar to the impaired shaft seal (AES3), which is analysed by AMBER models (Section 11.2.4).

USDOE, 2009; Quintessa and Geofirma, 2011). However, some simple calculations have been undertaken to scope the potential significance of such failure should it occur. The shaft was cautiously assumed to provide a route from the wastes to all of the aquifers present in the overburden above the Chandler Formation. Furthermore, it was specified extremely pessimistically that the void space in the facility is water-saturated at the time of closure. In practice this is an extremely unlikely situation since, as noted previously, the wastes will be emplaced either in a dry form or in a hydraulic backfill; the latter is likely to contain very little free water after the backfill has cured.

Key results from this simulation are shown in Figure 11-14.

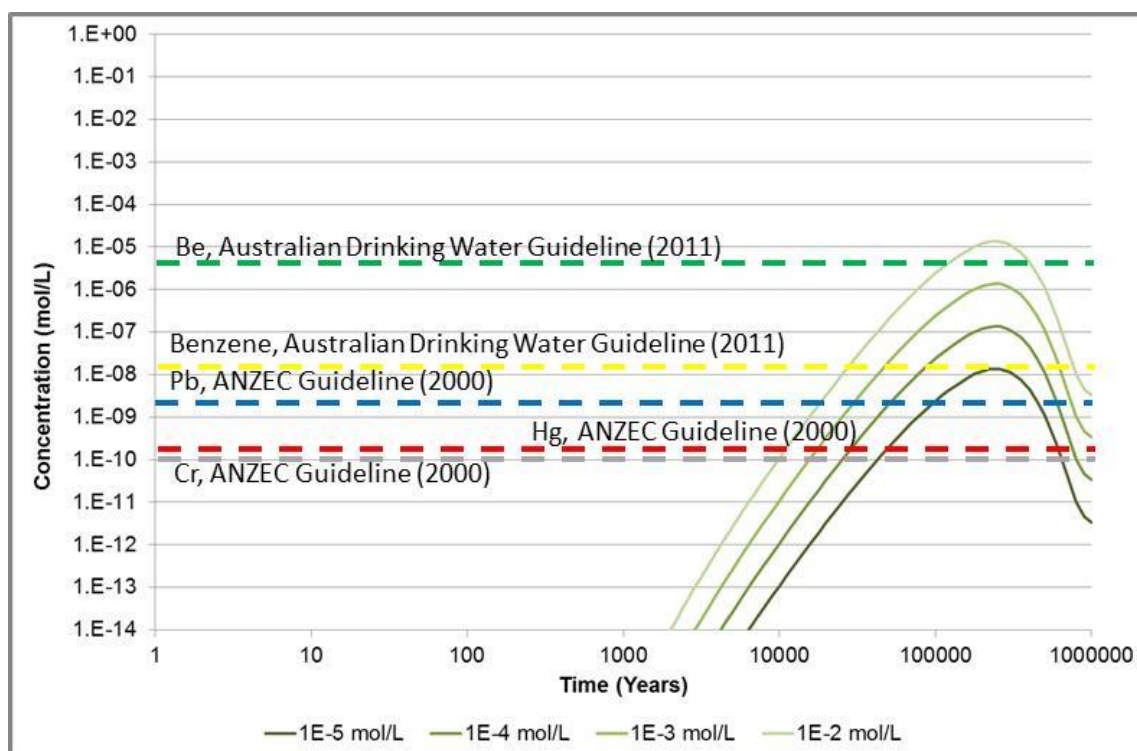


Figure 11-14: Contaminant concentrations at 10,000 m downstream from the CF in the Stairway Sandstone as a function of time following closure in AES3.

Contaminant release from the CF is solubility-limited (10^{-2} mol/L, 10^{-3} mol/L, 10^{-4} mol/L and 10^{-5} mol/L) and transport to the Stairway Sandstone is by advection up the impaired shaft until creep ceases and by diffusion thereafter. The hydraulic conductivity of the impaired shaft seal is 10^{-9} m/s.

In this calculation, the concentrations of contaminants in the aquifer within the Stairway Sandstone Formation increase to a maximum after about 220,000 years and thereafter decrease before beginning to level off (although they are calculated to continue to decrease at 1 Ma). The initial rising concentrations reflect contaminants being driven out of the CF by creep of the salt. The peak reflects the cessation of creep and thereafter contaminant diffuse from the facility at a much slower rate, leading to the fall in concentrations. The concentrations begin to level off as a dynamic equilibrium is approached between supply of contaminants to the aquifer from the CF

and transport of the contaminants away by the groundwater flowing naturally through the aquifer. The peak occurs long after the cessation of creep owing to the length of time taken for the contaminants to travel between the shaft and the point 10,000 m distant for which the calculation is undertaken.

This simulation shows that, depending upon its solubility and corresponding standard or guideline concentration, a contaminant's concentration could conceivably exceed the standard or guideline value in as little as 10,000 years at a distance of 10,000 m. On the other hand, it is also feasible that for those contaminants with solubilities towards the low end of the considered range and for which standard or guideline concentrations are relatively high, groundwater standard or guideline values would never be exceeded.

As explained for AES1 above, the maximum concentrations attained by contaminants in the Stairway Sandstone Formation aquifers would be lower than maximum concentrations that could be attained within shallower aquifers. Unless contaminated groundwater was sampled directly from the Stairway Sandstone Formation, near-surface receptors, including humans, would not come into contact with contaminants with concentrations as high as those in the Stairway Sandstone.

Additionally, with increasing distance from the CF the peak concentrations attained by contaminants in the Stairway Sandstone Formation would decrease. This can be appreciated by comparing Figure 11-14 with Figure 11-15.

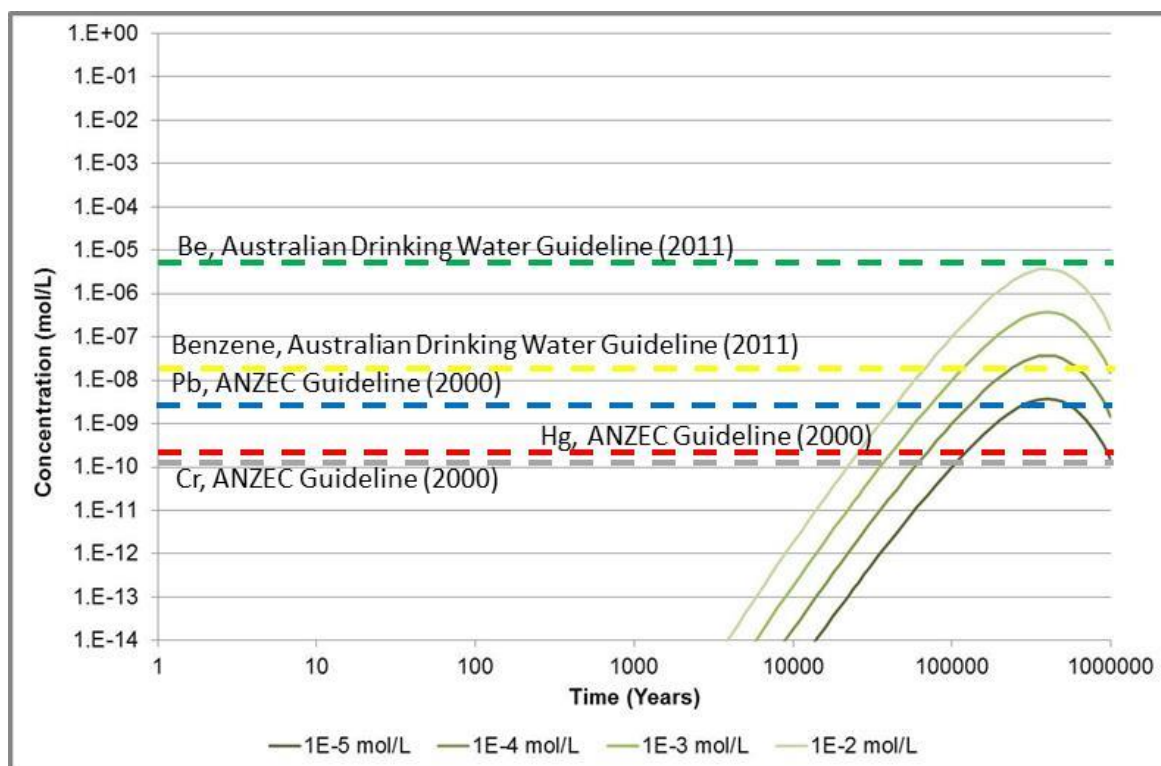


Figure 11-15: As for Figure 11-14 except that results are given for a point within the Stairway Sandstone Formation a distance of 20 km from the CF.

Comparing these two figures shows that, for the parameterization used, contaminant concentrations at any given time decrease by around half an order of magnitude as the distance from the CF increases from 10 km to 20 km. The time taken for a particular contaminant to reach a given concentration is much longer at 20 km distance than at 10 km. At 20 km, within the range of solubilities considered none of the standard or guideline concentrations are exceeded until 22,000 years have elapsed, whereas at 10 km only 10,000 years were taken.

This general result is applicable to any of the AES considered; dilution and dispersion would result in the concentrations of contaminants decreasing by around half an order of magnitude for each 10 km increase in distance from the facility. However, it should be noted that this conclusion is very dependent upon the values assigned to the parameters that represent dispersion. There are presently no hydrogeological data with which to judge these values. It is conceivable that, owing to the heterogeneous and nature of the aquifers, dispersion could result in a greater degree of dilution than has been calculated in these simulations.

The effect of increasing distance can also be appreciated by comparing the calculated contaminant concentrations at different locations in the Stairway Sandstone Formation when a notional 1t of contaminant is specified to be able to leak from the CF, rather than specifying a solubility control. Such results are shown for distances of up to 20,000 m from the facility in Figure 11-16.

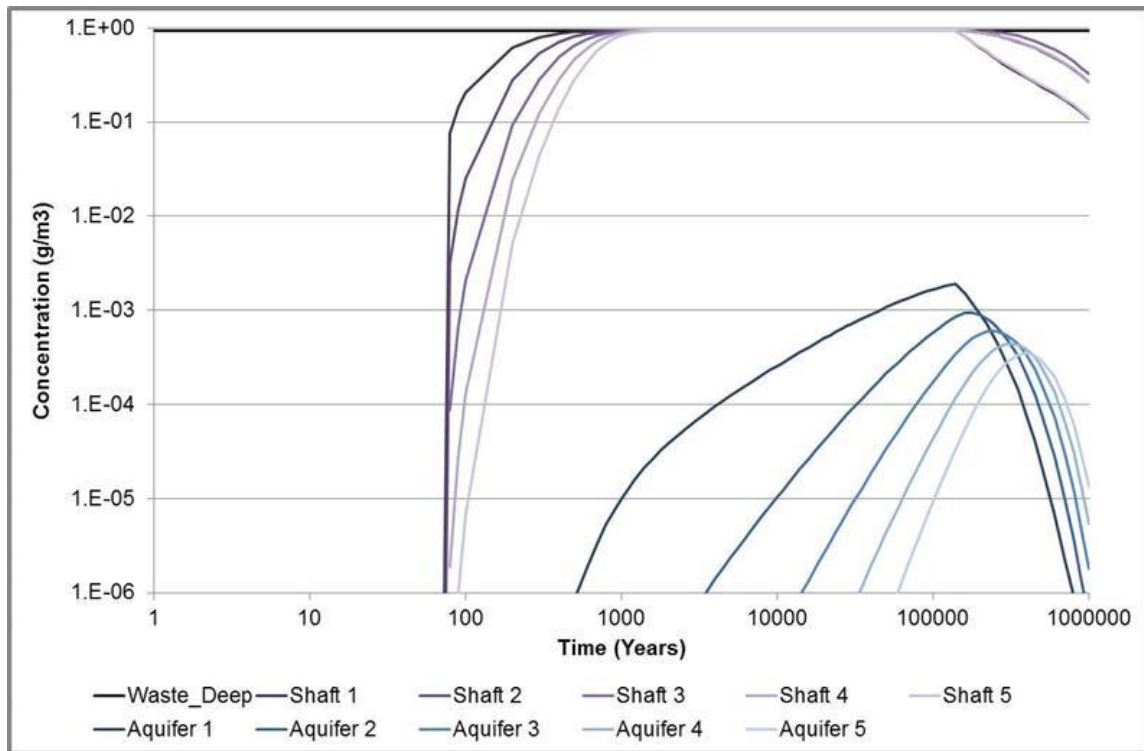


Figure 11-16: Results obtained when a notional 1t of a contaminant is released instantaneously to water saturating the CF at the time of closure and thereafter allowed to escape up a shaft with an impaired seal. Concentrations are given for each compartment in the model (see Figure 11-7) with "Shaft 1" and "Aquifer 1" representing the closest shaft and aquifer compartments to the CF respectively. "Aquifer 1" to "Aquifer 5" here represent the Stairway Sandstone, with "Aquifer 5" being up to 20,000 m from the CF. There is no retardation by sorption.

The absolute concentrations shown in Figure 11-16 cannot be compared with the groundwater standard or guideline levels, because they reflect the notional 1t inventory rather than the actual inventory. However, they do illustrate that in reality, there limited inventory would place a limit on the concentration attained by any contaminant at any point in the system. That is, concentrations would initially rise to a peak, before falling as the contaminant becomes exhausted. The size of the peak would depend upon the size of the inventory.

For some contaminants in the facility it is conceivable that this inventory size limitation would prevent groundwater standard or guideline concentrations from being attained. Once data become available that allow the total inventories of all contaminants to be determined, then greater clarity will be possible concerning those contaminants for which this limitation might occur

For the parameterization used, the inventory-limited calculations give rise to peak contaminant concentrations in the Stairway Sandstone Formation after around 400,000 years at a distance of 20 km from the facility.

NORM Wastes

It is possible that some NORM may be included in the wastes to be emplaced in the CF.

The dominant radionuclide in the NORM inventory for the CF is Ra-226. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales (Section 4.2.2). If all of the 200 m³ / y of such wastes that arise each year in Australia were sent to the CF for the 25 year operational life, a total of 5000 m³ of NORM waste would be in the CF at closure. Assuming a waste density of 2000 kg/m³ gives 10¹⁰g of waste.

Section 4.2.2 indicates that the typical activity of such waste is 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales. Assuming that all of the activity is attributable to Ra-226, 1 Bq/g Ra-226 corresponds to 2.7×10^{-11} g Ra-226 per g waste. If the activity of the NORM wastes is 1 Bq/g, the initial inventory of Ra-226 is 0.3 g and if it is 10 Bq/g the initial inventory of Ra-226 is 3 g.

The WHO drinking water standard for Ra-226 is 1Bq per litre (WQA Technical Fact Sheet), which corresponds to 2.7×10^{-11} g/L or 2.7×10^{-8} g/m³. Therefore the results for a non-decaying contaminant provide a starting point for determining whether or not the drinking water standard would be exceeded.

Taking the results of the calculations for a non-sorbing contaminant for the EES at 1km, 10km and 20km, the peak concentrations seen in the Stairway aquifer are 4×10^{-4} g/m³, 3×10^{-6} g/m³ and 1×10^{-8} g/m³ respectively for an initial inventory of 10⁶ g. For the EES the contamination does not reach detectable concentrations in the aquifer sampling point for at least 70,000 years (1 km case; 350,000y for the 10 km case) Scaling by the inventory (0.3 to 3 g Ra-226) suggests that the drinking water standard would be met even before sorption and decay have been taken into account.

Ra-226 has a half-life of 1600 years. After 10 half-lives (16,000 years) the activity will have reduced by a factor of 1000 and after 20 half-lives (32000 years) by a factor of 10⁶. Thus decay rapidly reduces the concentration of Ra-226 and it could only conceivably be a threat for alternative evolution scenarios that assume rapid release to the aquifers and sampling close to the facility (the Ra-226 will decay to negligible activities during 10 km transport in the aquifer takes 20,000 years). Finally, sorption would be expected to further retard transport and reduce concentrations in water.

11.2.5 Application of Risk Terminology to the CF

The scale of likelihood given in Table 10-6 is applied to the various post-closure scenarios specified for the CF (Section 11.1 and Section 11.2) in Table 11-7. For each specification of likelihood an explanation is also given.

Table 11-7 shows only the likelihood that each scenario will occur *at some time* during the future evolution of the facility and does not indicate the likelihood at any particular time.

Table 11-8 uses the terminology for environmental impacts explained in Table 10-7 to summarize the worst impacts that could plausibly arise should a scenario be realized. It is conceivable that should one of the AES occur the impact could be less severe than is indicated; the EES is judged to have no significant adverse impact and therefore could not have a smaller impact than is given in Table 11-8.

Table 11-7: Summary of judgements of likelihood that each scenario will occur.

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
EES	None	Expected Evolution Scenario	Likely	There is theoretical and analogue evidence from studies in other countries that the natural and engineered barriers will maintain their integrity in the long-term (e.g. USDOE, 2009; Quintessa, 2011; Quintessa and Geofirma, 2011). Geomechanical models have shown that the roof of the facility will not undergo collapse during the operational phase or thereafter, with a large margin for safety, provided that the facility is appropriately implemented (Atkins, 2016). There are no boreholes penetrating to the depth of the facility within its footprint. Furthermore, the CF will be an inherently dry environment and will initially contain very little mobile free water at the time of closure and entry of water to the facility from the surrounding geosphere will be very slow owing to the extremely low permeability of the halite. Post-closure, creep will reduce the connected void space in the facility before any formation water is able to enter the facility. In the absence of creep there is very little force to drive water from the facility. Thus, at the time when the driving force is at its maximum there will be very little water present that is able to transport contaminants, while there will be very little driving force during the time period when water is available to mobilize this water.
Alternative Evolution Scenarios				
AES1	None	Connected porosity through the halite roof of the facility	Unlikely	There is abundant evidence from many localities throughout the world that halite contains no connected porosity and is impermeable. Furthermore, halite has an inherent self-sealing capability owing to its ability to creep. In many hydrocarbon fields halite forms the caprock to oil and gas reservoirs and has retained hydrocarbons for many millions

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
				of years (e.g. Capture Power and National Grid, 2016). However, the halite deposit in which the CF will be constructed is only 80-95% pure halite (ERCOSPLAN, 2013), which raises some possibility that other materials present (e.g. anhydrite interbeds) could contribute to connected porosity
AES2	a	Collapsed roof in the operational phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Highly Improbable	There is abundant evidence from underground excavations in salt deposits elsewhere in the world (e.g. the WIPP in New Mexico (Matthews and Eriksson, 2003); Winsford Salt Mine, Cheshire, UK (Swift and Reddish, 2005)) to support the conclusion that the CF can be designed and constructed so as to prevent roof collapse during the operational phase of a magnitude sufficient to compromise the integrity of the halite. Geomechanical modelling also supports this conclusion for the specific case of the CF (Atkins, 2016).
	b	Collapsed roof in the post-closure phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Highly Improbable	Once the facility is filled with waste and backfilled there will be a much smaller void space into which a roof collapse could occur than in the operational phase. Hence roof collapse of a sufficient magnitude to compromise the barrier function of the halite is highly improbable. Scoping calculations (Section 11.2.4 Error! Reference source not found.) support this conclusion.
AES3	None	Impaired shaft seal scenario	Unlikely	There is theoretical and analogue evidence that shaft seals can be constructed so as to maintain their integrity in the long-term (e.g. assessments for the WIPP in New Mexico, U.S.A (USDOE, 2009) or for the DGR planned for Bruce in Ontario (Quintessa, 2011; Quintessa and Geofirma, 2011)). The main reason why this scenario is not highly improbable is that there remains some possibility that imperfect implementation of the shaft seals will cause their performance to be

Scenario	Variant	Title	Probability	Rationale for Likelihood Judgement
				impaired compared to the EES.
AES4	None	Accidental human intrusion	Unlikely	Accidental human intrusion can never be ruled out entirely. However, the remote geographical location of the CF and the lack of any obvious natural resources at the depth of the facility make this scenario unlikely. It cannot be assumed that records of the facility's location and characteristics (e.g. emplaced wastes) will be available to future generations. However, it is technically demanding to drill boreholes or undertake excavations to the depth of the CF. It is a reasonable assumption that any future society with the technical capability to undertake such activities would also undertake prior investigations (e.g. seismic surveys) that would identify the facility, thereby enabling intrusion to be avoided.

Table 11-8: Summary of judgements of maximum potential impact of each scenario should it occur.

Scenario	Variant	Title	Impact	Rationale for Likelihood Judgement
EES	None	Expected Evolution Scenario	None	The expected evolution scenario is that contaminants will not leak from the facility. There is abundant evidence from many localities throughout the world that halite contains no connected porosity and is impermeable. In many hydrocarbon fields halite forms the caprock to oil and gas reservoirs and has retained hydrocarbons for many millions of years (e.g. Capture Power and National Grid, 2016). The site of the CF lies in the stable interior of a tectonic plate, far from the zones of active deformation which characterise the boundaries of such plates. The Chandler Formation shows no evidence for significant tectonic disturbance over the >500 million years since it was deposited and there is every reason to suppose that it will not be disturbed over any relevant future time period. The shafts will be sealed with multiple seals that contain materials that will not degrade significantly over relevant timescales. Assessments of similar kinds of sealing system for other deep waste facilities elsewhere in the world have demonstrated the feasibility of constructing shaft seals that will maintain their performance for at least 1 Ma (e.g. USDOE, 2009; Quintessa and Geofirma, 2011).
Alternative Evolution Scenarios				
AES1	None	Connected porosity through the halite roof of the facility	Low	Evidence for this comes from calculations described in Section Error! Reference source not found. These suggest even in the unlikely, pessimistic situation where the facility is water-saturated at closure and where contaminant migration is unretarded by sorption it will take at least several hundred thousand years for contaminant concentrations to exceed water quality standard or guideline values at distances of more than 10 km from the facility, even in the deepest aquifers of the Stairway

Scenario	Variant	Title	Impact	Rationale for Likelihood Judgement
				Sandstone Formation.
AES2	a	Collapsed roof in the operational phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Medium	Were roof collapse to occur during the operational phase, a contaminant transport pathway to the Stairway Sandstone could develop. However, the only way that the contaminants could then be transported to shallower aquifers that might be exploited for groundwater supplies would be via boreholes with imperfect seals, open boreholes, transmissive faults or diffusion.
	b	Collapsed roof in the post-closure phase, combined with contaminant transport through borehole/transmissive fault/aquifer pathways	Medium	As for AES1a
AES3	None	Impaired shaft seal scenario	Medium	Calculations to explore the effects of impaired shaft seal performance suggest that groundwater standard or guideline levels for contaminants could be exceeded within the aquifers on timescales of as little as 10,000 years at a distance of 10,000 m from the facility (Section 11.2.4). However, levels of contamination would decrease rapidly with respect to distance from the shaft. Additionally the concentrations could be several orders of magnitude lower than this, should account be taken of retardation due to sorption.
AES4	None	Human intrusion	High	While the effect of human intrusion could be high, it is likely that the adverse effects of human intrusion could be mitigated more readily than the case of the failed shaft (largely because it is more likely that such effects would be recognized by the people responsible for the human intrusion). Hence the impact is judged to be less than the impact for the failed shaft seal.

The judgement of risk, based upon the judgements of likelihood that each scenario will occur and the impacts should it occur, presented in Table 11-7 and Table 10-8 and respectively, are summarized in Table 11-9.

**Table 11-9: Summary of risks related to post-closure scenarios (green = no risk).
Colour coding as in Table 10-5.**

Likelihood	Impact					
	None	Very Low	Low	Medium	High	Very High
Highly Probable						
Likely	EES					
Possible						
Unlikely			AES1	AES3	AES4	
Highly Improbable				AES2a, AES2b,		

The following conclusions can be drawn about relative risks:

- ▲ The EES would give rise to zero risk, since contaminants have no impact beyond the CF itself.
- ▲ AES1, AES2a and AES2b would give rise to the lowest risk among the different AES.
- ▲ AES3 would have the highest (though still low) risk among the scenarios that represent possible contaminant leakage paths that either exist or develop without human intervention.
- ▲ AES4 could potentially give rise to the highest risk among the AES, although the fact that this scenario is unlikely and any impact would likely be of restricted spatial extent means that the overall risk is not judged to be particularly high.

11.2.6 Temporal Variations in Risk

Factors Affecting Temporal Variations in Risk

At increasingly long times in the future, the uncertainties concerning the behaviour of the CF become progressively greater and quantitative estimates of risk become increasingly less meaningful. However, the most likely scenario is for an indefinite continuation of containment (i.e. for the EES to continue indefinitely¹⁹). The key uncertainty is the degree to which any small contaminant flux from the CF would be diluted within the overlying aquifers, such that groundwater standards / guideline values are not exceeded anywhere. This uncertainty reflects uncertainties in:

- ▲ groundwater recharge rates;
- ▲ hydraulic head gradients;
- ▲ the hydraulic properties of the aquifers; and
- ▲ the properties of the rocks that govern contaminant transport and retardation processes.

If a pathway via which contaminants can leave the CF were to develop unexpectedly (i.e. an AES is realized) plausibly, given long enough, groundwater standards/guideline values could be exceeded in one or more aquifers. However, even in these circumstances, the likelihood that the standard / guideline values would be exceeded is lower for shallower aquifers than for deeper ones since upwards transport of contaminants will be accompanied by at least some dilution and dispersion.

Even given some very pessimistic parameterization (e.g. assuming the CF is water saturated at closure and that there is no retardation of contaminants by sorption), it would require several hundred thousand years for groundwater standard / guideline values to be exceeded at a distance of 10 km from the facility.

Even though the temporal variations in risk cannot be estimated confidently, confident pessimistic estimates of risk can be made, as described in Section 11.2.5. It is also possible to identify a number of temporally varying factors that have the potential to affect risk:

- ▲ Over time, “societal memory” of the facility is likely to become weaker and eventually will be lost altogether. This factor will tend to influence the risk that human intrusion will occur (i.e. the likelihood that AES4 will be realized). However, the actual risk of human intrusion will also depend upon other

¹⁹ Here “indefinitely” refers to the maximum period that is of concern to stakeholders.

factors, such as the spatial distributions of human populations in the future and the level of technological development that these populations possess.

- ▲ Future climate change will influence the hydrogeology of the area around the CF. If rainfall in future is higher than at the present, potentially hydraulic gradients could be increased compared to current ones and the groundwater fluxes through the various aquifers in the geological sequence above the CF could be greater than now. Increased fluxes could lead to increased dilution of any contaminants that were to be released from the CF into these aquifers. This dilution in turn could diminish the likelihood that contaminant concentrations that entered the aquifers might exceed groundwater standard / guideline values there. Such dilution might also have the effect, however, of making the aquifers more attractive targets for groundwater abstraction, which would increase the likelihood of borehole drilling, thereby producing pathways for contaminant transport. Decreases in rainfall could possibly have the reverse implications, but it seems unlikely that rainfall, and hence recharge, could diminish much from their present values, given the desert conditions of the area. The preservation of the salt in the Chandler Formation for approximately 520 million years, during which time there have been profound environmental changes, provides evidence that future climate change will not cause significant environmental changes at the level of the facility.
- ▲ Changes in population distributions and land use, potentially related to climate change, could cause a greater likelihood that humans, animals and vegetation could be exposed to any contaminants that were to enter the aquifers in the overburden above the CF. Over the very long timescales that must be considered, it is conceivable that climate change could enable increased human populations to inhabit the area around the CF and / or enable agriculture to be undertaken in this area.
- ▲ Irrespective of any changes in human activity and resultant variations in land use, ecosystems in the vicinity of the CF could change naturally, in response to climate change or, given long enough, evolution. Conceivable consequences could be changes to the nature of biological receptors that might be impacted by any contaminants that were to be transported into the overburden.

25 years to 300 years (potential institutional control period)

During the institutional control period the engineered and natural barriers in the system are expected to work as designed; the EES is by far the most likely scenario. Only in the event that shaft seals were not emplaced properly is it conceivable that

shaft seals would not function as designed. However, even in the event of impaired shaft seal function due to this cause, it is not credible that during this relatively short period contamination could migrate via the shaft sufficiently far to contaminate any aquifer that might be exploited for groundwater.

In principle, were contaminants to be transported from the CF to the overburden during this period, open monitoring boreholes could form all or part of pathways to the near-surface biosphere (depending on the depth of the boreholes). However, in practice this is extremely unlikely as there will be very little, if any, mobile water within the facility. Additionally there will be very little driving force to cause contaminated water to migrate into the overburden, even assuming that there are sufficiently transmissive pathways via which the water could be transported (considered unlikely). It is therefore highly unlikely that, within this time frame, contaminant concentrations within aquifers that might be exploited for groundwater could exceed groundwater quality standard or guideline values. Support for this conclusion is provided by the numerical models presented in Section 11.2.4.

Accidental human intrusion is considered even more unlikely to occur in this period than in later (and longer) time periods, owing to the presence of people with knowledge of the facility (by definition, since monitoring is on-going).

300 years to 1,000 years

The EES continues to be the most likely scenario throughout this time period.

During this period creep is likely to provide a driving force for any water that might be in the facility. However, there is likely to be little free, mobile water present and hence creep will not result in any significant increase in the likelihood of contaminants leaving the facility. Engineered barriers (principally shaft seals) are highly likely to retain their function. Even in the unlikely event that contaminants were to leave the facility during this period, numerical models presented in Section **Error! Reference source not found.** suggest that contaminant concentrations within the aquifers that might be exploited for groundwater resources would not exceed groundwater standard or guideline values. During this period climate change of a sufficiently great magnitude to cause large changes in human activity, and consequent agriculture and land use, is considered unlikely. However, “societal memory” of the existence of the CF could decrease progressively and the possibility of human intrusion cannot be ruled out. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

1000 years to 10,000 years

During this period, the EES remains by far the most likely scenario. While there is considerable uncertainty (geomechanical models have not fully explored this interval; Atkins, 2016), it is possible that significant creep will have ceased prior to the start of this period. It also seems unlikely that even in this period there will be sufficient free water to transport contaminants from the facility at a significant flux. Even in the event that contaminants were to leave the facility during this period, numerical models presented in Section 11.2.4 suggest that contaminant concentrations within the aquifers that might be exploited for groundwater resources would not exceed groundwater standard or guideline values.

During this period, potentially climate change and consequent variations in human populations, land uses and ecosystems could occur. It cannot be assumed that there would be any “societal memory” of the existence of the facility. Were human populations to increase in the future, then the potential for accidental human intrusion would likely increase. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

10,000 years to 1 million years

During this period, the EES remains by far the most likely scenario, but the effectiveness of engineered barriers in the shafts becomes more uncertain with increasing time. Nevertheless, there is considerable analogue and theoretical evidence that properly designed and emplaced shaft seals will retain their barrier function at least throughout this long period and that consequently the shaft seal impairment scenario (AES3) will not be realized.

It seems likely that even in this period there will be little free water, and a very small force driving groundwater flow. Therefore, even if a pathway via which contaminants can leave the CF were to develop unexpectedly (i.e. an AES is realized) any flux of contaminants from the facility would be very small. However, numerical models presented in Section 11.2.4 suggest that under these circumstances, over this very long time period, contaminant concentrations within the aquifers that might be exploited for groundwater resources could conceivably exceed groundwater standard or guideline values. Nevertheless, there are large outstanding uncertainties concerning the hydrogeology of the area. Taking these uncertainties into account it is plausible that contaminant dispersion in these aquifers could be sufficient to prevent these groundwater standard or guideline values from ever being exceeded. Further

modelling, based on a more complete hydrogeological dataset than is available at the present, could improve confidence in judgements as to whether or not such dispersion would occur in future.

During this period, climatic conditions will certainly fluctuate considerably. For at least a substantial proportion of the period these conditions will be considerably different from those of the present. Consequently there will be variations in human populations, land uses and ecosystems. It is almost certain that there will be no “societal memory” of the existence of the facility, even assuming that humanity continues to exist throughout this period. Were human populations in the area near the CF to increase in the future, then the potential for accidental human intrusion would likely increase as well. Such human intrusion could cause an increase in the likelihood that humans and ecosystems might be exposed to levels of contamination in excess of groundwater standard and guideline values.

12 Conclusions

This initial IRA provides confidence that, for the proposed categories of wastes and with appropriate facility design and operation, there will be no significant unmanageable risks in terms of:

- ▲ the operability of the CF;
- ▲ environmental safety of the CF during the operational phase; and
- ▲ environmental safety in the post-closure phase.

The most probable scenario for the operation of the CF is that it follows the operational plan and that if there are accidents, the consequences can be managed so that there are no lasting unacceptable impacts.

The most probable scenario for the future evolution of the CF after closure is that the facility behaves as planned and no significant contamination leaves (the Expected Evolution Scenario, EES).

To assess the risks of the CF unexpectedly not behaving as designed (i.e. the EES not being realized), a number of Alternative Evolution Scenarios (AES) have been defined, 6 for the operational phase and 4 for the post-closure phase:

▲ Operational Phase AES:

1. AES 1: Rockfall (in an unfilled or partially-filled room, tunnels);
2. AES 2: Vehicle fire;
3. AES 3: Fixed infrastructure fire;
4. AES 4: Waste package (ISO-container or bulka-bag) failure;
5. AES 5: Hydraulic backfill emplacement system failure; and
6. AES 6: Impaired shaft lining performance.

▲ Post-closure Phase AES:

1. AES1, Connected porosity through the halite roof of the CF;
2. AES2, Collapsed roof of the CF, with the variants:
 - (a) AES2a, Collapsed roof in the operational phase;
 - (b) AES2b, Collapsed roof in the post-closure phase;
3. AES3, Impaired shaft seal; and
4. AES4, Accidental human intrusion.

These scenarios are *not* predictions of future CF behaviour. Instead, they are designed to illustrate alternative ways in which the facility might behave in the event that the EES are not realized.

Very probably no actual future system evolution that hypothetically departs from expectations (as represented by the EES) would result in greater impacts than the highest impacts caused by any of the analysed set of AES. That is, the analyses of the AES are designed to “bracket” any plausible actual behaviour predicated upon the assumption of containment loss.

All the AES have been analysed qualitatively. In addition, the post-closure AES1, AES2 and AES3 have been analysed by means of numerical models.

For the operational phase, risks to the environment arising from the AES are assessed to be very low, because they are either of sufficiently low probability, or of negligible impact. The risks to operability of the CF that could be caused by plausible deviations from development plans are assessed to be greater than the risks to the environment beyond the CF.

For the post-closure phase AES1 is judged unlikely based on available data and may prove to be highly improbable when uncertainties concerning the characteristics of the halite are reduced. AES3 is judged to be unlikely and both variants of AES2 are judged highly improbable if the CF is appropriately implemented. AES4 is judged to be unlikely given the presently remote location and the fact that intruding into the facility by humans in the future implies significant technological capabilities which could be employed to avoid or mitigate environmental impacts.

Even if containment of the CF were to be lost during the post-closure period, contaminated water would not necessarily travel to near-surface receptors. Under these circumstances any contaminated water may travel upwards only as far as the aquifers in the Stairway Sandstone. The Stairway Sandstone Formation contains saline water (TDS = 15,000 g/L; Douglas Partners, 2013) and hence is unlikely to be exploited as a groundwater resource. Consequently it is unlikely that near-surface receptors, including humans, would be exposed to the peak contaminant concentrations calculated for the Stairway Sandstone, even if one of the AES were to be realized.

Should a post-closure AES be realized, any contaminants that enter the aquifers of the Stairway Sandstone would be diluted and transported laterally by groundwater flowing slowly under the natural head gradient. The contaminant concentrations would then decrease downstream owing to dispersion. Calculations show that it would take more than a hundred thousand years for the concentrations of any contaminants in the Stairway Sandstone to exceed groundwater standard/guideline values at a distance 10 km downstream from the facility in the post-closure AES1 and both variants of the post-closure AES2. In the case of the post-closure AES3, it would take as long as 10,000 years for these groundwater standard/guideline values to be exceeded in the Stairway Sandstone at a distance of 10 km downstream.

Were contaminants to be transported in the post-closure phase via any conceivable pathway from the Stairway Sandstone to shallower aquifers that are more likely to be exploited as water resources, the contaminants would be diluted and dispersed along the pathway to some degree. Thus, these shallower aquifers would tend to have lower contaminant concentrations than those in the Stairway Sandstone at the location where the contaminants left the Stairway Sandstone.

If a shallower aquifer was to become contaminated in this way, contaminants would be transported laterally within the aquifer by groundwater flowing under the influence of the natural head gradient, in the same way as contaminants within the Stairway Sandstone. Thus, contaminant concentrations would decrease laterally within the aquifer, with increasing distance from the CF.

In the event that the shaft seals are impaired in the post-closure phase (AES3) contaminants would be diluted and dispersed to some degree during upwards transport through impaired shaft seals.

The most significant uncertainties associated with the IRA arise due to:

- ▲ the detailed designs and operational plans for the CF not yet being finalized;
- ▲ the final characteristics and quantities of the wastes not having been defined; and
- ▲ uncertainties in the:
 - behaviour of the wastes under the conditions within the CF (notably the chemical forms in which contaminants occur and their solubilities);
 - driving force provided by the creep of the halite in the post-closure period;
 - magnitudes of processes controlling retardation of migrating contaminants (sorption, diffusion into parts of the rock matrix where there is no advection);
 - uncertain hydrogeological data, including:
 - hydraulic conductivities of the different rock formations;
 - porosities of the different rock formations;
 - groundwater head gradients;
 - groundwater recharge rates;
 - dispersivity of the aquifers; and
 - uncertain lateral connectivity of the aquifers.

These uncertainties have been treated in the assessments by making cautious qualitative arguments and using pessimistic values of relevant parameters, consistent with the available data. It is therefore likely that calculated contaminant concentrations in the aquifers for the post-closure AES tend to over-estimate the concentrations that would actually occur in the rock formations above the CF at any particular location and time in the future, should the CF lose containment.

Taking into account these uncertainties, it is conceivable that, should containment of the CF be lost in the post-closure phase, no contaminant concentrations in the Stairway Sandstone would ever exceed groundwater standard / guideline values beyond a distance of 10 km from the facility. Since the shallower aquifers are likely to contain even lower concentrations of contaminants than the Stairway Sandstone, it follows that it is even less likely that under these circumstances the shallower aquifers could contain concentrations of contaminants in excess of groundwater standards or guideline values.

It is expected that, as the designs and operational plans mature further, and as the waste characteristics and waste streams become more precisely defined, risks will be reduced further, below those assessed in this report.

Further numerical modelling of the system could reduce the outstanding uncertainties once complete compositions of the wastes have been established and relevant hydrogeological information becomes available.

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13 References

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Appendix A: Waste Screening

Waste stream data ("75" code) supplied by Tellus are given in Table A1.

Table A-1: Waste Descriptions and Projected Inventory ([1] Source: TCO-5-05-01_Tellus Sites_NEPM Code Volume & Transport Analysis Model_5May2016)

NEPM '75' code	Waste description (NEPM Schedule A, List 1)	Inputs	340,000	8,500,000
			tpa	t LOM
		Chandler Facility (%)[1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
	Total Haz chem waste	97.1%	330,160	8,253,992
	Total NORM's	2.9%	9,840	246,008
	Commercial and Industrial (passed onto to 3rd party landfill)			
	Total (Haz. waste & NORM's)	100.00%	340,000	8,500,000

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%)[1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
N205	Residues from industrial waste treatment/disposal operations	25.3%	85,969	2,149,221
N120	Soils contaminated with a controlled waste	16.6%	56,300	1,407,495
N150	Fly ash, excluding fly ash generated from Australian coal fired power stations	14.5%	49,198	1,229,957
N220	Asbestos	10.7%	36,250	906,250
J120	Waste oil/water, hydrocarbons/water mixtures or emulsions	6.6%	22,291	557,267
D220	Lead; lead compounds	4.9%	16,622	415,553
C100	Basic solutions or bases in solid form	4.9%	16,530	413,253
D110	Inorganic fluorine compounds excluding calcium fluoride (SPL)	4.3%	14,613	365,318
D230	Zinc compounds	2.9%	9,840	246,008
	NORMs	2.2%	7,456	186,399
J100	Waste mineral oils unfit for their original intended use	2.2%	7,439	185,986
D300	Non-toxic salts	1.2%	4,003	100,080
B100	Acidic solutions or acids in solid form	0.8%	2,874	71,855
N160	Encapsulated, chemically-fixed, solidified or polymerised wastes referred to in this list	0.5%	1,742	43,550
F100	Waste from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish	0.5%	1,649	41,225
M100	Waste substances and articles containing or contaminated with polychlorinated biphenyls, polychlorinated naphthalenes, polychlorinated terphenyls and/or	0.3%	1,127	28,185

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
	polybrominated biphenyls			
N100	Containers and drums that are contaminated with residues of substances referred to in this list	0.3%	962	24,038
N190	Filter cake contaminated with residues of substances referred to in this list	0.2%	765	19,120
G110	Organic solvents excluding halogenated solvents	0.2%	584	14,606
M250	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials	0.1%	422	10,546
A100	Waste resulting from surface treatment of metals and plastics	0.1%	403	10,080
K140	Tannery wastes (including leather dust, ash, sludges and flours)	0.1%	356	8,899
F110	Waste from the production, formulation and use of resins, latex, plasticisers, glues and adhesives	0.1%	310	7,756
J160	Waste tarry residues arising from refining, distillation, and any pyrolytic treatment	0.1%	292	7,311
G160	Waste from the production, formulation and use of organic solvents	0.1%	235	5,885
R120	Waste pharmaceuticals, drugs and medicines	0.1%	234	5,842
M230	Triethylamine catalysts for setting foundry sands	0.1%	192	4,810
H100	Waste from the production, formulation and use of biocides and phytopharmaceuticals	0.1%	186	4,643
T100	Waste chemical substances arising from research and development or teaching activities, including those which are not identified and/or are new and whose effects on human health and/or the environment are not known	0.0%	168	4,197
N230	Ceramic-based fibres with physico-chemical characteristics similar to those of asbestos	0.0%	149	3,729
D120	Mercury; mercury compounds	0.0%	94	2,351
D190	Copper compounds	0.0%	77	1,916
D140	Chromium compounds (hexavalent and trivalent)	0.0%	69	1,720
R140	Waste from the production and preparation of pharmaceutical products	0.0%	57	1,434
K190	Wool scouring wastes	0.0%	51	1,265
M150	Phenols, phenol compounds including chlorophenols	0.0%	50	1,259
G150	Halogenated organic solvents	0.0%	49	1,217
N140	Fire debris and fire wash waters	0.0%	47	1,166

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
G100	Ethers	0.0%	46	1,152
T200	Waste of an explosive nature not subject to other legislation	0.0%	42	1,060
T120	Waste from the production, formulation and use of photographic chemicals and processing materials	0.0%	38	961
D330	Inorganic sulfides	0.0%	35	870
H110	Organic phosphorous compounds	0.0%	30	749
D130	Arsenic; arsenic compounds	0.0%	27	681
M220	Isocyanate compounds	0.0%	19	468
D360	Phosphorus compounds excluding mineral phosphates	0.0%	17	423
E100	Waste containing peroxides other than hydrogen peroxide	0.0%	17	413
D210	Nickel compounds	0.0%	13	314
M260	Highly odorous organic chemicals (including mercaptans and acrylates)	0.0%	12	312
H170	Waste from manufacture, formulation and use of wood-preserving chemicals	0.0%	12	293
D100	Metal carbonyls	0.0%	7	174
A130	Cyanides (inorganic)	0.0%	5	134
M210	Cyanides (organic)	0.0%	5	123
D270	Vanadium compounds	0.0%	5	122
M160	Organo halogen compounds—other than substances referred to in this Table or Table 2	0.0%	4	110
D150	Cadmium; cadmium compounds	0.0%	2	62
A110	Waste from heat treatment and tempering operations containing cyanides	0.0%	2	60
D160	Beryllium; beryllium compounds	0.0%	2	38
D350	Chlorates	0.0%	1	25
D170	Antimony; antimony compounds	0.0%	1	25
D250	Tellurium; tellurium compounds	0.0%	1	13
D340	Perchlorates	0.0%	0	9
D200	Cobalt compounds	0.0%	0	6
D310	Boron compounds	0.0%	0	5
D290	Barium compounds (excluding barium sulphate)	0.0%	0	3
D240	Selenium; selenium compounds	0.0%	0	1
D180	Thallium; thallium compounds	0.0%	0	1
M170	Polychlorinated dibenzo-furan (any congener)	0.0%	0	1
M180	Polychlorinated dibenzo-p-dioxin (any congener)	0.0%	0	1
T140	Tyres	0.0%	-	-

NEPM "75" code	Waste description (NEPM Schedule A, List 1)	Chandler Facility (%) [1]	Chandler Facility (tpa)	Chandler Facility (t LOM)
K100	Animal effluent and residues (abattoir effluent, poultry and fish processing wastes)	0.0%	-	-
K110	Grease trap waste	0.0%	-	-
K130	Sewage sludge and residues including nightsoil and septic tank sludge	0.0%	-	-
R100	Clinical and related wastes	0.0%	-	-

The substances in Table A1 have been screened to identify representatives for detailed analysis, using expert knowledge and Australian drinking water guidelines. Substances are identified in Table A2. Pesticides are considered separately. For both OPRA and the PCRA, substances of possible concern present in each waste type have been considered. Illustrative substances potentially of concern have been identified based on expert judgement and a consideration of substances typically included in environmental risk assessment (including a consideration of the substances included in Australian drinking water guidelines; Australian Government, 2015). The substances are then ranked 1-3 (low-medium-high) in terms of possible inventory, mobility and toxicological hazard (Table A2). The product of the three values is then used to derive an "index" value used to identify substances of greater importance, a subset of which is suggested for post closure assessment in particular. This approach gives the following top ten ranked contaminants:

1. Beryllium (score 12);
2. Chromium (as Cr(VI)) (score 12);
3. Dichloromethane (score 12);
4. Hexachlorobutadiene (score 12);
5. Mercury (score 12);
6. Benzene (score 9);
7. Epichlorohydrin (score 9);
8. Lead (score 9);
9. Molybdenum (score 8); and
10. Nickel (score 8).

When account is taken of the different chemical properties of these elements and their likely forms in solution, it is suggested that from this list the following elements are considered in more detail in the analysis:

1. Beryllium;
2. Chromium;
3. Mercury;

Quintessa

4. Benzene; and
5. Lead.

Table A-2: Substances potentially present in wastes (excluding pesticides/herbicides/fungicides), Australian drinking water guidelines, rankings (1-3) and index of potential impact (product of values for 1-3).

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Aluminium (acid soluble)	c	0.2	based on post-flocculation problems	3	1	1	3	component of waste metals, possibly high volume, low solubility, low toxicity, not suitable for hydraulic backfill
Ammonia	c	0.5	typically associated with sewage contamination/microbial activity	1	2	1	2	probably only present in small amounts, soluble in water
Antimony	0.003		guidelines note that exposure may rise with increasing use of antimony-tin solder	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils)
Arsenic	0.01		natural sources, mining/industrial/agricultural wastes	2	1	3	6	heavy metal, numerous possible sources likely to be solubility-limited, some degree of sorption to minerals likely, possibly encapsulated in hydraulic backfill in some waste streams (e.g. soils, mining wastes)
Barium	2		primarily from natural sources	2	2	1	4	possible associated with mineral scales from oil industry, mobility in environment depends on

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								sulphate availability
Benzene	0.001		human carcinogen	1	3	3	9	associated with petroleum products (one of the "BTEX" compounds), possible present in small amounts (trace level/as breakdown product), highly flammable .
Beryllium	0.06		fossil fuel burning	2	2	3	12	associated with specialist alloys, possibly anionic speciation in water and relatively higher mobility than other metals
Cadmium	0.002		industrial/agricultural contamination, impurities in galvanised (zinc) fittings, solders and brases	2	1	3	6	heavy metal, numerous sources (including soils, mining wastes), potentially solubility-limited, likely to sorb to minerals, some waste streams may be suitable for hydraulic backfill
Chloride		250		2	3	1	6	from rock salt, drinking water guideline based on aesthetics
Chlorobenzene	0.3	0.01	intermediate, solvent, taste/odour threshold lower than health based concentrations	1	3	2	6	possibly present as waste from chemical industry or solvent, soluble in water to some extent

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Chromium (as Cr(VI))	0.05		associated with industrial/agricultural contamination	2	2	3	12	Cr(VI) from industrial waste of greater concern than Cr(III), which is found in stainless steel, Cr(VI) generally of more concern via inhalation exposure so index value possibly a little unrepresentative
Copper	2	1	associated with metal pipe corrosion	3	1	1	3	could be present in relatively large volume compared to other metals for some waste streams, of less concern than heavy metals in terms of toxicological properties, likely to have low solubility in water
Cyanide	0.08		associated with industrial waste	1	2	3	6	cyanide associated with wastes, not clear as to how likely it is to be present, presumably in relatively smaller amounts
1,2 dichlorobenzene	1.5	0.001	chemical intermediate, may be used as a solvent in some applications; taste/odour threshold lower than health based concentrations	1	1	3	3	possibly from chemical industry, may be used as a solvent
1,3 dichlorobenzene	c	0.02	taste/odour threshold lower than health based concentrations	1	1	3	3	

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
1,4 dichlorobenzene	0.04	0.0003	disinfectant, pesticide odour threshold lower than health based concentrations	1	1	3	3	
1,2-dichloroethane	0.003		vinyl chloride manufacture, intermediate, solvent	1	2	3	6	possibly from chemical industry, may be used as a solvent, limited solubility in water
1,1-dichloroethene	0.03			1	1	3	3	possibly largely immobilized in hydraulic backfill depending on waste streams that are disposed in such a manner, poorly soluble in water
1,2-dichloroethene	0.06			1	1	3	3	
Dichloromethane	0.004		widely used solvent	2	2	3	12	volatile liquid
Epichlorohydrin	0.0005d		used in manufacture of resins for water treatment	1	3	3	9	possibly associated with waste from water treatment, moderately soluble in water
Ethylbenzene	0.3	0.003	component of petrol and petroleum products	1	2	2	4	associated with petroleum products, may be used as solvent, possibly present in trace quantities (flammable), partly soluble in water, can be mobile in sub-surface environment
Ethlenediamine tetraacetic acid (EDTA)	0.25		metal complexing agent commonly used in industry	1	3	1	3	presumably could be present as residue from cleaning metals/ other

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
								materials, mobile in the environment
Hexachlorobutadiene	0.0007		Industrial solvent	2	2	3	12	relatively greater potential toxicological hazard compared to other materials, could be present as solvent residue
Lead	0.01			3	1	3	9	heavy metal, could be associated with different waste streams, relatively low solubility under most conditions, neurotoxin
Manganese	0.5	0.1		2	2	1	4	possibly present in some metal wastes
Mercury	0.001		Industrial sources	2	2	3	12	possibly present in some waste streams (including as a lower volume mercury waste stream). Forms amalgams with some metals, native form volatile, limited solubility of oxidised species in water. International efforts to reduce use given toxicological hazard

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Molybdenum	0.05		associated with mining, agriculture and fly ash	2	2	2	8	chemical and metallurgical applications, associated with mineral residue in fly ash, can have relatively high solubility in water compared with other metals, possibly associated with waste streams that could be hydraulic backfill (e.g. soil)
Nickel	0.02			2	2	2	8	associated with many metal products, can have relatively high solubility in water compared with other metals
Di(2-ethylhexyl)phthalate	0.01		associated with PVC products, may leach from them over prolonged periods of time	2	2	2	8	possibly associated with plastics (plasticiser) and may leach from them
Benzo(a)pyrene	0.0001		can leach from bituminous materials (linings in water distribution systems)	2	1	3	6	genotoxic carcinogen, polycyclic aromatic hydrocarbon (PAH), very low solubility, sometimes found in drinking water that has been transport through systems containing bituminous materials
Styrene	0.03	0.004	associated with industrial contamination	1	2	2	4	volatile oily liquid, limited solubility in water

Substance (iii, iv)	Australian Drinking Water Guideline "Health" (i, ii) (mg/L)	Australian Drinking Water Guideline "aesthetic" (i, ii) (mg/L)	General comments	(1) Relative Amount	(2) Relative Mobility	(3)Relative Toxicity (based on "health" guideline values)	(4) index of possible impact (1x2x3)	Comments on Form, Disposal Route, Behaviour (post closure)
Tetrachloroethene	0.05		solvent (dry cleaning especially), degreaser	2	2	2	8	colourless liquid, possibility that it is present in small quantities in some waste streams, classed as a dense non-aqueous phase liquid (DNAPL)
Toluene	0.8	0.025	petrol, natural gas, industrial contamination	2	1	1	2	industrial solvent and feedstock, low solubility in water
Trichlorobenzenes(total)	0.03	0.005	solvent and precursor chemical	2	1	2	4	possibly associated with some wastes
Uranium	0.017		associated with mill tailings, combustion of coal	1	1	2	2	possibly present in mineral residue from coal combustion, likely to have relatively low solubility, especially under anoxic conditions, possibly in waste streams suitable for hydraulic backfill
Zinc	c	3	associated with corrosion of galvanised pipes/fittings and brasses	3	2	1	6	associated with numerous metals and alloys, possibly in waste streams suitable for hydraulic backfill

Key

(i)c = insufficient data to generate value

(ii)d = issues with detecting concentrations associated with health guideline

Agricultural wastes and soil could potentially include pesticides, herbicides, fungicides and related compounds. A large number of such substances exist with varying compositions and physico-chemical and toxicological properties. A number of representative substances have been selected based on potential for environmental impact (i.e. lower drinking water guideline values) and solubilities in water which is of particular relevant to post closure risk assessment modelling. The following substances have been considered in post closure modelling, given their relatively low drinking water guideline values and ranges of solubility in water:

- ▲ Dieldrin
- ▲ Fenamiphos
- ▲ Diquat

Table A-3: Representative pesticides and herbicides, types, Australian Drinking Water Guidelines and reported aqueous solubilities.

Substance	Australian Drinking Water Guideline mg/L	Type of material	Solubility (mg/L)	Source of solubility data
Aldrin (+dieldrin)	0.0003	organochlorine pesticide	0.011 (aldrin) 0.11 (dieldrin)	ATSDR (2002) Chapter 4 of Toxicological Profile for Aldrin/Dieldrin. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp1-c4.pdf
Heptachlor	0.0003	organochlorine pesticide	0.05	ATSDR (2007) Chapter 4 of Toxicological Profile for Heptachlor. Agency for Toxicological Substances and Disease Registry, US Department of Health. http://www.atsdr.cdc.gov/toxprofiles/tp12-c4.pdf
Profenofos	0.0003	organophosphorous pesticide	28	PUBCHEM Open Chemistry Database https://pubchem.ncbi.nlm.nih.gov/compound/profenofos#section=Top
Fenamiphos	0.0005	organophosphorous pesticide	700	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/jmpr/jmpmono/v074pr23.htm
Aldicarb	0.004	carbamate insecticide	6000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/0304_72/en/index3.html
Paraquat	0.02	herbicide	620 000	ICHEM (Chemical Safety Information from Intergovernmental Organizations) http://www.inchem.org/documents/icsc/icsc/eics0005.htm
Diquat	0.007	herbicide	718 000	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/diquat.pdf
Molinate	0.004	herbicide	880	World Health Organization (Water Sanitation and Health Database) http://www.who.int/water_sanitation_health/dwq/chemicals/molinate.pdf

The wastes that may be disposed of at the Chandler facility also include NORM (naturally-occurring radioactive material). NORM is the term used to describe materials that contain naturally-occurring isotopes at concentrations that might require consideration of their radioactive properties. Importantly, it does not include materials, products or by-products of the nuclear industry (e.g. uranium mine tailings). Key NORM radionuclides include potassium-40 and uranium and thorium and the radionuclides in their decay chain such as radium.

NORM is found in a wide variety of products (e.g. fertilisers) and process wastes (e.g. pipe scale in the oil industry). The concentration of NORM in most natural substances is low, but processing the resources can unintentionally concentrate NORM.

The Australian Radiation Health and Safety Advisory Council (2005) and Cooper (2005) discuss the occurrence of NORM in Australia. The main industries giving rise to NORM are oil and gas production, mineral sands processing (for the recovery of rare earth metals), titanium dioxide production, phosphate processing, and ash from coal. Typical ubiquitous concentrations of uranium and thorium series radionuclides are around 0.04 – 0.05 Bq/g. Concentrations in NORM can be tens of Bq/g or more.

The NORM wastes intended for the Chandler facility are understood to originate from the oil industry. A key characteristic of such wastes is the presence of enhanced concentrations of radium-226. This is the result of its precipitation (with barium) as a sulphate. It can take the form of sludges, films or hard scales. It may also be in secondary wastes generated when cleaning scale from equipment. Radionuclide concentrations vary widely, but are typically of the order of 1 Bq/g for sludges with higher concentrations (tens of Bq/g) in scales.

In 2005 around 200 m³ of such waste arose per year, with about 1% being the most hazardous hard scales. The volume is correlated to the amount of oil production, which has remained relatively static over the subsequent decade.

Appendix B: FEP List

A list of FEPs derived for the Chandler design concept is given in Table B-13-1 along with a list of potential EFEPs. The FEPs have been audited against those considered in a risk assessment for storage of municipal incinerator waste in salt caverns in the Netherlands (Metcalf et al., 2013).

A top-down examination of the main components of the process system suggests that the main FEPs of interest can be classified as belonging to the following main FEP groups.

1. Cavern zone (the caverns themselves, and the cavern rock).
2. Host geological environment.
3. Boreholes (including those boreholes used for backfill, and others).
4. Access shafts and ventilation system.
5. Biosphere and surface water bodies.

Table B-13-1: FEPs List

FEPs	Notes
1. Cavern zone 1.1. Room features 1.1.1. Roof 1.1.2. Pillars 1.1.3. Floors 1.1.4. Access tunnels 1.1.5. Rooms for disposal of waste 1.1.5.1. Containerised waste emplacement 1.1.5.2. Hydraulic backfill waste emplacement 1.1.6. Rooms for storage of wastes 1.1.7. Doors/seals/partitions 1.2. Room internal geometry 1.2.1. Change in geometry due to salt creep 1.2.2. Change in geometry due to loss of material from roofs 1.2.3. Change in geometry due to any salt dissolution/precipitation 1.3. Mobile and Fixed Infrastructure 1.3.1. Vehicles for excavation (continuous miner) 1.3.2. Vehicles for salt product 1.3.3. Vehicles for waste boxes 1.3.4. Other machinery for emplacement 1.3.5. Lighting 1.4. Salt product	Data supplied by Chandler Assuming bulkhead doors, potential partitioning of rooms Assuming diesel/petrol vehicles

FEPs	Notes
1.4.1. Halite 1.4.2. Containers 1.5. Wastes 1.5.1. Metal container for bags/barrels 1.5.2. Hydraulic backfill waste (HBW) 1.5.2.1. Backfill physical properties 1.5.2.2. Backfill chemical properties 1.5.2.3. Backfill mechanical properties 1.5.2.4. Contaminants 1.5.2.4.1. Heavy metals 1.5.2.4.2. Organics 1.5.3. Containerised Wastes 1.5.3.1. Containers (drums/bags) 1.5.3.2. Contaminants 1.5.3.2.1. Solid inorganics, includes Heavy metals/metalloids 1.5.3.2.2. Liquid inorganics 1.5.3.2.3. Organics, solid 1.5.3.2.4. Organics, liquid 1.5.4. Gas associated with wastes/waste degradation 1.5.5. Salt extraction processes 1.5.5.1. Excavation of salt 1.5.5.2. Underground transport of salt to access shaft 1.5.5.3. Removal of salt product via access shaft 1.5.6. Waste emplacement processes 1.5.6.1. Hydraulic backfilling 1.5.6.2. Underground transport of metal boxes of waste 1.5.6.3. Containerised waste emplacement 1.5.7. Hydraulic backfill consolidation and related processes 1.5.7.1. Geometry evolution 1.5.7.2. Chemical and physical properties evolution 1.5.7.2.1. Solids 1.5.7.2.2. Pore fluids 1.5.7.2.3. Contaminant release due to chemical or physical evolution during consolidation 1.5.7.2.3.1. Due to initial consolidation 1.5.7.2.3.2. Due to longer-term continued consolidation 1.5.7.2.3.3. Due to salt creep and waste pressurisation 1.5.8. Hydraulic backfill migration (liquid/uncured or solid) inc. response to cavern geometry change /pressurisation	T-B-C Type of barrels? Liquids? Assuming physical separation of hydraulically backfilled waste and containerised wastes For rooms with containerised waste

FEPs	Notes
1.6. Loose salt backfill 1.7. Void space 1.8. Workers 1.9. Advective flow/transport in hydraulic backfill (inc. contaminant transport) 1.9.1. Waters (inc. brine) 1.9.2. Gas 1.9.3. Other fluids (e.g. hydrocarbons) 1.10. Diffusive transport in backfill (inc. contaminant transport) 1.10.1. Waters (inc. brine) 1.10.2. Gas 1.10.3. Other fluids (e.g. hydrocarbons) 1.11. Contaminant retardation 1.11.1. Sorption/ de-sorption and cation exchange 1.11.2. Contaminant solubility / co-precipitation 1.11.3. Rock-matrix diffusion	
2. Geology 2.1. Salt deposit - halite 2.2. Salt deposit - impurities/ other minerals/interbeds 2.3. Overlying salt 2.4. Underlying salt 2.5. Confining salt 2.6. Overlying lithologies (including aquifers) 2.7. Underlying lithologies (including aquifers) 2.8. Hydrogeological properties 2.9. Chemical properties 2.10. Mechanical properties 2.11. Change in salt geometry due to creep 2.12. Change in salt geometry due to dissolution / precipitation 2.13. Fracturing/ faulting 2.14. Induced seismicity 2.15. Self-healing 2.16. Hydraulic gradients and pressures 2.17. Advective flow/transport (inc. contaminant transport) 2.17.1. Waters (inc. brine) 2.17.2. Gas 2.17.3. Other fluids (e.g. hydrocarbons) 2.18. Diffusive transport (inc. contaminant transport) 2.18.1. Waters (inc. brine)	Descriptions to be added

FEPs	Notes
2.18.2. Gas 2.18.3. Other fluids (e.g. hydrocarbons) 2.19. Contaminant retardation 2.19.1. Sorption/de-sorption and cation exchange 2.19.2. Contaminant solubility / co-precipitation 2.19.3. Rock-matrix diffusion 2.20. Temperature gradients	
3. Boreholes 3.1. Borehole walls 3.2. Borehole casing 3.3. Borehole backfill 3.4. Borehole seals 3.5. Borehole disturbed zone 3.6. Chemical evolution of borehole seals 3.7. Evolution of borehole seals 3.8. Corrosion of steel casings 3.8.1. Evolution of cement bonding 3.8.2. Evolution of the borehole seal 3.8.3. Physical deformation due to external stresses (e.g. rock creep) 3.8.4. Physical deformation due to chemical processes 3.8.5. Gas pressurisation within bores (due to corrosion, mechanical effects etc.) 3.8.6. Pressure gradients across seals 3.9. Contaminant pathways in borehole/damaged zone 3.10. Contaminate transport within disturbed zone 3.11. Residual contamination from borehole drilling	
4. Access shafts and ventilation system 4.1. Shaft wall rock 4.2. Ventilation system 4.3. Doors/partitions 4.4. Elevator 4.5. Elevator machinery 4.6. Workers 4.7. Shaft sealing materials 4.7.1. Concrete monolith 4.7.2. Seals	T-B-C
5. Biosphere and Surface Water Bodies 5.1. Environmental media (soil, surface water bodies, flora and fauna) 5.2. Workers at surface	

FEPs	Notes
5.3. Members of the public 5.4. Livestock 5.5. Surface run-off/floodwaters	

The “EFEPs” (external FEPs) that were identified are listed below:

1. **Future human actions** (e.g. accidental human intrusion);
2. **Exploitation of resources** (e.g. mining, water management);
3. **Neotectonics** (including seismicity, which may induce cavern instability);
4. **Climate and landscape change** (e.g. influence water table; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall); and
5. **Accidents and unplanned events (e.g. container drop/breach leading to spills)**
6. **Changes to the mine operational regime** (e.g. types of waste accepted, changes in facility concept)

Note that *deliberate* human intrusion, whereby a future human group might intentionally intrude into the wastes, is not considered as (a) such an action is highly unlikely to occur and (b) the risk involved would be the responsibility of the deliberate intruding party to manage. Thus, future human actions here focus on accidental intrusion, for example contact with wastes during borehole exploration for resources. This scenario is also, however, considered unlikely to occur.