Staged Risk Assessment of Salt Cavern Stabilisation, Phase 1:

Contribution to the Pilot Stabilisation Caverns Twente (PSTC) Project

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Executive Summary

This document reports work carried out during Phase 1 of a two-phase project to assess the risks that would be associated with stabilising unstable salt caverns in the Twente region of the Netherlands. Whether or not the second phase is undertaken will depend partly upon the outcomes of the first phase. The work is a contribution to AkzoNobel's Pilot Cavern Stabilisation Twente (PSCT) project.

The PSCT project aims to determine the feasibility of stabilising salt caverns developed in the Twente region of the Netherlands during brine production. The caverns to be stabilised were developed by AkzoNobel during the 1960's and 1970's, and have not yet migrated significantly due to roof collapse. Stabilisation will involve backfilling the caverns with a slurry made from brine, materials produced by waste-to-energy plants (e.g. fly ashes, flue gas cleansing salts), and possibly a cementitious material that will harden. Initially, only materials from a waste-to-energy plant operated by Twence BV are being considered for use in the backfill. However, if the project develops beyond the pilot stage, in future materials from other waste-to-energy plants may be considered for use in backfill. The plant operated by Twence BV lies within the area of land that potentially will be influenced by unstable caverns.

The two phases of the risk assessment aim to:

- Phase 1: identify significant risks to provide a basis for AkzoNobel's project team to decide upon the feasibility of cavern stabilisation by the proposed method; and
- Phase 2: based on the risk assessment in Phase 1, develop risk management and monitoring plans arguments thereby contributing to a permit application to the Dutch regulator, should the decision be taken to proceed with pilot-scale cavern stabilisation.

To achieve the objectives of the assessment a systematic work programme was followed in Phase 1 to:

- identify safety criteria;
- identify risks associated with the proposed backfilling;
- rank these risks in terms of their significance for the overall success of backfilling, *supported by clear justifications for the ranking*;
- determine whether any of these risks are likely to be sufficiently large as to call into question the viability of stabilisation by backfilling;
- quantify the risks as far as practicable;
- provide well-justified and documented arguments for conclusions about risks, presented in a fashion that is appropriate to support a permit application.

The conclusions from the Phase 1 work, which are based on information available at the on 1st January 2013, are:

- Strong confidence exists that the proposed backfilling stabilisation methodology will be safe and effective.
- No issues have been identified that would definitely call into question the feasibility of the methodology, but uncertainties remain that can be addressed by additional investigations (e.g. assessment of actual backfill formulations, acquisition of hydrogeological information etc.).
- There is some evidence that suggests there are small remaining risks to performance. In the main this reflects the potential for contaminants to migrate from the backfill into the shallower water resources. These risks can be further reduced by:
    - adopting more realistic assumptions in the numerical models that underpin the assessment based, for example, on additional information about the natural and engineered systems; and
    - development of a risk management plan.
- Key uncertainties that remain concern:
    - fluid flow driving forces (specifically head gradients);
    - contaminant transport retardation parameters (specifically sorption coefficients);
    - the existence or otherwise of flow paths; and
    - the mechanical requirements and performance of the backfill itself.

The uncertainties will be considered in further work, which will include:

- a review of retardation parameters;
- more detailed consideration of potential driving forces and flow paths, including hydrogeological scoping calculations, which will inform additional assessment calculations; and
- backfill formulation development, geotechnical testing and analysis work, the outcomes of which will be integrated into the assessment.

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1 Introduction

As a contribution to its “Pilot Stabilisation Caverns Twente” (PSCT) project, Akzo Nobel Industrial Chemicals B.V. (henceforth “AkzoNobel”) has contracted Quintessa to undertake a structured risk assessment of a proposed salt cavern stabilisation methodology. The PSCT project aims to determine the feasibility of stabilising unstable salt caverns developed in the Twente region of the Netherlands during brine production. The unstable caverns were developed by AkzoNobel during the 1960’s and 1970’s and have the potential to cause significant subsidence due to upward migration instigated by roof collapse. Stabilisation will involve backfilling the caverns with a slurry made from brine, materials produced by waste-to-energy plants (e.g. fly ashes, flue gas cleansing salts), and possibly a cementitious material that will harden. Initially, only materials from a waste-to-energy plant operated by Twence BV are being considered for use in the backfill. However, if the project develops beyond the pilot stage, in future materials from other waste-to-energy plants may be considered for use in backfill. The plant operated by Twence BV lies within the area of land that potentially will be influenced by the unstable caverns.

The assessment is divided into two phases:

- Phase 1: Identification of significant risks; and
- Phase 2: Development of risk management and monitoring plans.

Both of these phases concern only sub-surface risks.

The present document reports the findings of the first phase. This phase aims to identify safety criteria and whether or not there are any risks that could call into question the safety and effectiveness of the proposed cavern stabilisation method. Phase 1 aims to define safety criteria and to identify and rank all technical risks associated with sub-surface aspects of cavern stabilisation, *together with a detailed explanation for the ranking*. The phase is generic in so far as the assessment would be relevant to any of the unstable caverns within the Twente region for which AkzoNobel is responsible.

The second phase will focus more specifically on the three selected caverns to be considered for the pilot stabilisation and will aim to provide risk management and monitoring plans based on the documented risk assessment. These outputs will be in a form that could be used as part of a permit application, specifically presented using the Bow-Tie methodology. This second phase will be reported in separate documents.

2 Approach

Initially, detailed discussions took place between staff from AkzoNobel and Quintessa in order to develop and document a shared vision about the context and scope. Once the context and scope had been documented, the assessment then built on initial risk assessment work undertaken previously by AkzoNobel and reported in Hendriks et al. (2012). The work also drew on previous risk assessments reported in van Duijne et al. (2011a,b) for gas oil storage in broadly similar (but stable) caverns to those proposed for backfilling.

The assessment progressed systematically from an evaluation of information about the geology of the Twente region where the caverns occur, and the proposed backfilling methodology, to the development of structured arguments about risks. These structured arguments were based upon evaluations of both qualitative and quantitative information. An important aspect of the approach was the development of a fully documented audit trail, so that all conclusions about risks can be linked to the evidence base transparently and appropriately questioned by stakeholders.

The assessment approach followed these steps:

1. assemble information concerning:
    - the geology and hydrogeology of the Hengelo area in general, and about the PSCT in particular (Section 4);
    - previous assessment work (Section 5); and
    - relevant general published information about the state of knowledge concerning cementitious backfilling materials and their behaviours in the presence of highly saline groundwater (Section 6);
2. structured and comprehensive analysis of all potentially relevant Features, Events and Processes (FEPs) leading to identification of all key risk-influencing factors (Section 7, Appendix A);
3. scenario development to bound ranges of plausible evolutions and bracket uncertainties (Section 7);
4. development of conceptual models for interactions among FEPs within each scenario (Section 8);
5. scoping calculations undertaken to explore scenarios (Section 9); and
6. structuring of risk arguments using Evidence Support Logic (ESL) (Section 10).

3 Assessment Context

3.1 Requirements of AkzoNobel

The project needs to deliver to AkzoNobel a clear statement about the risks associated with the pilot cavern stabilisation project, together with supporting documentation of the evidence base and rationale. The immediate purpose is to inform key decisions that are intended to be taken in late 2012. Specifically, the level of confidence that can be placed in performance, on the basis of available evidence, needs to be clearly articulated in a timely fashion. Any factors that might call into question the feasibility of backfilling need to be communicated to AkzoNobel immediately as soon as they are identified. Therefore, the assessment needs to be undertaken systematically such that all relevant risks are identified, prioritised and assessed in priority order such that any ‘show-stoppers’ are identified at the earliest possible stage.

The project also needs to recognise regulatory requirements such that the outputs help to support:

- discussions between AkzoNobel and the regulator; and
- preparation by AkzoNobel of relevant documentation, including an eventual permit application if the decision is taken to proceed with pilot-scale stabilisation.

Health and safety risks during operations are outside the scope of the assessment. Similarly, it is not within the scope of the project to assess the risks associated with alternative treatments / uses of the waste materials from the Twence B.V. plant, in the event that they are not used to produce backfill. The work concerns only with underground processes connected with cavern backfilling by the proposed method and their associated environmental risks.

A “do nothing” reference case is an important part of the assessment, but this should consider only the caverns and surrounding sub-surface environment, and not risks associated with not using the waste materials from the Twence B.V. plant as backfill.

3.2 Stakeholders

Stakeholders in the project include State Supervisor of Mines (SSM), TNO and the Dutch Ministry of Economic Affairs. Both SSM and TNO have regulatory roles. If the evidence presented to SSM in support of an application to proceed with backfilling is sufficient to persuade SSM that technical (wells, above-ground infrastructure) and regulatory (risk assessment, risk management plan) requirements are met, then SSM will advise to the Ministry to grant the permit. TNO will give independent advice to the Ministry on the quality of the permit application from a geotechnical point of view (geology, geochemistry, geophysics).

3.3 Regulatory Requirements

The Dutch National Waste Management Plan '09-'21 (LAP-2) states that:

"Waste materials can be useful applied in the deep subsurface for example when old mineshafts or salt caverns are backfilled to mitigate the risk of collapse or challenging stability. The instability makes backfilling necessary and by using waste primary resources are saved."

and

"…a pilot project can be carried out with the aim to determine which waste materials, not originating from the local subsurface, can be applied in principle for the stabilisation of a (potentially) unstable cavern without environmental risk."

(LAP-2, paragraph 21.17.3, page 188)

Thus it is stated that there should be *no* environmental risk. When interpreting what this requirement means in practice, SSM use the concept of "as low as reasonably practicable" (ALARP).

3.4 Timescales

If undertaken, the pilot backfilling project will probably last 6 – 7 years, which is approximately the time it takes to backfill the three caverns. During the first 2 years waste materials from the Twence B.V. energy from waste plant will be used to prepare the backfill. Thereafter materials from other sources will be needed to make the backfill since the Twence B.V. facility produces only about 20,000 tonnes of waste per year, which will be insufficient to prepare the required volumes of backfill.

The specific timescale that the risk assessment must consider is undefined, but the regulatory requirements in Section 3.3 that the backfilling must not cause any environmental risks implies that the assessment must consider the entire period for which the backfilled caverns are likely to exist. While in principle this means timescales of millions of years, a practical approach is to demonstrate that risks will remain negligible for a period of 10,000 years. This period is sufficiently long that trends in site evolution will be established by the end of the period and probably the internal processes driving this evolution will have approached a steady state.

3.5 Backfilling Plans

Only caverns that are judged to be unstable and are predicted to collapse in future will be stabilised. Caverns that have already started to collapse will not be stabilised because it will be impossible to achieve stabilisation through backfilling under these circumstances. However, it is not clearly defined when the fall of material from the roof of a cavern is deemed to be sufficient to constitute cavern collapse. To be considered a collapse, this fall of material would need to continue for a sufficiently long time for there to be the eventual development of a column of rubble extending the ground surface. It follows, therefore, that a small initial fall of material at a decreasing rate and eventually stopping altogether (that is, before a rubble column develops sufficiently far that the overlying rocks cannot support their own weight), would not be cavern collapse.

Backfilling plans have not been finalised. Probably backfilling will be accompanied by monitoring of consolidation, but the most appropriate method has not yet been identified. Possibly microseismics will be used to be able to detect roof collapse in caverns for a period of 1 – 2 years before backfilling commences. Work to develop a baseline is also on-going. Backfilling plans will be very similar from cavern to cavern, but backfilling may take place with layers of backfilling having different physical properties (related to different grain size).

Phase 1 of the assessment should not consider alternative backfill compositions, but only one based on the waste materials from the Twence B.V. plant. The backfill will be injected through an appropriate borehole, with remaining brine being extracted from the caverns at the same time. The extracted brine will be evaporated to form residual slurry that will then be returned to the cavern with the backfill. The backfill will self-consolidate under its own weight and as a result of chemical hardening/curing effects. As backfilling of each cavern is completed, the boreholes used for brine extraction and backfill injection will be sealed. After sealing, self-consolidation may continue. There may be some residual cavern migration as it will not be feasible to achieve 100% backfilling of all caverns, but the base assumption (to be tested in the risk assessment) is that future mechanical evolution of the caverns will not be significant. This is because it is assumed that the backfill will be effectively contained and will provide the required mechanical properties. The response of the system to backfilling will be subject to monitoring.

In addition, a further assumption (also to be tested through the risk assessment) is that the process will not pose a significant environmental risk during or after backfilling.

The description of the backfill process above is generic. For the assessment it will be important to understand the rate at which it is intended to backfill the ‘potential sink-hole’ caverns identified, and associated prioritisation arguments. Indeed, an outcome of the work will be to inform updates to this prioritisation.

3.6 Previous Assessment Work

AkzoNobel has already undertaken some initial risk assessment (Hendriks et al., 2012). This concerned use of an expert elicitation process to identify key risks. The risks were classified as “major” or “minor”. Additionally, some work has been undertaken by AkzoNobel to assess the safety of proposed gas oil storage in caverns that are broadly similar to the ones proposed for backfilling. This gas oil storage-related assessment is described in van Duijne et al. (2011a,b).

4 Information and Data

AkzoNobel supplied the data and information given in Table 4-1 below. This information was used to inform the development of scenarios (Section 7) and conceptual models based on these scenarios (Section 8), and to carry out scoping calculations (Section 9). The information also helped to inform reviews of previous assessment work (Section 5) and expert judgements as to the safety and effectiveness of the proposed backfilling (Section 10).

Most of the information supplied was used qualitatively. However, numerical information, concerning the chemical compositions and physical properties of the backfill and the physical properties of the rock mass, was used to support quantitative aspects of the assessment.

Table 4-1: Information and data supplied by AkzoNobel to support the assessment

Reference	Information	Application
Pinkse and Groenenberg – PowerPoint presentation entitled "Pilot Stabilisation Caverns Twente (PSCT) Rationale & Storyline"	Rationale and outline plans for the PSCT project	The information in this PowerPoint presentation was used as an input to developing scenarios.
Table of potentially unstable caverns (supplied in Microsoft Excel file: "Table of potentially unstable caverns.xlsx")	Locations, depths, development times, completion details and details of salt, for potentially unstable caverns	The range of potentially unstable cavern dimensions was used to inform judgements about the general validity of scoping calculations.
Map of the area of direct interest (in a pdf file entitled "Area of direct interest.pdf")	Locations and horizontal dimensions of caverns of interest to the project, including the lateral extents of salt pillars between adjacent caverns	Knowledge of the lateral extents and relative positions of the caverns was used in specifying scenarios and in defining scoping calculations. The map was used to help constrain the dimensions of the generic cavern considered in the scoping calculations and the separation of this cavern from adjacent caverns in the cavern interaction scenario.
Map of all caverns in the Hengelo area (in a pdf file entitled "Cavern map.pdf")	Locations and horizontal dimensions of caverns of interest to the project, including the lateral extents of salt pillars between adjacent caverns	Knowledge of the lateral extents and relative positions of the caverns was used in specifying scenarios and in defining scoping calculations. The

Reference	Information	Application
		map was used to help constrain the dimensions of the generic cavern considered in the scoping calculations and the separation of this cavern from adjacent caverns in the cavern interaction scenario.
Maps and cross sections of caverns (the latter determined from sonar) (in a PowerPoint file "Screenshots sonar contours v2.pptx")	Dimensions of caverns of interest to the project	Knowledge of the dimensions and relative positions of the caverns was used in specifying scenarios and in defining scoping calculations. The cavern dimensions enabled the volumes of backfill to be specified in the calculations and the separation of this cavern from adjacent caverns in the cavern interaction scenario.
Map of caverns judged to be unstable (in a pdf file "Stability map.pdf")	Locations and horizontal dimensions of caverns judged to be unstable, including the lateral extents of salt pillars between adjacent caverns	Knowledge of the lateral extents and relative positions of the caverns was used in specifying scenarios and in defining scoping calculations. The map was used to help constrain the dimensions of the generic cavern considered in the scoping calculations and the separation of this cavern from adjacent caverns in the cavern interaction scenario.
Hendriks et al. (2012)	Details of scenarios developed prior to the present work; threats, as judged by experts, to safe and effective backfilling.	An independent review of this earlier work was carried out. Checking this earlier work against the new scenarios helped to build confidence that no important processes had been missed.
Duijne van et al. (2011a)	General information about the nature of caverns developed in salt deposits	The information contained was used as one basis for the development of

Reference	Information	Application
	in the eastern Netherlands and potential fluid pathways. The caverns and the rock sequences within which they are located are similar to those considered in the present study.	scenarios in the present report.
Duijne van et al. (2011b)	General information about the nature of caverns developed in salt deposits in the eastern Netherlands and potential fluid pathways, including hydrogeological parameter values. The caverns and the rock sequences within which they are located are similar to those considered in the present study.	The information contained was used as one basis for the development of scenarios in the present report. The hydrogeological parameter values were used as a basis for the hydrogeological parameter values employed in the present study.
Goodman et al. (2006)	Geology of the salt deposits in the Hengelo area	General information used in defining scenarios, particularly concerning the stratigraphy, the nature of the salt deposits themselves and the overburden between the Röt Salt and the basal Tertiary.
GEOWULF Laboratories (2007)	Lithological and stratigraphical information for the Hengelo area	General information used in defining scenarios, particularly concerning the stratigraphy, the nature of the salt deposits themselves and the overburden between the Röt Salt and the basal Tertiary.
GEOWULF Laboratories (2008)	Lithological and stratigraphical information for the Hengelo area	General information used in defining scenarios, particularly concerning the stratigraphy, the nature of the salt deposits themselves and the overburden between the Röt Salt and the basal Tertiary.
GEOWULF Laboratories (2010)	Geological description of the brine field in the Hengelo area, plus	General information used in defining scenarios, particularly concerning the

Reference	Information	Application
	supporting geological logs and maps	descriptions of geological structures.
GEOWULF Laboratories (2011)	Geological description of the brine field in the Hengelo area, plus supporting geological logs and maps	General information used in defining scenarios, particularly concerning the descriptions of geological structures.
Giesen and Vrouwe (2009)	Seismic interpretation of the Röt Salt in the Hengelo – Entschede area of the north-eastern Netherlands	Background information used in the development of scenarios
Well logs from the PSCT area	Wireline well logs	Background information underlying development of scenarios
Geluk et al. (1994)	Stratigraphy and tectonics of the Roer Valley	Information on the tectonic setting was used as a guide in scenario development.
Schléder and Urai (2005)	Structural setting of the Röt Salt in the Hengelo area and details of the composition of mechanical characteristics of this salt	Information about the characteristics of the salt deposits used as an input to scenario development.
Halliburton (1982)	Pressure test in the Bunter Sandstone in well 313	The pressure data were used to estimate the hydraulic gradient for use in scoping calculations.
Rantzsch et al. (2011)	Qualitative and quantitative phase analyses of waste materials	Information about the phase composition of the waste material was used as general background information to assess the kinds of leachates that will be produced in the backfill.
K-UTEC (2011a) (25 separate pdf files)	Analyses of squeezed porewaters from the proposed backfill mix and the grain size distribution and other physical properties of this mix. Also analyses of organic constituents of the mix	These analyses were used to guide the choice of porewater composition for use in calculations of heavy element solubilities and to estimate levels of heavy metal contamination that might arise in shallower formation fluids. Additionally, physical properties of the backfill mix were used to guide judgements about the quantity of leachate for a given amount of squeezing.

Reference	Information	Application
K-UTEC (2011b) (in pdf file Porenfluid AN 08_AN 14.pdf)	Analyses of squeezed porefluid from samples AN08 and AN14	Compositions of AN08 porewater were used in geochemical calculations aimed at identifying the solid phases that might potentially control the aqueous concentrations of contaminants. The analyses were also used as the basis for the concentrations of heavy metals used in the scoping calculations to explore scenarios.
Lindenau and Pinkse T (2012)	Presentation on the development of the backfill recipe	The information on the backfill recipe was used to help define scenarios. The AN08 porewater composition reported in this document was used for solubility calculations.
K-UTEC (2012)	Extract of a spreadsheet (file name: Ergebnisse Dispermat BMC Akzo.pdf) containing analyses of squeezed porewater from the proposed backfill mix	Heavy metal compositions of the porewater squeezed from the backfill were used to calculate levels of heavy metal contamination that might arise in shallower formation fluids.
Fliss et al. (2010)	Description of the Hengelo brine field, initial geomechanical calculations and recommendations for stabilisation	The reported results of the geomechanical calculations were used as background information for the development of scenarios.
Drost (2012)	Geomechanical properties of a proposed backfill material and a numerical model for backfill consolidation and cavern migration	The reported geomechanical properties and the results of the geomechanical calculations were used as background information for the development of scenarios.
Odeometer test results for various backfill mixes (in pdf file "Oedometerversuche AKZO_13-08-12.pdf")	Odeometer test results for various backfill mixes	The odeometer test results were used as background information when developing scenarios for the consolidation of the proposed backfill.
Brückner (2012)	Description of the geomechanical factors influencing the stability of salt caverns	The description of the geomechanical factors influencing cavern stability was used as background

Reference	Information	Application
		information when developing scenarios for the development of a collapse column.
Eickemeier and Heusermann (2003, 2004)	Information on the mechanical deformation of the Röt Salt and overburden	Information about the deformation of the Röt Salt and overburden was used to help develop scenarios and conceptual models for cavern collapse and the evolution of a rubble column above a collapsed cavern.
Bekendam (2005, 2009)	Information about the compaction of a rubble column above a collapsed cavern and models for subsidence	Information about the compaction of the rubble column above a collapsed cavern was used to help develop scenarios and conceptual models for cavern roof collapse and propagation of the collapsed zone.

5 Review of Previous Risk Assessment Work

5.1 Introduction

This section summarizes briefly a review of the previous work undertaken by AkzoNobel to assess the risks associated with the proposed cavern backfilling method and reported in Hendriks et al. (2012). Also covered are assessments of risks connected with the proposed underground storage of gas oil in the Twente area (Duijne et al., 2011ab). Although these latter assessments concern stable caverns, it was appropriate to review the assessments to identify any information relevant to cavern backfilling that had been covered. The purpose of the reviews was to determine any relevant omissions from the previous work that should be targeted by the assessment described here, and ensure that the present work did not needlessly replicate earlier studies.

5.2 Previous PSCT Risk Assessment

The previous risk assessment work for the PSCT, which is documented in Hendriks et al. (2012) has:

- defined scenarios for possible containment loss in a backfilled storage cavern;
- described possible effects of containment loss; and
- classified threats to safe and effective cavern backfilling according to whether they are judged to be "major threats" or "minor threats".

The approach of Hendriks et al. (2012) was based on an expert workshop, held on 1st December 2011 and attended by 20 participants with wide-ranging relevant expertise (e.g. in the fields of geology, hydrogeology, geomechanics, risk assessment etc.). These participants discussed sub-surface technical, geological and hydrogeological risks associated with the proposed backfilling and gave their opinions about these risks. At the end of the meeting, 17 of the participants considered the PSCT to be feasible, while the remaining 3 were undecided.

The workshop considered only the risks associated with a failure of a backfilled cavern to contain potential contaminants within the backfill material and prevent them from leaking into the surrounding groundwater. That is, the risk of surface deformation due to collapse of the residual headspace following backfilling was not considered. The risks due to loss of containment were analysed qualitatively using a bow-tie model (Figure 5-1), but no quantitative analyses were undertaken. According to this model, each possible cause of containment loss corresponds to an "incident", which is represented in the centre of a "bow-tie". For each incident the possible causes and effects were identified and represented on the left and right of the bow-tie respectively (Figure 5-1). In each case required analysis and control measures to reduce uncertainty, probability of failure and impact were also proposed and represented within the model (Figure 5-1). The combination of an incident and its associated causes and effects represented a scenario. However, the actual bow-tie developed is not presented in Hendriks et al. (2012).

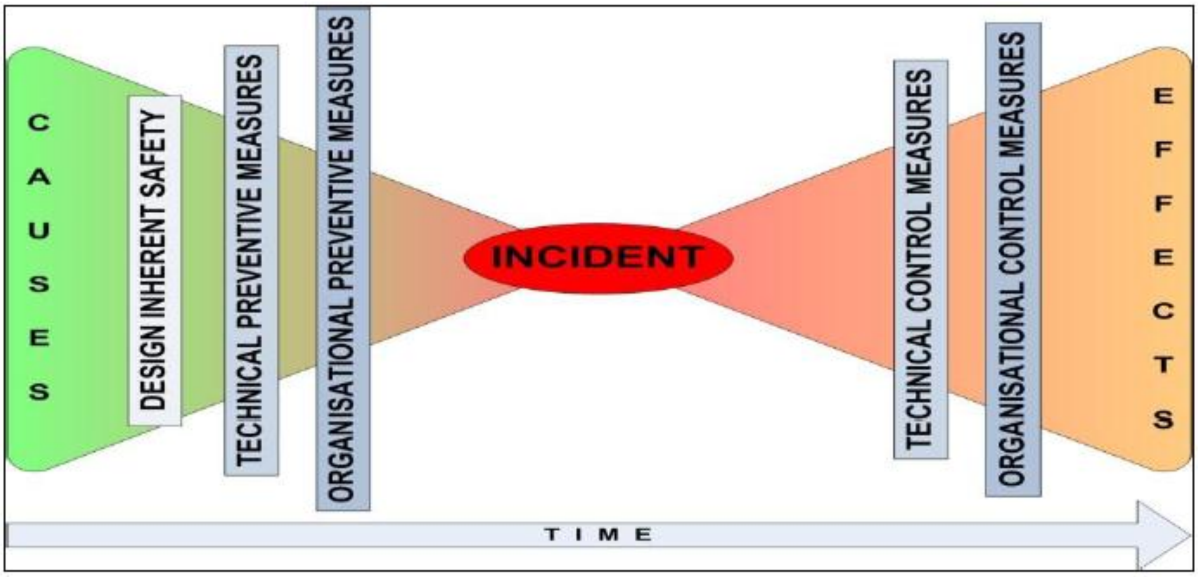


Figure 5-1: The bow-tie model used by Hendriks et al. (2011).

Following the workshop, experts from TNO and Deltares, who convened the meeting, then developed a list of threats. This list was sub-divided into major threats that it was considered necessary to analyse in detail, and minor threats that it was considered sufficient to investigate more generally (Table 5-1).

Table 5-1: Summary of major and minor threats to safe backfilling identified by Hendriks et al. (2011).

Threats	Major	Minor
A. Failing backfill resulting in cavern migration	X	
B. Leakage along rubble column of migrating cavern	X	
C. Leakage along wells	X	
D. Leakage along faults	X	
E. Leakage into Solling Formation (beneath the cavern)		X
F. Temperature change resulting in cavern instability		X
G. Leakage along hydraulic fractures in cavern walls		X
H. Leakage through permeable layers in cavern walls		X

The work concluded that only two kinds of failure would give rise to serious risks:

- Cavern migration and leakage of brine-backfill mixture into the upper groundwater bodies;
- Cavern migration and leakage of brine-backfill mixture into the Muschelkalk in combination with the presence of permeable structure(s) that are in contact with the

Muschelkalk such that a migration path is created for the brine-backfill mixture to the upper groundwater bodies.

The work listed the factors that would determine the impacts of contaminants that originate in the backfill and leak into the shallower groundwater system. These factors were grouped into scenarios. The scenarios were then ranked in terms of their perceived degree of risk; "High risk scenarios", "Medium risk scenarios" and "Low risk scenarios" were distinguished, based predominantly on the level of impact that they would have if they occurred, rather than the probability of a scenario occurring.

These levels of risk were based only on expert judgements rather than a quantitative assessment and the detailed approach used to make the judgements is unclear from Hendriks et al. (2012). However, Hendriks et al. (2012) did recognize the limitation of relying solely upon qualitative expert judgements and made recommendations for analysing the scenarios more quantitatively. They proposed that an inventory of the effects of contaminant release, including "decisive factors", should be developed, followed by scenario analyses and risk quantification of all scenarios based on a combination of hydrogeological modelling and contaminant transport modelling. In summary, their recommendations for further work concerned:

1. compilation of a conceptual model;
2. establishment of criteria for the containment boundary and confining layer(s) to prevent leakage;
3. undertaking a complementary literature study on potential risks of loss of containment with respect to both the cause and effect;
4. consolidation of identified risks associated with causes of loss of containment (leakage) and analysis of likely scenarios (this may include additional expert interviews);
5. semi-quantitative risk assessment of the causes of loss of containment (this may include additional expert interviews);
6. identification of risks associated with effects of loss of containment and analysis of likely scenarios;
7. quantification of effects of loss of containment;
8. literature study on monitoring and remediation techniques; and
9. compilation of a checklist for case-specific risk analysis of backfill containment.

5.3 Assessment of Underground Gas Oil Storage

Certain stable salt caverns within the Twente area are being considered as possible underground stores for gas oil (van Duijne et al., 2011a,b). Clearly this storage would have fundamental differences to the proposed backfilling of unstable caverns as part of the PSCT, notably:

- Gas oil will be stored only in caverns that are judged to be stable, so that there is no danger of collapse during operations.
- Gas oil is less dense than the groundwater within the area and hence would be buoyant, meaning that there is no potential for downwards migration into the Solling Formation, and very limited potential for lateral migration; any unexpected migration would be dominantly upwards.
- Gas oil would not be retained permanently within the caverns since the intention is that emplaced gas oil would be removed for consumption, unlike the proposed backfill to be used in potentially unstable caverns, which will be emplaced permanently.
- Gas oil has no mechanical strength, unlike the backfill proposed for use in unstable caverns.

Nevertheless, there are certain similarities between some of the risks from the proposed gas oil storage and the proposed backfilling. In particular, potential pathways for broadly upwards gas oil leakage are anticipated to be similar to those for potential upwards leakage of backfill porefluid and/or backfill.

Van Duijne et al. (2011a) described a technical risk assessment for the proposed gas oil storage based on the Secondary Use of Caverns Containment Concept (2UC-CC). The containment concept describes all the barriers and facilities that would cause the stored gas oil to be retained within a salt cavern. The concept was analysed using bow-tie models to represent different scenarios by which containment could be compromised.

Expert judgement was used to create a set of scenarios by which it is plausible containment might be lost, and then to sub-divide these scenarios into those considered more likely and those considered less likely. The former group of scenarios was then analysed in more detail, including by quantitative methods, while the latter group of scenarios were analysed more generally (qualitatively). The expert judgements were captured by means of a series of interviews with experts and a workshop.

Table 5-2: Overview of containment loss scenarios developed by van Duijne et al. (2011a).

Pathways for Detailed Analysis	Pathways for General Analysis
Flux through cavern walls	Salt creep
Flux through cavern floor	Temperature effects
Flux through cavern roof	Flux through the well (packers)
Flux through the well (casing show)	
Flux through faults	

Leakage through the wellbore was considered to be a major risk in the storage of gas oil in salt caverns, although it was noted that leakage through packers has rarely occurred in other, similar hydrocarbon storage projects. In contrast leakage through the walls of the cavern was considered unlikely since pressures during operations can be managed suitably to prevent this and caverns can be chosen to ensure that salt pillars between adjacent caverns are sufficiently thick (at least 25 m). Furthermore in the Twente area, permeable layers in between the rock salt layers have not been observed. Leakage through faults was ruled out on the grounds that faults in salt will be impermeable and self-sealing. 10 m. A detailed study of the fault structures was also used to support the conclusion that major faults to the northeast and southwest of the area of salt solution mining are unlikely to affect the caverns.

The assessment considered the possibility that methane might be released from the salt during cavern, since this phenomenon has been observed during the development of brine caverns elsewhere in the world. However, it was concluded that methane release from the Röt halite has never been observed in the Twente area. As a result this process was not analysed further.

The effects of leakage, if it should occur, were analysed using the multi-phase flow simulation software STOMP (Lenhard et al., 1995; White et al., 1995). These simulations considered a worst case in which leakage from the storage cavern occurred for 30 years, after which the leak ceased, but already leaked gas oil was allowed to disperse in the geosphere. Simulations were run for periods of up to 10,000 years in order to determine how leaked gas oil might behave. This numerical work concluded that only in the following circumstances would gas oil actually enter the shallower aquifers from which drinking water might be extracted:

- leakage from the well below the hydrogeological base into a fault with relatively high permeability; and
- leakage from the well above the hydrogeological base.

The probability that each of the various scenarios would occur was estimated by a semi-quantitative approach, using a combination of expert judgements and information on past incidents at underground hydrocarbon storage facilities throughout the world. A probability of failure model was developed, which showed the probability of containment failure to be very small and human error to be the most likely ultimate cause of failure.

5.4 Implications for the Present Phased Risk Assessment

The initial risk assessments reported in Hendriks et al. (2011) and in van Duijne et al. (2011a,b) provide useful background information for the present project. Central to the initial assessment in Hendriks et al. (2011) is a qualitative analysis of potential leakage paths. However, the conclusions reached require further justification. In particular the reported assessment process does not explain fully what steps were taken to ensure that no important phenomena that might influence risks have been overlooked. Furthermore, there are no analyses of potential driving forces for leakage of contaminants, nor of sensitivities of system behaviour to uncertainties about system characteristics. Understanding these sensitivities is important for developing proper risk management and monitoring plans. Consequently, the review justifies the present work focussing on a more structured and transparent qualitative analysis of the proposed backfilling methodology, accompanied by calculations to explore sensitivities of contaminated leakage to uncertainties in system properties.

The limitations of the initial assessment work were, to a large degree, recognized by Hendriks et al. (2011), as is implicit in their recommendations for further work (Section 5.2). To address these limitations, the project reported in this document generally followed these recommendations except for the literature review of monitoring and remediation techniques (Item 8 in the list of Hendriks et al. (2011); Section 5.2). This review will be undertaken in Phase 2 of the work. Also, to reflect the ways in which the recommended activities are logically related to one another they were ordered differently to the list of Hendriks et al. (2011), as described in Section 2.

The assessment for the gas oil storage project reported in van Duijne et al. (2011a,b) contains useful information about the geosphere and in particular the characteristics of possible pathways by which contaminants may leave a cavern and subsequently migrate. Therefore, the information reported in Duijne et al. (2011a,b) will be especially relevant to the development of a bow-tie model describing threats, hazards and potential consequences connected with cavern backfilling, which will be developed in Phase 2 of the project. Additionally, the possible monitoring methods described by these authors are mostly relevant to the proposed cavern backfilling and therefore this source can be used as an input to the development of a monitoring plan during Phase 2 of the project.

The development of multi-phase flow models during the assessment reported by Duijne et al. (2011a) was appropriate for the gas oil storage project, which requires the behaviour of liquid hydrocarbons in the presence of groundwater to be evaluated. In contrast, multi-phase flow models are un-necessary to evaluate the direct potential impacts from the proposed cavern backfill. However, the outputs from the models reported by Duijne et al. (2011a) are useful background information for evaluating the behaviour of an oil blanket that was used to protect the roof during the development of some caverns (e.g. Bekendam (2009).

6 Literature Review

6.1 Purpose of Review

The proposed backfill formulation differs from cementitious materials that are commonly employed in underground applications (e.g. tunnel supports, borehole seals etc.). Furthermore, there is in any case little known about the very long-term (more than a few tens of years) behaviour of cementitious materials in the presence of highly saline solutions like those that occur in and around the salt caverns in the Twente region. However, to ensure that relevant published information is taken into account in the assessment a brief literature review was undertaken, covering:

- the nature and properties of cementitious materials that include saline water or brine (rather than fresh water) as a constituent (such materials may be referred to as 'salt cement' or 'salt concrete'); and
- the nature and properties (especially chemical composition) of municipal solid waste incinerator (MSWI) ash and APC (Air Pollution Control) residues.

6.2 Salt Cement

6.2.1 Usage

"Salt cement" has been used in environments rich in evaporite minerals. Examples include as an infilling material used in the stabilisation of abandoned salt mines (Brooks et al., 2006; Milliken, 1994) and radioactive waste facilities in evaporite deposits (Wakeley and Roy, 1982; Pruess et al., 2002; Eilers et al., 2003). In addition, Cowan et al. (1994) registered a patent for a cement slurry composition and method to cement well borings in salt formations. The cement slurry includes blast furnace slag, water and salt.

"Salt concrete" has been considered as a material for sealing radioactive waste repositories that are situated in evaporite deposits. Mixtures 'M2' and 'M3' have been considered as a backfill materials for the Morsleben Repository in Germany (Eilers et al., 2003). Here the function of the backfill is to stabilize cavities and to seal single cavities or groups of cavities containing radioactive waste (Eilers et al., 2003). The repository concept includes 26 drift seals comprised of segments of 'M2' salt concrete.

6.2.2 Salt Cement Composition

Brooks et al. (2006) provide a brief description of the composition of the infilling material used to stabilise abandoned salt mines in the North West of England. The grout mix used comprised PFA (pulverised fuel ash, also called "fly ash"); cement and brine (note that the proportions of each are not given). The material was tested in order to understand the influence of salt crystals and the potential for salt to leach out of the set grout. Brooks et al.

(2006) report that analysis by X-ray diffraction (XRD) and electron microscopy was performed on the material and give an annotated XRD pattern which includes peaks corresponding to tobermorite (a calcium silicate hydrate phase), mullite (an aluminosilicate phase, $3Al_2O_32SiO_2$ or $2Al_2O_3$ SiO_2), Friedel's salt ($Ca_2Al(OH)_6(Cl, OH) \cdot 2\,H_2O$), thaumasite ($Ca_6Si_2(OH)_{12}(CO_3)_2(SO_4)_2 \cdot 24H_2O$) /ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) and halite (NaCl) (Figure 6-1).

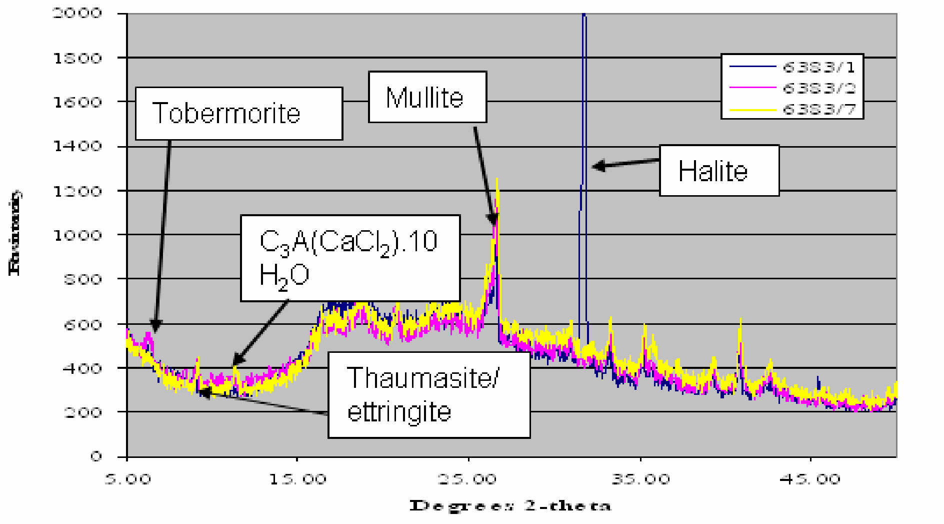


Figure 6-1: XRD pattern of salt-cement (reproduced from Brooks et al., 2006).

M2 and M3 Salt concrete compositions are summarised in Table 6-1.

Table 6-1: Compositions of M2 and M3 salt concretes (from Pruess et al., 2002).

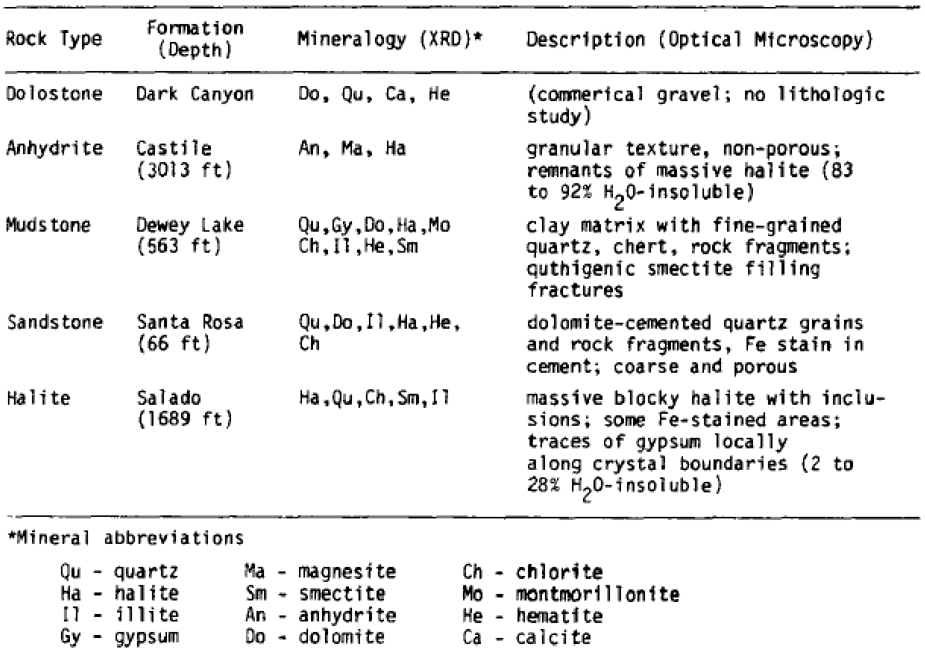
	M2		M3	
Components	kg/m³	wt.%	kg/m³	wt.%
Cement	328	16.4	197	9.9
Coal Fly Ash	328	16.4	459	23.0
Water	267	13.4	252	12.6
Crushed rock salt	1,072	53.8	1,087	54.5

The total porosity of salt concrete M2 is 18.1 vol%. The porosity that could be measured by porosimetry methods was 14.2 vol. % (Eilers et al., 2003). These two materials have different properties. M2 produces a relatively higher amount of hydration heat as a result of a greater cement content (Pruess et al., 2002). The cement (high sulphate resistant type) and the coal fly ash are classified as building materials according to the German industrial standards (DIN). The maximum grain size of the crushed rock salt is 20 mm. The water content guarantees a transport of the suspension over long distances (Pruess et al., 2002).

Pruess et al. (2002) state that the advantage of the use of such hydraulically setting concrete materials is that stabilization occurs over a relatively short time and that the water needed for the hydraulic transport becomes fixed in the crystal structure of the hydration products and the pore volume of the concretes. Therefore, transportation of contaminated water into the biosphere is not expected (Pruess et al., 2002).

Wakeley and Roy (1982) describe concretes comprising rock material from evaporite deposits from Los Medaños, New Mexico (Table 6-2), cement and brine; and report the results of experiments to test their physical properties. Five aggregate materials were considered: sandstone, mudstone, anhydrite, dolostone, and halite. The brine used for curing and testing had a total dissolved solids of ~ 300g / L (Table 6-3). The cement is similar to a Class H Portland cement and a high lime fly ash (Table 6-4). The phases present in the material are given in Table 6-5.

Table 6-2: Aggregate data for concretes described by Wakeley and Roy (1983)

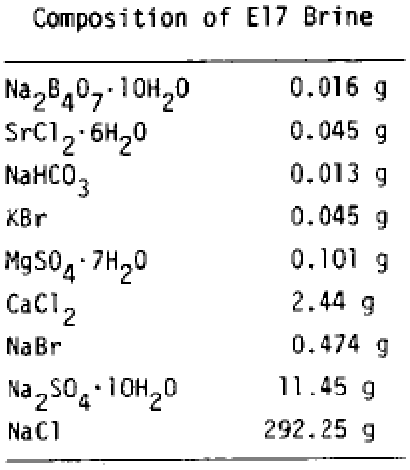


Rock Type	Formation (Depth)	Mineralogy (XRD)*	Description (Optical Microscopy)
Dolostone	Dark Canyon	Do, Qu, Ca, He	(commerical gravel; no lithologic study)
Anhydrite	Castile (3013 ft)	An, Ma, Ha	granular texture, non-porous; remnants of massive halite (83 to 92% H_2O-insoluble)
Mudstone	Dewey Lake (563 ft)	Qu,Gy,Do,Ha,Mo Ch,Il,He,Sm	clay matrix with fine-grained quartz, chert, rock fragments; quthigenic smectite filling fractures
Sandstone	Santa Rosa (66 ft)	Qu,Do,Il,Ha,He, Ch	dolomite-cemented quartz grains and rock fragments, Fe stain in cement; coarse and porous
Halite	Salado (1689 ft)	Ha,Qu,Ch,Sm,Il	massive blocky halite with inclusions; some Fe-stained areas; traces of gypsum locally along crystal boundaries (2 to 28% H_2O-insoluble)

*Mineral abbreviations

Qu - quartz
Ha - halite
Il - illite
Gy - gypsum
Ma - magnesite
Sm - smectite
An - anhydrite
Do - dolomite
Ch - chlorite
Mo - montmorillonite
He - hematite
Ca - calcite

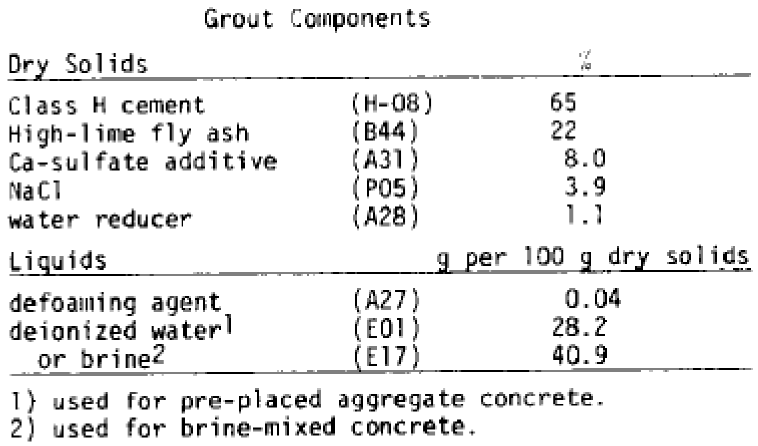
Table 6-3: Composition of brine used to cure and test concretes described by Wakeley and Roy (1983).



Composition of E17 Brine

$Na_2B_4O_7 \cdot 10H_2O$	0.016 g
$SrCl_2 \cdot 6H_2O$	0.045 g
$NaHCO_3$	0.013 g
KBr	0.045 g
$MgSO_4 \cdot 7H_2O$	0.101 g
$CaCl_2$	2.44 g
$NaBr$	0.474 g
$Na_2SO_4 \cdot 10H_2O$	11.45 g
$NaCl$	292.25 g

Table 6-4: Composition of cement used to cure and test concretes described by Wakeley and Roy (1983).

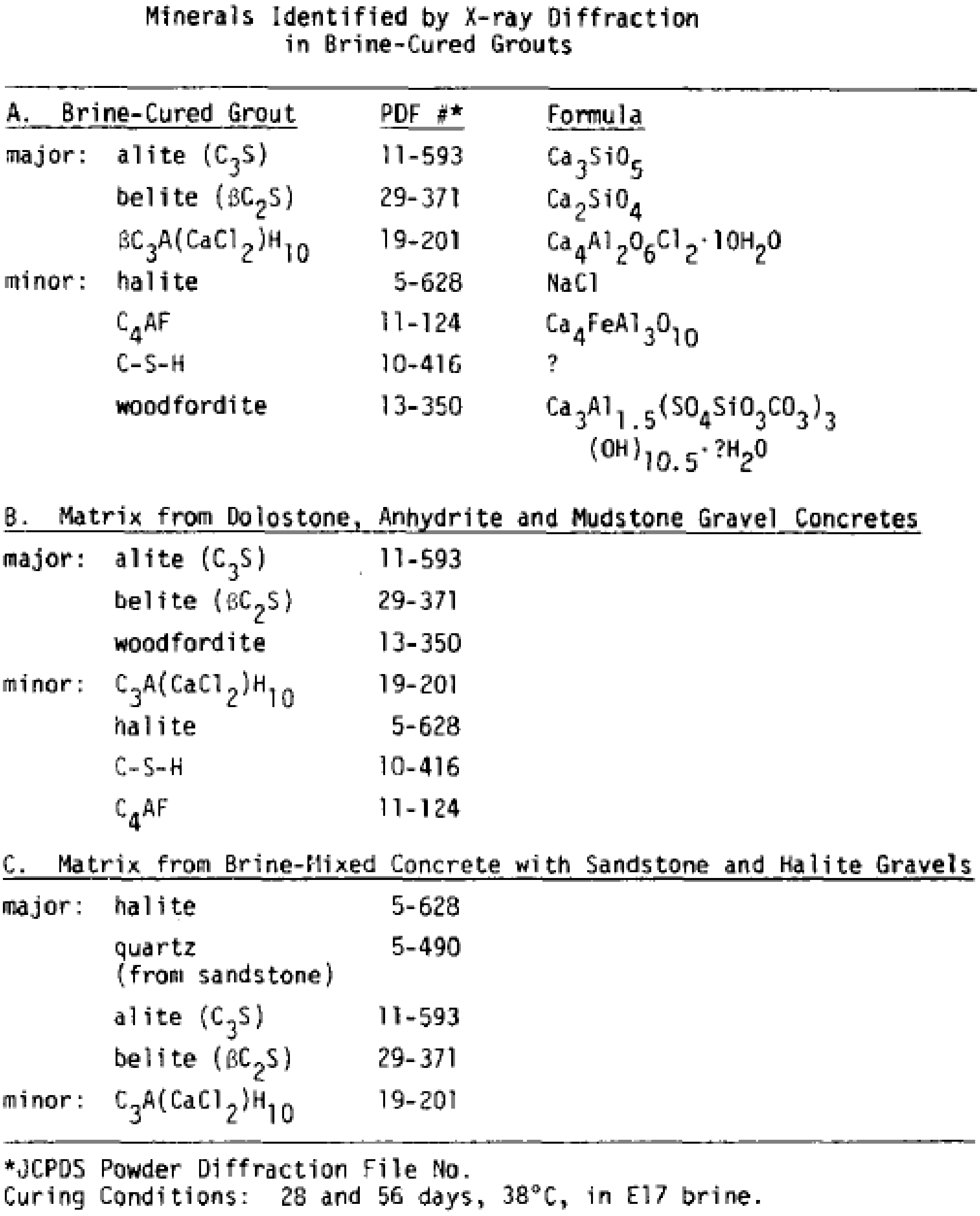


Grout Components

Dry Solids		%
Class H cement	(H-08)	65
High-lime fly ash	(B44)	22
Ca-sulfate additive	(A31)	8.0
NaCl	(P05)	3.9
water reducer	(A28)	1.1
Liquids		**g per 100 g dry solids**
defoaming agent	(A27)	0.04
deionized water[1]	(E01)	28.2
or brine[2]	(E17)	40.9

1) used for pre-placed aggregate concrete.
2) used for brine-mixed concrete.

Table 6-5: Phases identified in cement materials described by Wakeley and Roy (1982).



Minerals Identified by X-ray Diffraction
in Brine-Cured Grouts

	A. Brine-Cured Grout	PDF #*	Formula
major:	alite (C_3S)	11-593	Ca_3SiO_5
	belite (βC_2S)	29-371	Ca_2SiO_4
	$\beta C_3A(CaCl_2)H_{10}$	19-201	$Ca_4Al_2O_6Cl_2\cdot 10H_2O$
minor:	halite	5-628	NaCl
	C_4AF	11-124	$Ca_4FeAl_3O_{10}$
	C-S-H	10-416	?
	woodfordite	13-350	$Ca_3Al_{1.5}(SO_4SiO_3CO_3)_3$ $(OH)_{10.5}\cdot ?H_2O$
	B. Matrix from Dolostone, Anhydrite and Mudstone Gravel Concretes		
major:	alite (C_3S)	11-593	
	belite (βC_2S)	29-371	
	woodfordite	13-350	
minor:	$C_3A(CaCl_2)H_{10}$	19-201	
	halite	5-628	
	C-S-H	10-416	
	C_4AF	11-124	
	C. Matrix from Brine-Mixed Concrete with Sandstone and Halite Gravels		
major:	halite	5-628	
	quartz (from sandstone)	5-490	
	alite (C_3S)	11-593	
	belite (βC_2S)	29-371	
minor:	$C_3A(CaCl_2)H_{10}$	19-201	

*JCPDS Powder Diffraction File No.
Curing Conditions: 28 and 56 days, 38°C, in E17 brine.

6.2.3 Properties of Salt Cement/Concrete

'M2' Salt Concrete

Hydraulic test data for 'M2' salt concrete are summarised in Table 6-6. The data show a very high hydraulic resistance due to a pore radius of less than 20 nm (Eiler et al., 2003). An upper bound of the Lithium ion diffusion coefficient was measured to be less than $1 \cdot 10^{-14}$ m^2/s (Eiler et al., 2003).

Table 6-6: M2 Salt Concrete Hydraulic Test Data (reproduced from Eiler et al., 2003)

storage conditions temperature[°C] /relative humidity [%]	**confining pressure [MPa]**	**axial fluid pressure [MPa]**	**medium**	**permeability [m^2]**
20/65	2.5 –10.0	1,34 – 5,6	gas	$5.8*10^{-20} - 5.3*10^{-21}$
dried samples	1.0 – 10.0	0,56 – 9.0	gas	$5.4*10^{-18} - 1.0 * 10^{-18}$
20/65	2.5	1.8	gas	$6.1*10^{-20} - 1.5 *10^{-20}$
pore space saturated	2.5	1.8	Q-brine	$\leq 3.0*10^{-23}$ (measuring range)
pore space saturated	2.5	1.8	NaCl-brine	$\leq 6.0*10^{-24}$ (measuring range)
				threshold pressure [MPa]
pore space saturated	2.5	2.1	gas	no gas intrusion measured
pore space saturated	8.0	7.0	gas	no gas intrusion measured

Cement and Concrete Data from Wakeley and Roy (1982)

Wakeley and Roy (1982) suggest that curing in brine does not seem to adversely affect the low permeabilities of some of the materials they describe. Compressive strength data for grout and composite materials is reproduced in Table 6-7.

Table 6-7: Compressive strength data for grout and salt concrete described by Wakeley and Roy (1982).

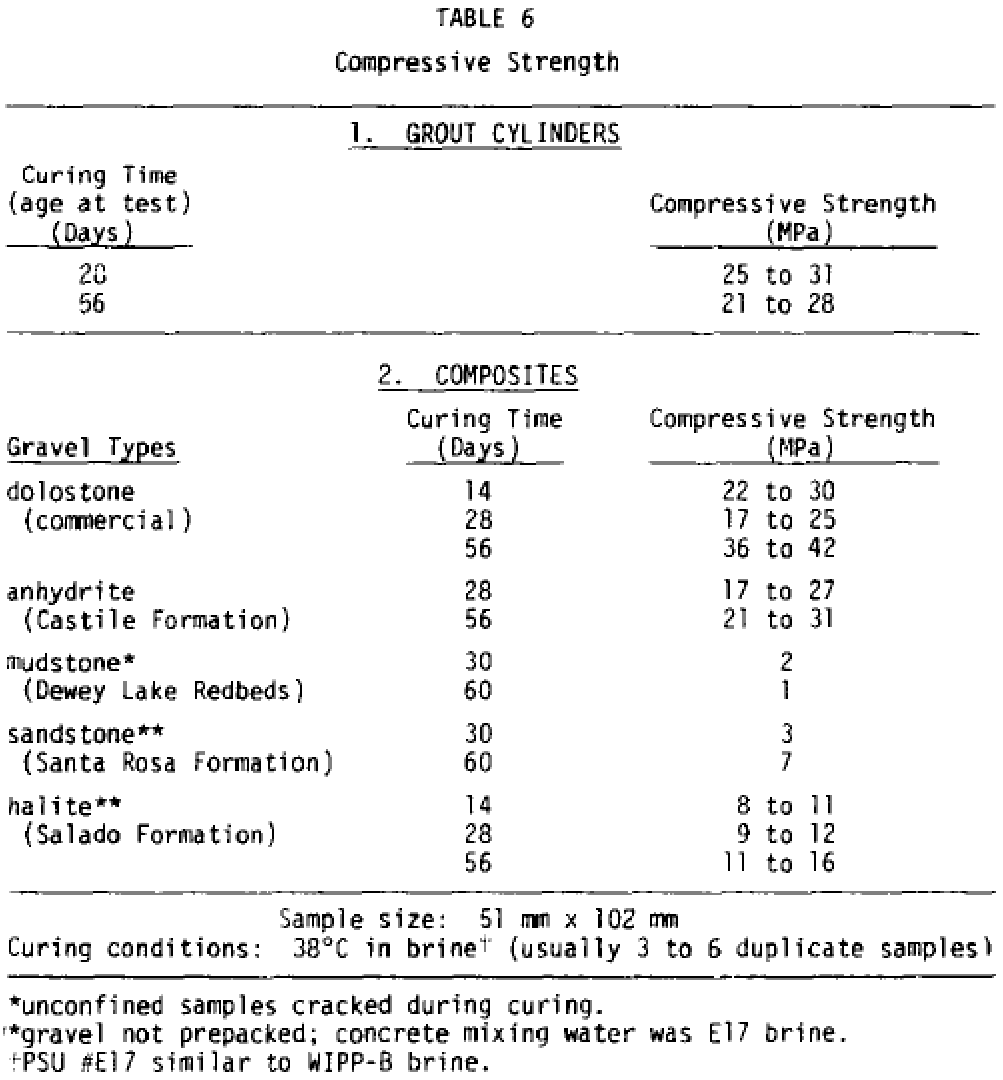


TABLE 6

Compressive Strength

1. GROUT CYLINDERS

Curing Time (age at test) (Days)	Compressive Strength (MPa)
28	25 to 31
56	21 to 28

2. COMPOSITES

Gravel Types	Curing Time (Days)	Compressive Strength (MPa)
dolostone (commercial)	14	22 to 30
	28	17 to 25
	56	36 to 42
anhydrite (Castile Formation)	28	17 to 27
	56	21 to 31
mudstone* (Dewey Lake Redbeds)	30	2
	60	1
sandstone** (Santa Rosa Formation)	30	3
	60	7
halite** (Salado Formation)	14	8 to 11
	28	9 to 12
	56	11 to 16

Sample size: 51 mm x 102 mm
Curing conditions: 38°C in brine† (usually 3 to 6 duplicate samples)

*unconfined samples cracked during curing.
**gravel not prepacked; concrete mixing water was E17 brine.
†PSU #E17 similar to WIPP-B brine.

6.3 Municipal Solid Waste Incinerator Materials

6.3.1 Background

Waste-to-energy conversion reduces waste volumes. The energy produced when burning waste in an MSW (Municipal Solid Waste) is recovered by a boiler system that is equipped with turbines and connected to the energy supply grid. Municipal Solid Waste Incineration (MSWI) may also allow material recovery (De Boom and Degrez, 2012).

Incorrect terms are sometimes used in the literature when it is appropriate to identify the ash according to the MSWI unit that contributes to the waste (Quina et al., 2008). In their review, Quina et al. (2008) cite studies that specify the following types of material:

- Heat recovery system ash, which is collected in hoppers below the boiler, superheater and economiser (sometimes referred to as fly ash – FA).
- Electrostatic precipitator ash (ESP).
- Fabric filter or baghouse ash (FF).
- Dry scrubbing residues (DS), semi-dry scrubbing residues (SDS) or wet scrubbing residues (WS), with sorbents such as Na_2CO_3, $Ca(OH)_2$ and activated carbon
- Cyclone ash (CA).
- Air pollution control (APC) residues, which may include FA and the solid material captured downstream from the acid gas treatment units and before the gases are released into the atmosphere.

A schematic diagram that highlights the management of APC residues is given in Figure 6-2.

An overview of management practised for MSWI materials is provided by Quina et al. (2008) and summarised in Table 6-8.

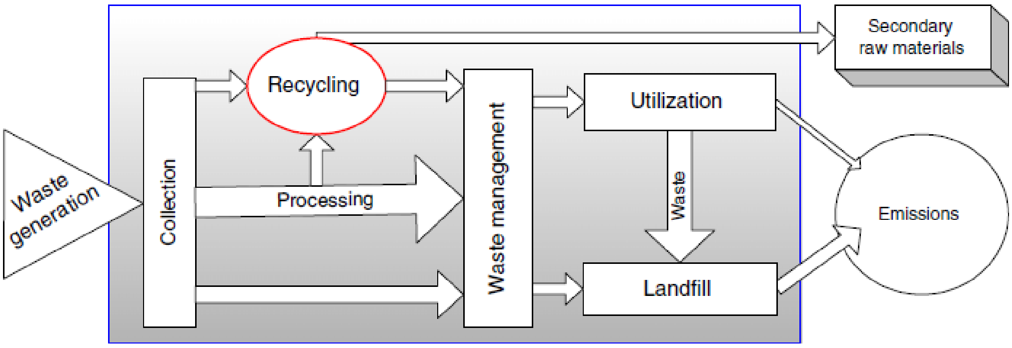


Fig. 1. Integrated waste management system, based on Sabbas et al. (2003).

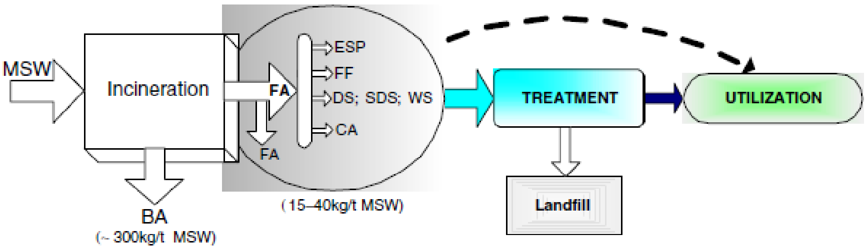


Figure 6-2: Management of APC residues from MSW incineration (reproduced from Quina et al., 2008).

Table 6-8: Waste management of FA/APC residues from MSWI processes in various countries (reproduced from Quina et al., 2008).

Country	Management strategies for FA/APC residues	Reference
USA	APC residues and bottom ash are mixed at most MSW incineration (MSWI) plants and disposed as a "combined ash". The most frequent dumping option is disposal in landfills which receive only MSWI residues (monofills)	Eighmy and Kosson (1996) Sakai et al. (1996) Millrath et al. (2004)
Canada	APC residues are disposed in a hazardous waste landfill after treatment	Sakai et al. (1996)
Sweden	APC residues are disposed in secure landfills after treatment	Sakai et al. (1996)
Denmark	APC residues and fly ashes are classified as a special hazardous waste and are currently exported or stored temporarily in big bags. Significant efforts are being spent to develop treatment methods which can guarantee that APC residues can be landfilled in a sustainable way	Hjelmar (1996a,1996b) Sorensen et al. (2001)
Germany	The APC residues are mainly disposed of in underground disposal sites, such as old salt mines	Vehlow (1996) IEA (2000)
Netherlands	Flue-gas cleaning wastes are disposed temporarily in large sealed bags at a controlled landfill until better options are available. The utilization of APC residues is presently not considered. The re-use of the waste is subject to investigation	Van der Sloot (1996)
France	After industrial solidification and stabilization processes based on the properties of hydraulic binders, the waste is stored in confined cavities in a specific landfill (French class I and II). The high cost of this treatment is promoting the companies to search alternatives to disposal	Piantone et al. (2003)
Italy	Various technologies have been proposed, but the most widely adopted comprehends solidification with a variety of hydraulic binders (such as cement and/or lime, blast furnace slag, etc.)	Polettini et al. (2001)
Portugal	APC residues are treated with hydraulic binders (solidification/stabilization method) and landfilled in specific sites (monofills)	Quina (2005)
Japan	MSWI fly ash and APC residues are considered as hazardous, and before landfill intermediate treatments must be performed, such as melting, solidification with cement, stabilization using chemical agents or extraction with acid or other solvents. Melting slag may be used in road construction and the materials of S/S with cement are landfilled	Sakai (1996) Nagib and Inoue (2000) Ecke et al. (2000)

The solid particles produced during MSWI in mass burning units may be grouped into bottom ashes (BA) and fly ashes (FA) (Quina et al., 2008). Fly ashes are defined as: *'the particulate matter carried over from the combustion chamber and removed from the flue gas stream prior to addition of any type of sorbent material'* (Quina et al., 2008, citing IAWG, 1997).

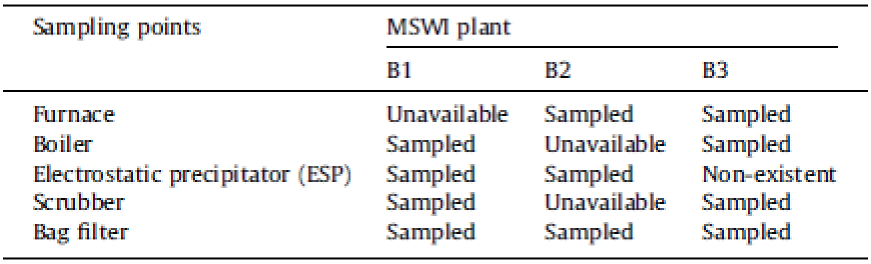
Bottom ash is used (after aging) as a construction material (e.g. road embankments) and for other civil engineering works (De Boom and Degrez, 2012 and references therein). Fly ash and Air Pollution Control (APC) residues are generally considered as hazardous waste because of their content in heavy metals coupled with high level of chlorides, as well as the presence of organic pollutants such as dioxins. Therefore these materials undergo stabilisation/solidification treatment before being landfilled as hazardous waste (De Boom and Degrez, 2012).

6.3.2 Properties of MSWI Fly Ash

Belgian MSWI Fly Ash

De Boom and Degrez (2012) present a characterisation of several fly ashes and APC residues from Belgium. These were sampled separately at different MSWI plants (designated B1, B2, B3) and at different APC devices (Table 6-9).

Table 6-9: Sampling points at B1, B2, and B3 MSWI plants in Belgium (reproduced form De Boom and Degrez, 2012).



Sampling points	MSWI plant		
	B1	B2	B3
Furnace	Unavailable	Sampled	Sampled
Boiler	Sampled	Unavailable	Sampled
Electrostatic precipitator (ESP)	Sampled	Sampled	Non-existent
Scrubber	Sampled	Unavailable	Sampled
Bag filter	Sampled	Sampled	Sampled

De Boom and Degrez (2012) describe the three different plant configurations. In brief, the B1 plant APC system comprises (after the boiler) a scrubber (lime atomisation), followed by an ESP (electrostatic precipitator). After the ESP, a mix of lime and activated carbon is injected in the gases. The gases finally go through a bag filter before being released in the atmosphere. At the B2 plant, gases coming from the boiler pass through an ESP; afterwards, they undergo a wet washing (soda addition), followed by an activated carbon injection. Finally, gases go through a bag filter and are released into the atmosphere. The B3 incinerator has an APC system composed of (following the gas road) a semi-wet scrubber (lime milk atomisation), a bag filter and a wet scrubber. Activated carbon is injected before the bag filter. The size distribution of several residues is given in Figure 6-3.

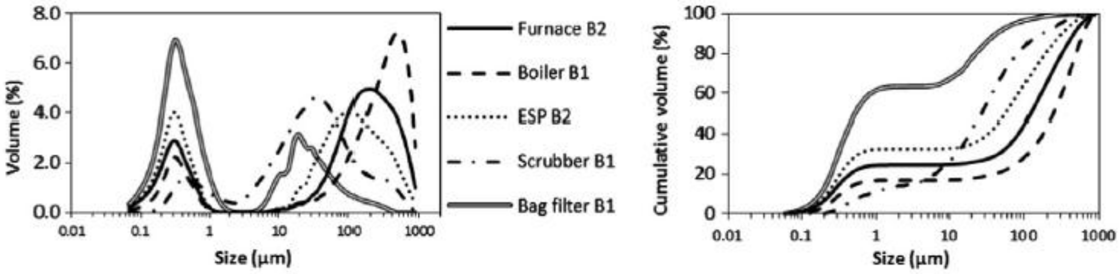


Figure 6-3: Size distribution of several residues described by De Boom and Degrez (2012): left in volume (%), right in cumulative volume (%).

Concentrations of different elements in the residues are summarised in Table 6-10. In most of the residues, Ca is the main element. Concentrations of Cl are also high in some samples from the ESP, scrubber and bag filter. Furnace and boiler residues contain more than 10 g/kg Al, Fe, K, Mg, Na, S and Si.

Table 6-10: Residue compositions from De Boom and Degrez (2012).

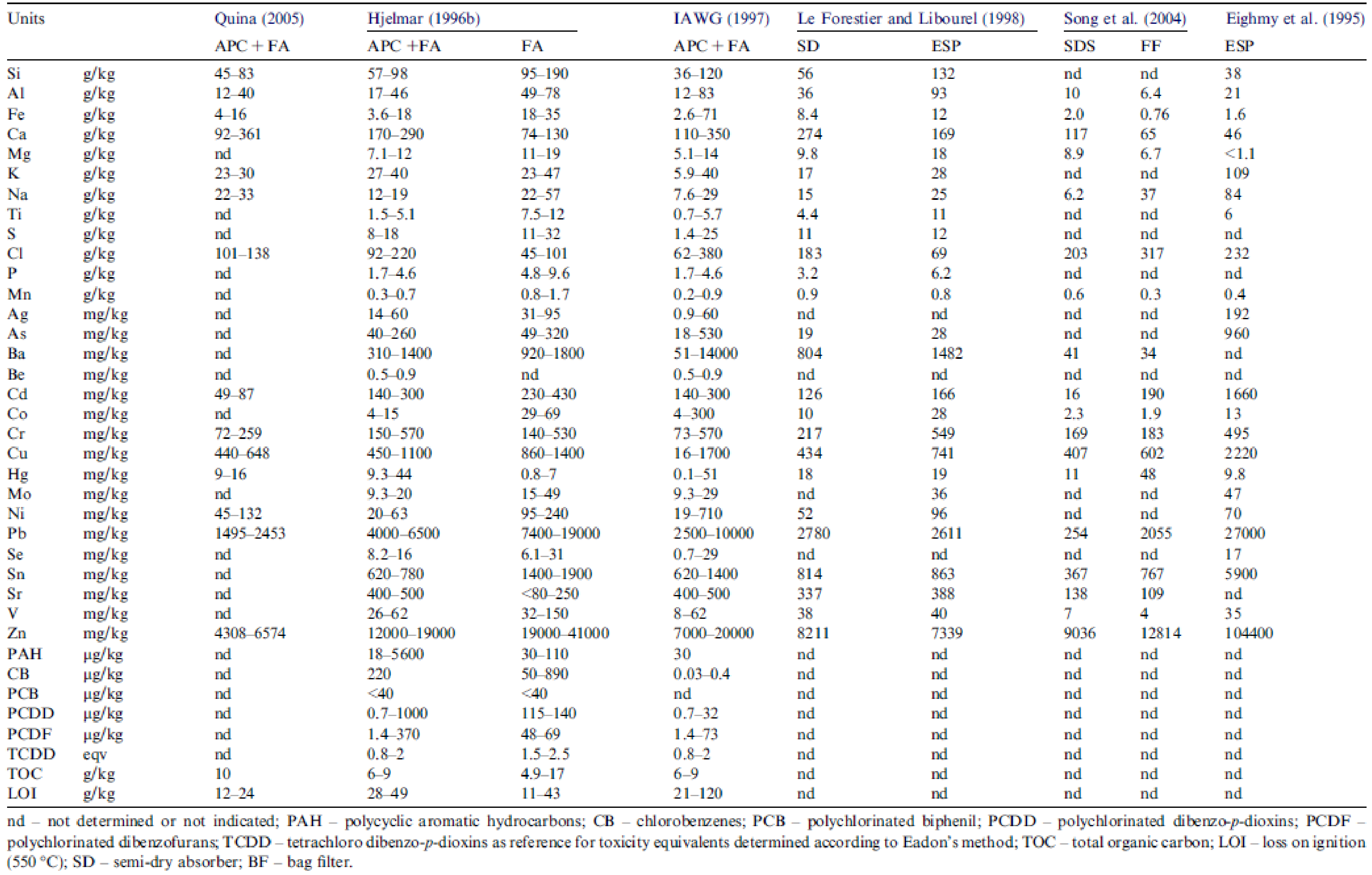
Element (g/kg)	Furnace	Boiler	ESP	Scrubber	Bag filter
Al	50–55	40–51	6.1–36	2.8–4	2.4–7.4
Ca	234–241	196–212	172–322	211–583	52–496
Cl	19–27	34–79	129–250	60–383	16–395
Fe	17–24	12–16	4.8–11	1.9–3.2	2.7–17
K	13–17	17–29	30–54	2.5–4.4	2.6–37
Mg	17–31	13–15	5.4–10	4–11	4.9–13
Mn	0.65–0.81	0.6–0.65	0.33–0.51	0.14–0.53	0.15–0.46
Na	16–19	29–37	56–84	3.1–70	3.3–120
P	14–20	9.6–10	2.2–13	0.09–0.83	0.1–2.1
Pb	0.64–0.85	1–3.2	3.72–4.94	0.41–0.45	0.4–3.6
S	24–57	77–79	38–69	6.6–68	24–67
Si	99–135	75–98	15–52	8.2–27	7.5–13
Ti	9.4–14	11–13	3.4–10	0.27–1.4	0.26–1.3
Zn	3.8–5.7	7.8–12	9.5–10	1.1–1.8	0.82–13
Element (mg/kg)	Furnace	Boiler	ESP	Scrubber	Bag filter
Ba	1300–1550	1310–1870	450–1270	230	340–950
Bi	n.d.	80–120	150	n.d.	70
Br	180	190–1080	460–1540	830–2240	190–5200
Cd	n.d.	160	210–270	n.d.	n.d.
Cr	460–640	650–820	170–450	70–120	190–260
Cu	530–5530	520–4700	650–730	110–2800	120–8400
Ni	160–200	120–130	100–150	n.d.	60
Pb	640–850	1000–3200	3720–4940	410–450	400–3580
Sb	100–380	400–1040	370–690	8130	330
Sn	240–250	260–550	870–1260	n.d.	220
Sr	640–740	540–610	360–550	160–340	140–320
Zr	150–160	150–480	120–170	10	10

Review of Air Pollution Control (APC) Residues by Quina et al. (2008)

Quina et al. (2008) provide an overview of the properties of APC materials. Table 6-11 includes the total contents of several elements and some organic compounds that were measured in a number of studies and collated by Quina et al. The major elements are reported to be Si, Al, Fe, Ca, Mg, K, Na and Cl. With regard to heavy metals, Cd, Cr, Cu, Hg, Ni, Pb and Zn are reported, with Zn and Pb generally being present in the largest amounts. Trace quantities of very toxic organic compounds were found in these residues, namely polycyclic aromatic hydrocarbons (PAH), chlorobenzenes (CB), polychlorinated biphenyls (PCB) and polychlorinated dibenzo-p-dioxins (PCDD) and furans (PCDF).

Quina et al. (2008) also collated data on the leaching behaviour of Pb and Cl from MSWI materials (Table 6-12 and Table 6-14) and major oxide compositions (Table 6-15).

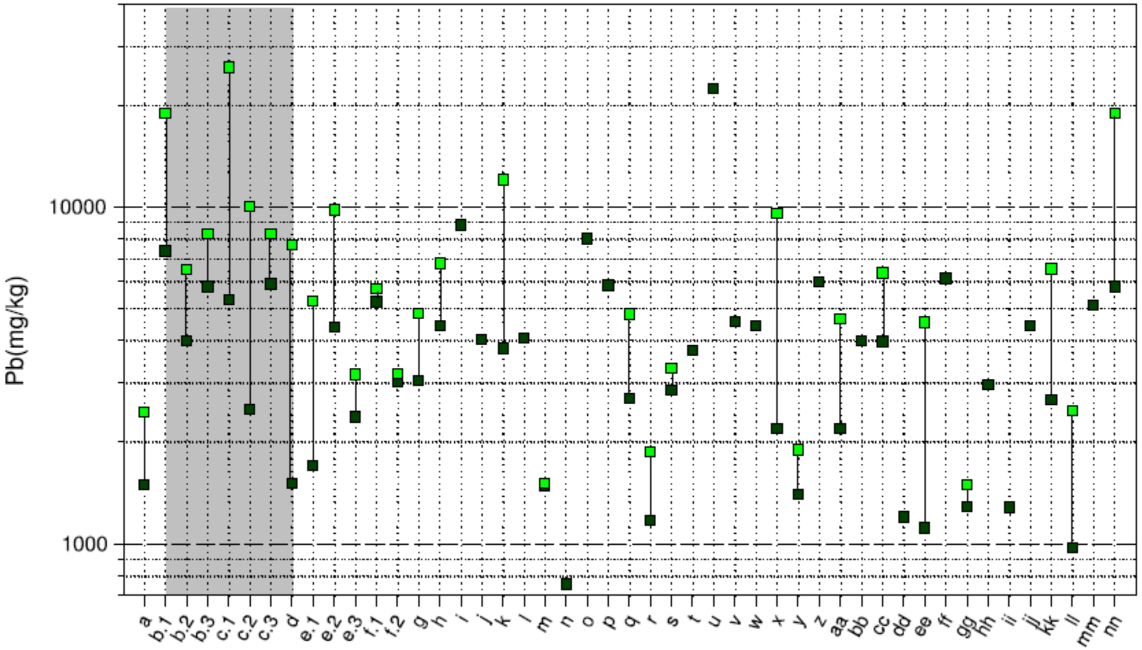
Table 6-11: Compositions of APC Materials (reproduced from Quina et al., 2008).



Units		Quina (2005)	Hjelmar (1996b)		IAWG (1997)	Le Forestier and Libourel (1998)		Song et al. (2004)		Eighmy et al. (1995)
		APC + FA	APC +FA	FA	APC + FA	SD	ESP	SDS	FF	ESP
Si	g/kg	45–83	57–98	95–190	36–120	56	132	nd	nd	38
Al	g/kg	12–40	17–46	49–78	12–83	36	93	10	6.4	21
Fe	g/kg	4–16	3.6–18	18–35	2.6–71	8.4	12	2.0	0.76	1.6
Ca	g/kg	92–361	170–290	74–130	110–350	274	169	117	65	46
Mg	g/kg	nd	7.1–12	11–19	5.1–14	9.8	18	8.9	6.7	<1.1
K	g/kg	23–30	27–40	23–47	5.9–40	17	28	nd	nd	109
Na	g/kg	22–33	12–19	22–57	7.6–29	15	25	6.2	37	84
Ti	g/kg	nd	1.5–5.1	7.5–12	0.7–5.7	4.4	11	nd	nd	6
S	g/kg	nd	8–18	11–32	1.4–25	11	12	nd	nd	nd
Cl	g/kg	101–138	92–220	45–101	62–380	183	69	203	317	232
P	g/kg	nd	1.7–4.6	4.8–9.6	1.7–4.6	3.2	6.2	nd	nd	nd
Mn	g/kg	nd	0.3–0.7	0.8–1.7	0.2–0.9	0.9	0.8	0.6	0.3	0.4
Ag	mg/kg	nd	14–60	31–95	0.9–60	nd	nd	nd	nd	192
As	mg/kg	nd	40–260	49–320	18–530	19	28	nd	nd	960
Ba	mg/kg	nd	310–1400	920–1800	51–14000	804	1482	41	34	nd
Be	mg/kg	nd	0.5–0.9	nd	0.5–0.9	nd	nd	nd	nd	nd
Cd	mg/kg	49–87	140–300	230–430	140–300	126	166	16	190	1660
Co	mg/kg	nd	4–15	29–69	4–300	10	28	2.3	1.9	13
Cr	mg/kg	72–259	150–570	140–530	73–570	217	549	169	183	495
Cu	mg/kg	440–648	450–1100	860–1400	16–1700	434	741	407	602	2220
Hg	mg/kg	9–16	9.3–44	0.8–7	0.1–51	18	19	11	48	9.8
Mo	mg/kg	nd	9.3–20	15–49	9.3–29	nd	36	nd	nd	47
Ni	mg/kg	45–132	20–63	95–240	19–710	52	96	nd	nd	70
Pb	mg/kg	1495–2453	4000–6500	7400–19000	2500–10000	2780	2611	254	2055	27000
Se	mg/kg	nd	8.2–16	6.1–31	0.7–29	nd	nd	nd	nd	17
Sn	mg/kg	nd	620–780	1400–1900	620–1400	814	863	367	767	5900
Sr	mg/kg	nd	400–500	<80–250	400–500	337	388	138	109	nd
V	mg/kg	nd	26–62	32–150	8–62	38	40	7	4	35
Zn	mg/kg	4308–6574	12000–19000	19000–41000	7000–20000	8211	7339	9036	12814	104400
PAH	µg/kg	nd	18–5600	30–110	30	nd	nd	nd	nd	nd
CB	µg/kg	nd	220	50–890	0.03–0.4	nd	nd	nd	nd	nd
PCB	µg/kg	nd	<40	<40	nd	nd	nd	nd	nd	nd
PCDD	µg/kg	nd	0.7–1000	115–140	0.7–32	nd	nd	nd	nd	nd
PCDF	µg/kg	nd	1.4–370	48–69	1.4–73	nd	nd	nd	nd	nd
TCDD	eqv	nd	0.8–2	1.5–2.5	0.8–2	nd	nd	nd	nd	nd
TOC	g/kg	10	6–9	4.9–17	6–9	nd	nd	nd	nd	nd
LOI	g/kg	12–24	28–49	11–43	21–120	nd	nd	nd	nd	nd

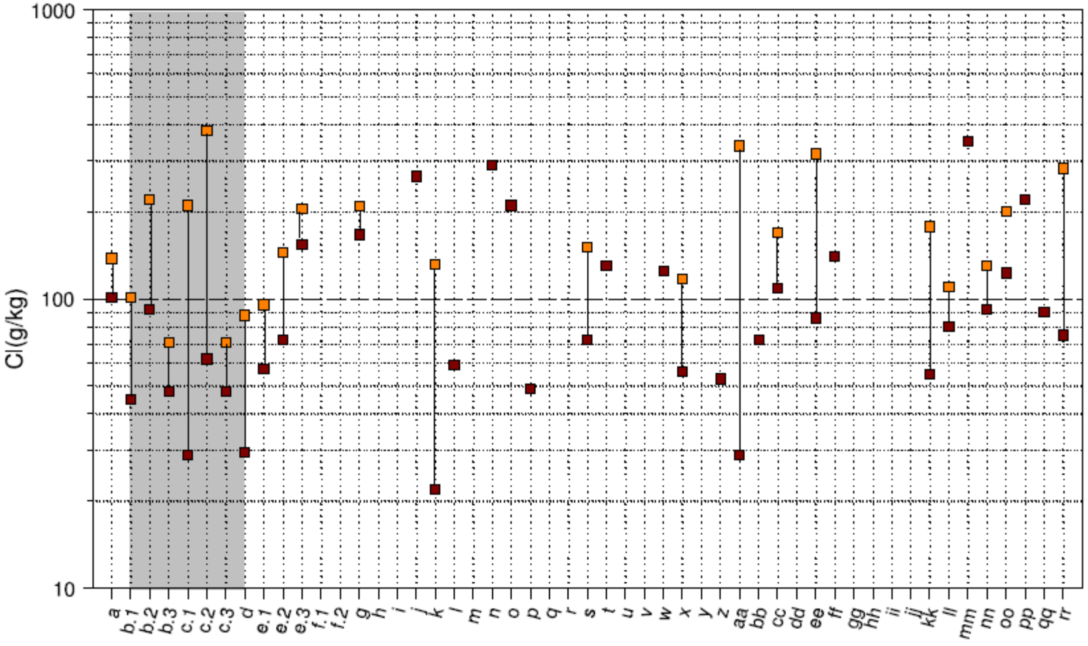
nd – not determined or not indicated; PAH – polycyclic aromatic hydrocarbons; CB – chlorobenzenes; PCB – polychlorinated biphenil; PCDD – polychlorinated dibenzo-*p*-dioxins; PCDF – polychlorinated dibenzofurans; TCDD – tetrachloro dibenzo-*p*-dioxins as reference for toxicity equivalents determined according to Eadon's method; TOC – total organic carbon; LOI – loss on ignition (550 °C); SD – semi-dry absorber; BF – bag filter.

Table 6-12: Lead concentration in incineration residues from MSWI (APC, FA, DS, SDS, WS, ESP, FF, CA) (reproduced from Quina et al., 2008).



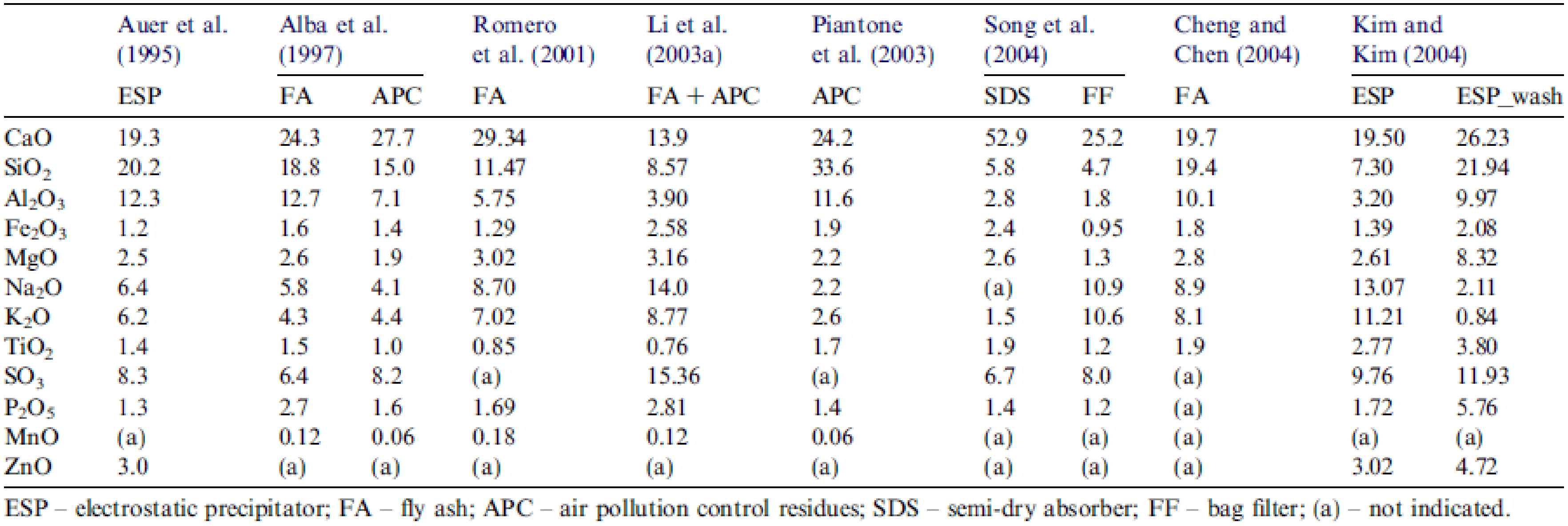
a- Quina (2005)	APC -Portugal
b.1- Hjelmar (1996b)	FA -Usual range
b.2- Hjelmar (1996b)	SDS/DS- Usual range
b.3- Hjelmar (1996b)	WS- Usual range
c.1- IAWG (1997)	FA- Usual range
c.2- IAWG (1997)	SDS/DS- Usual range
c.3- IAWG (1997)	WS - Usual range
d- Stegemann and Buenfeld (2003)	FA (APC)- Usual range
e.1- Le Forestier and Libourel (1998)	ESP- France
e.2- Le Forestier and Libourel (1998)	SDS (no ESP)- France
e.3- Le Forestier and Libourel (1998)	SDS- France
f.1- Alba et al (2001)	FA- Spain (*)
f.2- Alba et al (2001)	APC- Spain (*)
g- Geysen et al (2004b)	APC (SD+FF)- Belgium
h- Li et al (2003a)	FA (APC*)- China
i- Aubert et al (2004)	FA (APC*)- France
j- Chimenos et al (2005)	FF- Spain
k- Derie (1996)	FA (APC*) -Belgium France
l- Piantone et al (2003)	FA (APC*)- Belgium
m- Youcai et al (2002)	FF- China
n- Park and Heo (2002a)	ESP- Korea
o- Pedersen (2002)	ESP- Denmark
p- Wunsch et al (1996)	ESP- Germany (*)
q- Izumikawa (1996)	FA(APC*)- Japan(*)
r- Jianguo et al (2004)	APC- China
s- Jung et al (2005)	FA(APC*)- Japan
t- Kamon et al (2000)	ESP- Japan
u- Katsuura et al (1996)	ESP- Japan
v- Kuo et al (2004)	APC- Taiwan
w- Li et al (2004)	ESP- China
x- Mangialard (2001)	FA (APC*)- Italy
y- Mizutani et al (1996)	APC - Japan
z- Mulder (1996)	FA (APC*)- Netherlands
aa- Polettini et al (2001)	ESP; FF- Italy
bb- Rémond et al (2002a)	APC (WS)- France
cc- Lundtorp et al (200)	DS; ESP- Denmark
dd- Nagib and Inoue (2000)	ESP- Japan
ee- Song et al (2004)	WS; SD; FF- South Korea
ff- Ubbriaco et al (1998)	ESP- Italy
gg- Wang et al (2001)	CA- Taiwan
hh- Wang et al (2002)	CA- Taiwan
ii- Wang et al (2004)	CA- Taiwan
jj- Yang and Tsai (1998)	CA- Taiwan
kk- Carignan et al (2005)	FA, ESP, DS, FF- France
ll- He et al (2004)	APC- China
mm- Park et al (2005)	FA (APC*)- Korea
nn- Sorensen et al (2001)	APC, ESP- Denmark

Table 6-13: Chloride concentration in incineration residues from MSWI (APC, FA, DS, SDS, WS, ESP, FF, CA) (reproduced from Quina et al., 2008).



a- Quina (2005)	APC- Portugal	k- Derie (1996)	FA (APC*)- Belgium, France	bb- Rémond et al (2002a)	APC (WS)- France
b.1- Hjelmar (1996b)	FA- Usual range	l- Piantone et al (2003)	FA (APC*)- Belgium	cc- Lundtorp et al (2003)	DS; ESP- Denmark
b.2- Hjelmar (1996b)	SDS/DS- Usual range	m- Youcai et al (2002)	FF- China	dd- Nagib and Inoue (2000)	ESP- Japan
b.3- Hjelmar (1996b)	WS- Usual range	n- Park and Heo (2002a)	ESP- Korea	ee- Song et al (2004)	WS; SD; FF- South Korea
c.1- IAWG (1997)	FA- Usual range	o- Pedersen (2002)	ESP- Denmark	ff- Ubbriaco et al (1998)	ESP- Italy
c.2- IAWG (1997)	SDS/DS- Usual range	p- Wunsch et al (1996)	ESP- Germany (*)	gg- Wang et al (2001)	CA- Taiwan
c.3- IAWG (1997)	WS- Usual range	q- Izumikawa (1996)	FA(APC*)- Japan(*)	hh- Wang et al (2002)	CA- Taiwan
d- Stegemann and Buenfeld (2003)	FA (APC)- Usual range	r- Jianguo et al (2004)	APC- China	ii- Wang et al (2004)	CA- Taiwan
e.1- Le Forestier and Libourel (1998)	ESP- France	s- Jung et al (2005)	FA(APC*)- Japan	jj- Yang and Tsai (1998)	CA- Taiwan
e.2- Le Forestier and Libourel (1998)	SDS (no ESP)- France	t- Kamon et al (2000)	ESP- Japan	kk- Carignan et al (2005)	FA, ESP, DS, FF- France
e.3- Le Forestier and Libourel (1998)	SDS- France	u- Katsuura et al (1996)	ESP- Japan	ll- He et al (2004)	APC- China
f.1- Alba et al (2001)	FA- Spain(*)	v- Kuo et al (2004)	APC- Taiwan	mm- Park et al (2005)	FA (APC*)- Korea
f.2- Alba et al (2001)	APC- Spain(*)	w- Li et al (2004)	ESP- China	nn- Sorensen et al (2001)	APC, ESP- Denmark
g- Geysen et al (2004b)	APC (SD+FF)- Belgium	x- Mangialard (2001)	FA (APC*)- Italy	oo- Qian et al (2006a,b)	FA- China
h- Li et al (2003a)	FA (APC*)- China	y- Mizutani et al (1996)	APC - Japan	pp- Kim and Kim (2004	FA(APC*)- Korea
i- Aubert et al (2004)	FA (APC*)- France	z- Mulder (1996)	FA (APC*)- Netherlands	qq- Iretskaya et al (1999)	APC- France
j- Chimenos et al (2005)	FF- Spain	aa- Polettini et al (2001)	ESP; FF- Italy	rr- Bodénan and Deniard (2003)	APC- Several countries

Table 6-14: Major oxide compositions of APC residues (wt.%) (reproduced from Quina et al., 2008).



	Auer et al. (1995)	Alba et al. (1997)		Romero et al. (2001)	Li et al. (2003a)	Piantone et al. (2003)	Song et al. (2004)		Cheng and Chen (2004)	Kim and Kim (2004)	
	ESP	FA	APC	FA	FA + APC	APC	SDS	FF	FA	ESP	ESP_wash
CaO	19.3	24.3	27.7	29.34	13.9	24.2	52.9	25.2	19.7	19.50	26.23
SiO_2	20.2	18.8	15.0	11.47	8.57	33.6	5.8	4.7	19.4	7.30	21.94
Al_2O_3	12.3	12.7	7.1	5.75	3.90	11.6	2.8	1.8	10.1	3.20	9.97
Fe_2O_3	1.2	1.6	1.4	1.29	2.58	1.9	2.4	0.95	1.8	1.39	2.08
MgO	2.5	2.6	1.9	3.02	3.16	2.2	2.6	1.3	2.8	2.61	8.32
Na_2O	6.4	5.8	4.1	8.70	14.0	2.2	(a)	10.9	8.9	13.07	2.11
K_2O	6.2	4.3	4.4	7.02	8.77	2.6	1.5	10.6	8.1	11.21	0.84
TiO_2	1.4	1.5	1.0	0.85	0.76	1.7	1.9	1.2	1.9	2.77	3.80
SO_3	8.3	6.4	8.2	(a)	15.36	(a)	6.7	8.0	(a)	9.76	11.93
P_2O_5	1.3	2.7	1.6	1.69	2.81	1.4	1.4	1.2	(a)	1.72	5.76
MnO	(a)	0.12	0.06	0.18	0.12	0.06	(a)	(a)	(a)	(a)	(a)
ZnO	3.0	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	3.02	4.72

ESP – electrostatic precipitator; FA – fly ash; APC – air pollution control residues; SDS – semi-dry absorber; FF – bag filter; (a) – not indicated.

Quina et al., (2008) note that APC largely consists of oxides, carbonates, sulphates and chlorides. They also note that high alkali content is often observed, mainly due to the calcium hydroxide or sodium carbonate used for acid gas removal. This can result in MSWI residues having a high pH, sometimes even greater than 12.5 (a value associated with $Ca(OH)_2$ equilibrium with water).

Quina et al. (2008) also provide an overview of possible treatments for these substances to mitigate environment hazards (a topic beyond the scope of this review). Treatments include: (i) separation processes; (ii) solidification/stabilization; and (iii), thermal methods.

Review of MSW Ash Compositions by Lam et al. (2010)

Lam et al. (2010) review the nature and uses of ash from MSWI and provide compilations of fly ash oxide compositions (Table 6-15), bottom ash oxide compositions (Table 6-16), fly ash heavy metal content (Table 6-17), bottom ash heavy metal content (Table 6-18), fly ash chloride content (Table 6-19) and bottom ash chloride content (Table 6-20). Lam et al. also collate published data on the dioxin content of fly ash and bottom ash (Table 6-21).

Lam et al. (2010) make the following observations:

- The major elements present in fly ash and bottom ash are: Si, Al, Fe, Mg, Ca, K, Na and Cl and SiO_2; Al_2O_3, CaO, Fe_2O_3, Na_2O, K_2O are the major oxides present.
- For heavy metals, Cr, Cu, Hg, Ni, Cd, Zn and Pb are the most commonly found in MSWI ash; Zn and Pb are usually present in relatively higher concentrations.
- MSWI fly ash contains much higher chloride content than MSWI bottom ash. This may be due to the lime scrubber in the air pollution control system, which removes acidic gases such as HCl, thus resulting in a high amount of chloride content remaining in fly ash.
- Generally, the dioxin levels in fly ash in most countries has demonstrated values higher than 1 ng I-TEQ/g, which is the Japan Ministry of the Environment (2001) Environmental Quality Standard for Soils.

Lam et al. (2010) also provide an overview of treatment processes for MSW ash (which is the beyond the scope of this review).

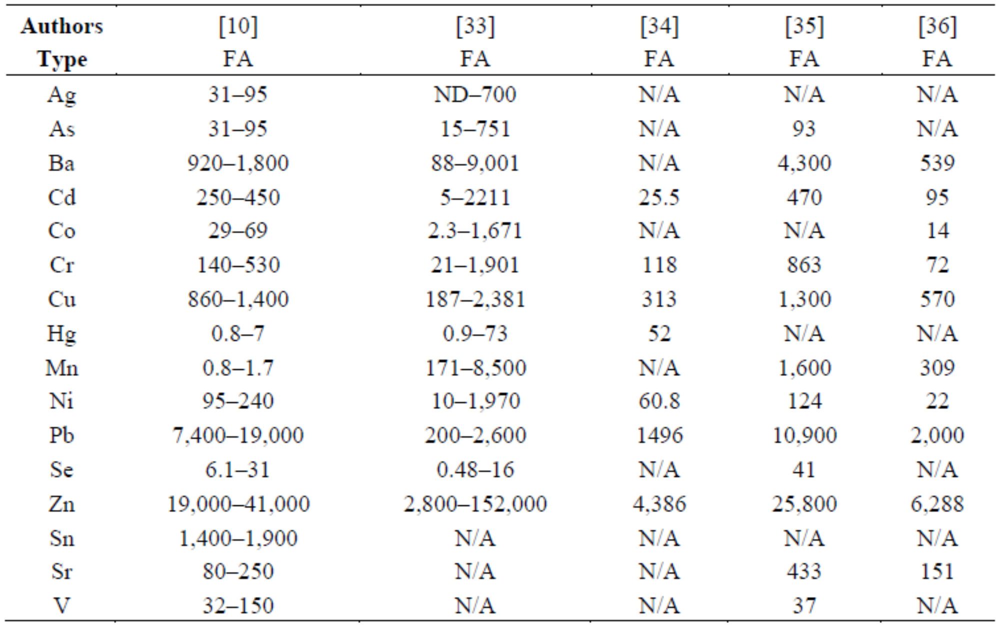
Table 6-15: MSWI Fly Ash Oxide Compositions (reproduced from Lam et al., 2010).

Authors	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]
Type	FA	FA	FA	FA	FA	FA	FA	FA
SiO_2	18.8	11.47	19.4	13.6	18.5	20.5	6.35	27.52
Al_2O_3	12.7	5.75	10.1	0.92	7.37	5.8	3.5	11
CaO	24.3	29.34	19.7	45.42	37.5	35.8	43.05	16.6
Fe_2O_3	1.6	1.29	1.8	3.83	2.26	3.2	0.63	5.04
MgO	2.6	3.02	2.8	3.16	2.74	2.1	1.38	3.14
K_2O	4.3	7.02	8.1	3.85	2.03	4	4.59	8.24
Na_2O	5.8	8.7	8.9	4.16	2.93	3.7	5.8	
SO_3	6.4	N/A	N/A	5.18	14.4	N/A	4.64	8.34
P_2O_5	2.7	1.69	N/A	N/A	1.56	N/A	N/A	N/A
TiO_2	1.5	0.85	1.9	3.12	1.56	N/A	N/A	1.88

Table 6-16: MSWI Bottom Ash Oxide Compositions (reproduced from Lam et al., 2010).

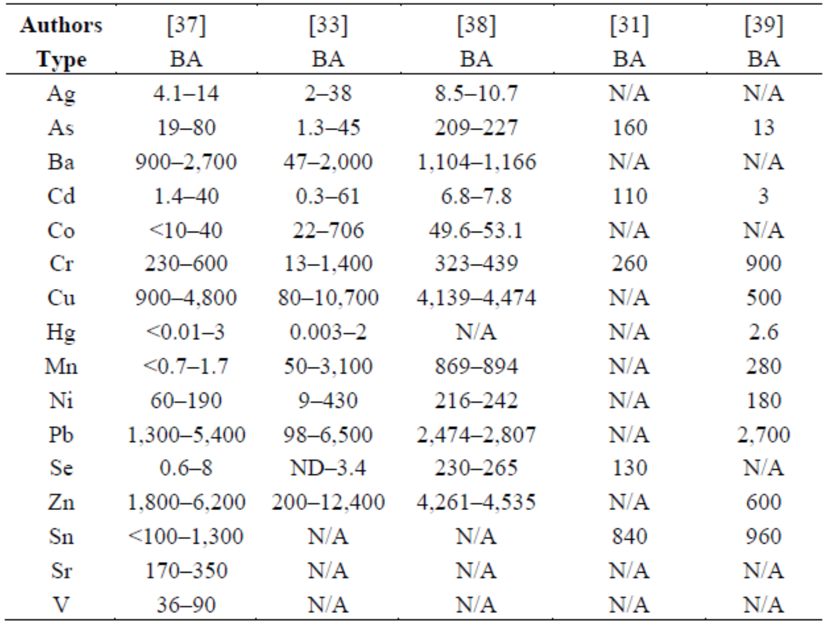
Authors	[29]	[30]	[31]	[32]	[24]	[25]	[27]
Type	BA (150–200 mesh)	MSWI ash	MSWI ash	MSWI ash	BA	BA	BA
SiO_2	27.8	29.4	12.01	5.44	13.44	46.7	49.38
Al_2O_3	9.9	18	8.1	3.1	1.26	6.86	6.58
CaO	25.9	27.2	13.86	42.55	50.39	26.3	14.68
Fe_2O_3	4	13.3	1.21	1.69	8.84	4.69	8.38
MgO	3.3	1.6	2.62	1.83	2.26	2.22	2.32
K_2O	1.8	0.9	7.41	4.31	1.78	0.888	1.41
Na_2O	3.3	3.6	17.19	4.82	12.66	4.62	7.78
SO_3	N/A	N/A	N/A	12.73	0.5	2.18	0.57
P_2O_5	6.9	N/A	N/A	1.62	N/A	0.855	N/A
TiO_2	2	N/A	N/A	0.92	2.36	0.77	N/A

Table 6-17: MSWI Fly Ash Heavy Metal Contents (reproduced from Lam et al., 2010).



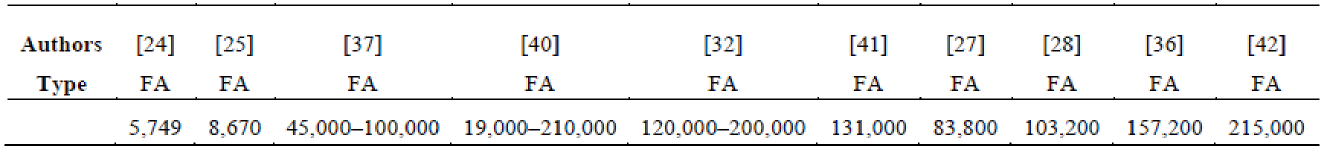
Authors **Type**	[10] FA	[33] FA	[34] FA	[35] FA	[36] FA
Ag	31–95	ND–700	N/A	N/A	N/A
As	31–95	15–751	N/A	93	N/A
Ba	920–1,800	88–9,001	N/A	4,300	539
Cd	250–450	5–2211	25.5	470	95
Co	29–69	2.3–1,671	N/A	N/A	14
Cr	140–530	21–1,901	118	863	72
Cu	860–1,400	187–2,381	313	1,300	570
Hg	0.8–7	0.9–73	52	N/A	N/A
Mn	0.8–1.7	171–8,500	N/A	1,600	309
Ni	95–240	10–1,970	60.8	124	22
Pb	7,400–19,000	200–2,600	1496	10,900	2,000
Se	6.1–31	0.48–16	N/A	41	N/A
Zn	19,000–41,000	2,800–152,000	4,386	25,800	6,288
Sn	1,400–1,900	N/A	N/A	N/A	N/A
Sr	80–250	N/A	N/A	433	151
V	32–150	N/A	N/A	37	N/A

Table 6-18: MSWI Bottom Ash Heavy Metal Contents (reproduced from Lam et al., 2010).



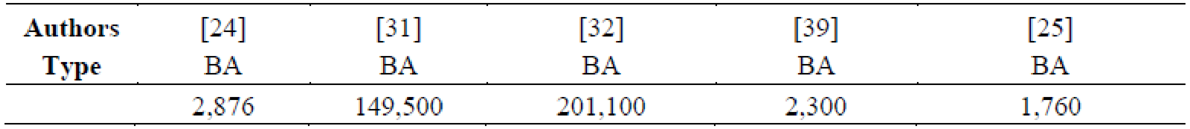
Authors	[37]	[33]	[38]	[31]	[39]
Type	BA	BA	BA	BA	BA
Ag	4.1–14	2–38	8.5–10.7	N/A	N/A
As	19–80	1.3–45	209–227	160	13
Ba	900–2,700	47–2,000	1,104–1,166	N/A	N/A
Cd	1.4–40	0.3–61	6.8–7.8	110	3
Co	<10–40	22–706	49.6–53.1	N/A	N/A
Cr	230–600	13–1,400	323–439	260	900
Cu	900–4,800	80–10,700	4,139–4,474	N/A	500
Hg	<0.01–3	0.003–2	N/A	N/A	2.6
Mn	<0.7–1.7	50–3,100	869–894	N/A	280
Ni	60–190	9–430	216–242	N/A	180
Pb	1,300–5,400	98–6,500	2,474–2,807	N/A	2,700
Se	0.6–8	ND–3.4	230–265	130	N/A
Zn	1,800–6,200	200–12,400	4,261–4,535	N/A	600
Sn	<100–1,300	N/A	N/A	840	960
Sr	170–350	N/A	N/A	N/A	N/A
V	36–90	N/A	N/A	N/A	N/A

Table 6-19: Chloride Contents of MSWI Fly Ash (reproduced from Lam et al., 2010).



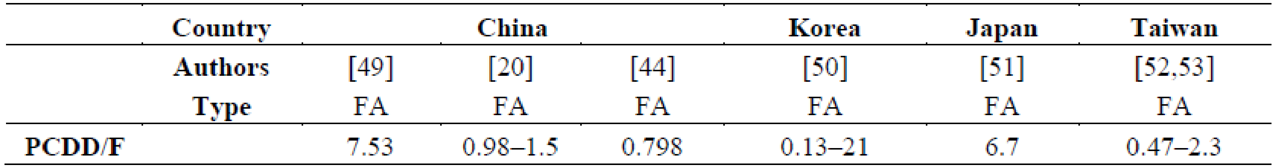
Authors	[24]	[25]	[37]	[40]	[32]	[41]	[27]	[28]	[36]	[42]
Type	FA	FA	FA	FA	FA	FA	FA	FA	FA	FA
	5,749	8,670	45,000–100,000	19,000–210,000	120,000–200,000	131,000	83,800	103,200	157,200	215,000

Table 6-20: Chloride Contents of MSWI Bottom Ash (reproduced from Lam et al., 2010).



Authors	[24]	[31]	[32]	[39]	[25]
Type	BA	BA	BA	BA	BA
	2,876	149,500	201,100	2,300	1,760

Table 6-21: Dioxin content of fly ash (reproduced from Lam et al., 2010).



	Country	**China**			**Korea**	**Japan**	**Taiwan**
	Authors	[49]	[20]	[44]	[50]	[51]	[52,53]
	Type	FA	FA	FA	FA	FA	FA
PCDD/F		7.53	0.98–1.5	0.798	0.13–21	6.7	0.47–2.3

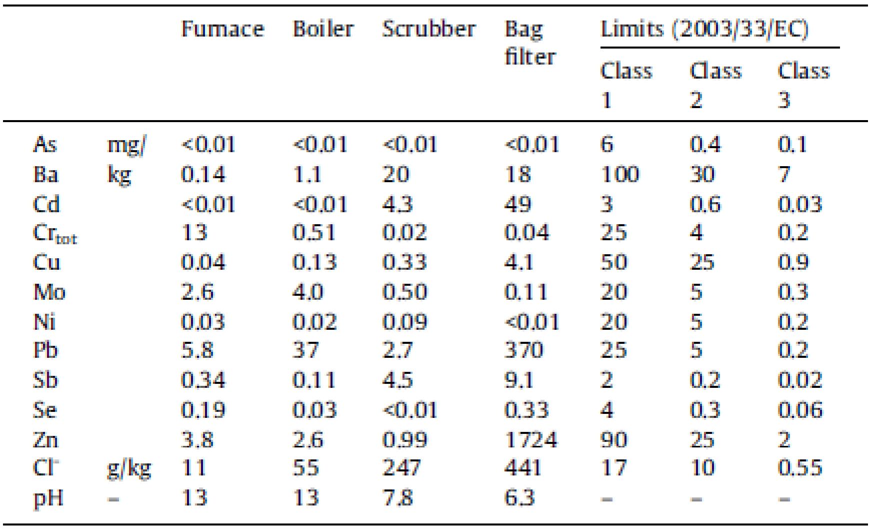
6.4 MSWI Fly Ash Leachate

6.4.1 Belgian MSWI Fly Ash Leachate Data

De Boom and Degrez (2012) report leachate data for the previously described MSWI materials. Leaching tests were applied in accordance with the EN 12457-1 standard (EN 12457-1, 2002) to the different fly ashes and APC residues from the B3 MSWI plant in order to get a global idea of the leaching differences between residues from a same plant (De Boom and Degrez, 2012).

The extracted amounts of the analysed elements are presented in Table 6-22 and are compared with the landfill limits stated by 2003/33/ EC decision (EC, 2003). The limits are for 3 landfill classes: Class 1, 2 and 3, respectively for hazardous, non-hazardous and inert waste. As documented by De Boom and Degrez (2012), furnace ashes are the only residues that would be accepted in a Class 1 landfill without any treatment. The other residues exceed at least the limit in chlorides. The Pb amounts extracted from boiler and particularly bag filter residues are beyond the Class 1 limit. The high Pb leaching from the bag filter residues may be explained by the leachate pH, which is the lowest of all the residues. Zn amounts are likewise quite high for the bag filter residues due to pH. Bag filter residues present the highest extracted amount of Cd, Cu, Sb and Se. The concentrations of Mo and Se in the leachate are too high in some cases for a Class 3 landfill.

Table 6-22: Leachate data for plant B3 MSWI residues and EU landfill limits (reproduced from De Boom and Degrez, 2012).



		Furnace	Boiler	Scrubber	Bag filter	Limits (2003/33/EC)		
						Class 1	Class 2	Class 3
As	mg/kg	<0.01	<0.01	<0.01	<0.01	6	0.4	0.1
Ba		0.14	1.1	20	18	100	30	7
Cd		<0.01	<0.01	4.3	49	3	0.6	0.03
Cr_{tot}		13	0.51	0.02	0.04	25	4	0.2
Cu		0.04	0.13	0.33	4.1	50	25	0.9
Mo		2.6	4.0	0.50	0.11	20	5	0.3
Ni		0.03	0.02	0.09	<0.01	20	5	0.2
Pb		5.8	37	2.7	370	25	5	0.2
Sb		0.34	0.11	4.5	9.1	2	0.2	0.02
Se		0.19	0.03	<0.01	0.33	4	0.3	0.06
Zn		3.8	2.6	0.99	1724	90	25	2
Cl^-	g/kg	11	55	247	441	17	10	0.55
pH	-	13	13	7.8	6.3	-	-	-

Detailed Leaching Studies

A number of detailed studies have been published on the leaching behaviour of MSWI materials. A selection of these studies is briefly described herein.

Arickx et al. (2008) present the results of a study on speciation of Cu in MSWI bottom ash and its relation to leaching behaviour, given that in Flanders the recycling of bottom ash is mainly inhibited by the high leaching of Cu. Although it has been proved that dissolved organic C plays a major role in the Cu leaching, the possible role of inorganic Cu mineral speciation had previously received little attention. Therefore, Arickx et al. investigated the speciation of Cu and found that metallic Cu (with or without an oxide shell), CuO and Cu_2O were the most abundant materials and were most likely present in wire-like structures. Copper also occurred as alloy (brass, bronze, zamak) and was frequently found together with elements such as Ca, Cl and S. Small metallic Cu particles appeared to be trapped in or precipitated on oxides and silicates. Based on these findings, pure Cu minerals were selected and leached as a function of time. The solubility after equilibrium of all studied Cu minerals never exceeded 20 µg/L (which equals 10% of the total Cu leaching). The effect of heating (2 h at 400 °C) was that metallic Cu seemed to be converted to Cu oxide (mostly CuO) and that the particles were more porous after heating. These conclusions were verified by XRD analysis of the heated pure Cu minerals. After heating, the Cu minerals were also leached as a function of time. Results indicate that their leaching had slightly increased in comparison with the non-heated Cu minerals. However, the major decrease in Cu leaching in heated bottom ash, more than counters this effect and was thus attributed to the destruction of organic matter and not to the relatively small change in Cu speciation.

Carsch et al. (1986) report the results of batch and column experiments in which polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans where leached from incinerator fly ash using distilled water, toluene, hexane, and methanol/water. Toluene extracted up to 90% of the polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF). In hexane and 80% methanol in water, all homologues were detected in the ppt range. In water, low concentrations of the high chlorinated PCDD/PCDF could be detected. Such contaminated water was passed through soil and it was shown that even sandy soil reduced PCDD/PCDF in water to below limits of detection.

Cornelis et al. (2012) describe the leaching of antimonate (Sb(V)) and antimonite (Sb(III)) in MSWI bottom ash as a function of pH and degree of carbonation. Total (Sb(V)+ Sb(III)) leaching was lowest (1.2 mg kg^{-1}) at the natural pH (10.6) of uncarbonated bottom ash. Chemical analysis showed that acidification and carbonation increased Sb(V) leaching , but decreased Sb(III) leaching. Geochemical modelling suggested that Sb(V) concentrations approached equilibrium with the romeites (calcium antimonates). It was therefore hypothesised that dissolution of romeite controls antimonate leaching in the pH range 8–11 in MSWI bottom ash.

Dabo et al. (2009) describe the chemical evolution of leachate associated with MSWI bottom ash used in a test road site over a period of 10 years. Data interpretation was supported by geochemical modelling in terms of main pH-buffering processes. The leachate pH and concentrations of major elements (Ca, Na and Cl) as well as Al and heavy metals (Cu, Pb and Zn) quickly dropper during the first 2 years to asymptotically reach a set of minimum values over 10 years. This behaviour is similar to that associated with a reference road built with natural calcareous aggregates.

Dijkstra et al. (2006) studied the leaching behaviour of major components (Al, Ca, SO_4, Mg, Si, Fe, Na and DOC) and trace elements (Ni, Zn, Cd, Cu, Pb, Mo and Sb) from MSWI bottom ash as a function of time over a wide range of pH. Equilibrium geochemical modelling was used to enable a process-based interpretation of the results and to investigate whether equilibrium was attained during the time scale of the experiments. Although the majority of the elements did not reach steady state, leached concentrations over a wide pH range were shown to closely approach model curves within 168 h. The different effects that leaching kinetics may have on the pH dependent leaching patterns were identified for a wide range of elements, and could generally be explained in a mechanistic way.

Fischer et al. (1992) conducted a study in which fly ash samples were contaminated or spiked with chlorinated benzenes, polychlorinated biphenyls and dioxins/furans. These were investigated for their leachability from waste deposits such as salt mines by standard elution tests. The leaching rate with water was low. Using a saturated saline solution the leaching rates of chlorinated benzenes and polychlorinated biphenyls become even lower, while there was a minor effect on higher chlorinated dioxins/furans. The solidification of fly ash with 25 % cement increased the leachates contents of higher chlorinated benzenes and biphenyls.

François and Criado (2007) report the results of a study in which leachate was monitored at a test road that included treated fly ash (TFA) from a MSWI. The treatment process included: washing intended to remove soluble salts; phosphate addition intended to trap heavy metals in stable crystalline phases as apatite (a calcium phosphate mineral); and lastly, calcination intended to oxidise organic compounds, in particular dioxins and furans. The 1-year monitoring campaign included a large number of water quality parameters and showed that three chemical parameters (SO_4, Cr, and chromates) were present in the test section leachate at concentrations which were significantly higher than in the reference section. However, the authors note that that the TFA used in this experiment had been chosen for its high Cr content out of a group of 10 samples collected from across Europe.

Hyks et al. (2009) report the results of 24 month duration column percolation experiments, whereby Ca, Fe, Mg, K, Na, S, Al, As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Zn, Mo, Sb, Si, Sn, Sr, Ti, V, P, Cl, and dissolved organic carbon was leached from two different MSWI APC residues under conditions corresponding to more than 10 000 years of leaching within a conventional landfill. Less than 2% of the initially present As, Cu, Pb, Zn, Cr, and Sb leached during the course of the experiments. Concentrations of Cd, Fe, Mg, Hg, Mn, Ni, Co, Sn, Ti, and P were generally below 1 µg/L. Column leaching data were further used for the development of a two-step geochemical model (implemented using PHREEQC) in order to: (i) identify solubility controlling minerals; and (ii) evaluate their interactions in a water-percolated column system over L/S ratio of 250 L/kg. Adequate predictions of pH, alkalinity, and the leaching of Ca, S, Al, Si, Ba, and Zn were obtained and it was suggested that removal of Ca and S together with depletion of several minerals apparently caused the dissolution of ettringite-like phases. The authors also note that a significant increase in leaching of oxyanions (especially Sb and Cr) was observed at a late stage of the leaching experiments.

Liu et al. (2008) undertook a 70-day long experiment to investigate the release of major heavy metals (Cu and Pb) and polycyclic aromatic hydrocarbons (PAHs) from several particle fractions of bottom ash under a static leaching condition. Bottom ash was immersed in water at different initial pH values. Results showed that: (1) the leaching behaviour of Cu and Pb was much similar with that depicted by the standardized leaching tests, and fitted well with a solubility-controlling mechanism; (2) the sorption mechanism on the newly formed phases may control the solubility of Pb, whereas the dissolved organic carbon (DOC) may play an important role in the solubility of Cu; and (3) the leached PAHs were degraded during the later period of leaching process.

Olsson et al. (2009) investigated the influence of salt or dissolved organic matter (DOM) on metal leaching from MSWI bottom ash using a column experiment. The presence of salt (0.1 M NaCl) resulted in a small increase of As leaching; no impact on leachate concentration was found when lake water DOM (35.1 mg/L dissolved organic carbon) was added. Most of the added DOM was retained within the material. X-ray spectroscopy revealed that Cu(II) was the dominant form of Cu and that it probably occurred as a CuO phase. It was suggested that the Cu^{2+} activity in the MSWI bottom ash leachate was most likely determined by the dissolution of CuO together with the formation of Cu–DOM complexes and possibly also by adsorption to (hydr)oxide minerals. The addition of lake DOM in the influent resulted in lower saturation indices for CuO in the leachates, which may have been be due to slow CuO dissolution kinetics in combination with strong Cu–DOM complexation.

Yasuhara and Katami (2007) investigated the leaching behaviour of dibenzo-p-dioxins and furans from landfill containing bottom ash and fly ash from MSWI. Leaching tests used pure water, non-ionic surfactant solutions, ethanol solutions, or acetic acid solutions as elution solvents in a large-scale cylindrical column packed with ash. It was found that larger amounts of dioxins were eluted from both bottom ash and fly ash with ethanol solution and acetic acid solution than with pure water. Large quantities of dioxins were leached from fly ash (but not bottom ash) by non-ionic surfactant solutions.

Zhang et al. (2008) report the results of leaching experiments and geochemical modelling of the correlation between leaching behaviour of MSWI fly ash and variation in pH. The authors suggest that the leaching behaviour of Pb and Cd is controlled by dissolution/precipitation mechanisms; whereas for Zn and Ni, it is influenced by surface adsorption reactions. Zhang et al. (2008) also modelled the stabilisation of fly ash by phosphate addition.

7 Further Scenario Development

7.1 Approach

A "top-down" approach to evaluating FEPs and scenarios was undertaken. The aim was to develop a set of "high-level" FEPs representing the main features of the system, sufficient to broadly describe credible alternative evolution scenarios, and to identify key risk factors. A systematic process built confidence that all of the main factors are addressed, without using an overly complicated methodology.

The team's understanding of the "expected" status of each FEP was used to inform a description of an "expected evolution" scenario. Key "safety functions" were identified that represent functions of critical importance to safety provided by certain features within the expected evolution scenario. "Alternative evolution" scenarios were then defined based upon:

- an analysis of "external" FEPs (or EFEPs); and
- alternative assumptions for key FEPs whereby the safety functions assumed in the "expected evolution" scenario are not provided, or are compromised with time.

The EFEPs are a class of FEPs that, although being part of the global system, are external to the process system of interest. However, EFEPS might act upon the process system to alter its evolution.

The aim is to define a set of scenarios that cover the main "failure modes" for the system, and to bracket key uncertainties. The list of scenarios should not be overly detailed, but should be sufficient to address the main issues.

The subsequent assessment will aim to show that performance meets required criteria for the expected evolution scenario and that for alternative evolution scenarios, performance still meets the required criteria, and/or the probability of scenario occurrence is very low. Additional conceptual model variant and sensitivity runs beyond those listed in the scenario descriptions may be undertaken as part of the assessment process.

The FEP and scenario analysis was initially undertaken by two experts from the contractor team with experience in identifying FEPs and scenarios for a range of approximately analogous projects. Two other experts from the contractor team then reviewed the results. The analysis was then reviewed by staff of AkzoNobel and audited against:

- the risks identified in existing PSCT assessment documentation;
- detailed FEP lists produced for other approximately analogous assessment programmes.

The auditing process built confidence that the scenarios identified are sufficiently comprehensive to cover all the key issues of importance for demonstrating future performance.

7.2 Note on Timeframes

The process commenced with a brief review of the project context (Section 3). It was noted that to fully describe the scenarios likely to be of relevance, a more detailed description of the timeframes of interest may be valuable. The following key phases were identified.

- The process of backfilling each cavern is likely to take between 1 and 3 years.
- Backfill curing and initial self-consolidation will then occur over the next few years.
- Further self-consolidation is likely to continue over at least the following couple of decades.
- It is likely that monitoring will need to continue for a few more years after the rate of volume change due to self-consolidation has been shown to decrease sufficiently to build confidence that eventual stabilisation will be achieved. This period could be from a few years to a few decades, depending upon how the characteristics of the actual backfill that is developed (which had not been finally decided at the time of writing). Note that from an assessment perspective, this period is also important as the potential to undertake mitigating action in response to any issues noted through monitoring will help build confidence in safety during this period.
- The assessment needs to consider timeframes beyond the monitoring period to build confidence that the system will evolve towards long-term stability and environmental safety. An assessment period of up to 10,000 years has been identified.

7.3 High-Level FEPs

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. Underlying geological formation (i.e. the Solling Formation)
3. Overlying geological formations
4. Boreholes (including those boreholes used for backfill, and others)

These FEP groups were then considered individually in order to identify:

- Features associated with each sub-system component represented by the FEP groups;
- Processes by which those features might interact.

Note that at this stage the interaction processes were elicited directly.

The resulting high-level FEPs associated with these groups are listed respectively in Table 7-1 to Table 7-4 below.

Additional details for individual FEPs may be added in subsequent versions of this note; similarly the FEP list itself may be updated.

Table 7-1: High-level FEPs associated with the Cavern Zone.

Cavern Zone FEPs	Notes
1. Cavern	These FEPs describe features and processes associated with the internal geometry of each cavern of interest.
1.1. Cavern internal geometry	
1.1.1. Change in geometry due to salt creep	
1.1.2. Change in geometry due to loss of material from roof/walls, including roof / wall collapse	
1.1.3. Change in geometry due to any salt dissolution/precipitation (inc. pressure solution and direct fluid dissolution)	
1.1.4. Erosion due to backfilling process	
1.2. Cavern roof/wall	
1.2.1. Cavern roof/wall material	
1.2.2. Sump material	
1.3. Stabilisation Backfill	
1.3.1. Cementitious component	There is no cementitious component for the AN08 and AN14 backfill recipes that have been proposed by AkzoNobel, although the flyash contains a very small component of CaO and other clinker-like phases, which may behave as a cement.
1.3.2. Waste component	
1.3.2.1. Physical properties	
1.3.2.2. Contaminants	
1.3.2.2.1. Heavy metals	
1.3.2.2.2. Organics	Note that there are analytical data for dioxins and furans in the flyash that is proposed to be used for the backfill. These organics are not very soluble, but are toxic if ingested.
1.3.2.2.3. Brine	
1.3.2.2.4. Others	
1.3.3. Backfill heterogeneity	
1.3.3.1. Physical heterogeneity	
1.3.3.2. Chemical heterogeneity	
1.3.4. Backfill geometry	
1.3.5. Gas associated with wastes/backfill	
1.3.6. Waters associated with waste/backfill	
1.3.7. Backfill curing and related processes	

Cavern Zone FEPs	Notes
1.3.7.1. Geometry evolution	
1.3.7.2. Chemical and physical properties evolution	
1.3.7.2.1. Solids	
1.3.7.2.2. Pore fluids	
1.3.7.2.3. Contaminant release due to chemical or physical evolution during curing	
1.3.7.3. Temperature evolution	
1.3.8. Backfill consolidation and related processes[1]	
1.3.8.1. Geometry evolution	
1.3.8.2. Chemical (inc. biochemical) and physical properties evolution	
1.3.8.2.1. Solids	
1.3.8.2.2. Pore fluids	
1.3.8.2.3. Contaminant release due to chemical or physical evolution during consolidation	
1.3.8.2.3.1. Due to initial consolidation	
1.3.8.2.3.2. Due to longer-term continued consolidation	
1.3.8.2.3.3. Due to salt creep and waste pressurisation	
1.3.9. Backfill migration (liquid/uncured or solid) inc. response to cavern geometry change /pressurisation	
1.4. Existing cavern fluids	
1.4.1. Gas	
1.4.2. Brine	
1.4.3. Diesel oil (once used as blanket oil, not present in all caverns)	
1.5. Head space	
1.6. Advective flow/transport in backfill (inc. contaminant transport)	
1.6.1. Waters (inc. brine)	
1.6.2. Gas	
1.6.3. Other fluids (e.g. hydrocarbons)	
1.7. Diffusive transport in backfill (inc. contaminant transport)	
1.7.1. Waters (inc. brine)	

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[1] NB. Curing and consolidation timescales will overlap, so there is some double counting in these FEP descriptions.

Cavern Zone FEPs	Notes
1.7.2. Gas 1.7.3. Other fluids (e.g. hydrocarbons) 1.8. Contaminant retardation 1.8.1. Sorption/de-sorption and cation exchange 1.8.2. Contaminant solubility / co-precipitation 1.8.3. Rock-matrix diffusion	
2. Cavern rocks including pillars 2.1. Halite 2.2. Other Evaporites 2.3. Shale interbeds and shelving 2.4. Hydrogeological properties 2.5. Chemical properties 2.6. Mechanical properties 2.7. Cavern rock fluids 2.7.1. Gas 2.7.2. Brine 2.7.3. Diesel oil (once used as blanket oil, not present in all caverns) 2.8. Change in geometry due to creep 2.9. Change in geometry due to dissolution / precipitation 2.10. Fracturing 2.11. Induced seismicity 2.12. Self-healing 2.13. Hydraulic gradients and pressures 2.14. Advective flow/transport (inc. contaminant transport) 2.14.1. Waters (inc. brine) 2.14.2. Gas 2.14.3. Other fluids (e.g. hydrocarbons) 2.15. Diffusive transport (inc. contaminant transport) 2.15.1. Waters (inc. brine) 2.15.2. Gas 2.15.3. Other fluids (e.g. hydrocarbons) 2.16. Contaminant retardation 2.16.1. Sorption/de-sorption and cation exchange 2.16.2. Contaminant solubility / co-precipitation 2.16.3. Rock-matrix diffusion 2.17. Temperature gradients	These FEPs describe features and processes associated with the rock zone immediately surrounding each cavern. FEPs 2.4 “Hydrogeological properties”, 2.5 “Chemical properties” and 2.6 “Mechanical properties” cover both the present properties of the rock and the future evolution of these properties.

Table 7-2: High-level FEPs associated with the underlying Geological Formation.

Underlying Geological Formation FEPs	Notes
3. Solling Formation 3.1. Hydrogeological properties 3.2. Chemical properties 3.3. Mechanical properties 3.4. Induced seismicity 3.5. Solling Formation fluids 3.5.1. Gas 3.5.2. Brine 3.5.3. Hydrocarbon liquids 3.6. Advective flow/transport (inc. contaminant transport) 3.6.1. Waters (inc. brine) 3.6.2. Gas 3.6.3. Other fluids (e.g. hydrocarbons) 3.7. Diffusive transport (inc. contaminant transport) 3.7.1. Waters (inc. brine) 3.7.2. Gas 3.7.3. Other fluids (e.g. hydrocarbons) 3.8. Contaminant retardation 3.8.1. Sorption/de-sorption and cation exchange 3.8.2. Contaminant solubility / co-precipitation 3.8.3. Rock-matrix diffusion 3.9. Hydraulic gradients and pressures 3.10. Temperature gradients	These FEPs describe features and processes associated with the geological formation immediately underlying the cavern zone. FEPs 3.1 "Hydrogeological properties", 3.2 "Chemical properties" and 3.3 "Mechanical properties" cover both the present properties of the rock and the future evolution of these properties.

Table 7-3: High-level FEPs associated with overlying Geological Formations.

Overlying Geological Formations FEPs	Notes
4. Hydrogeological properties 4.1. Salt 4.2. Anhydrite 4.3. Claystone 4.4. Muschelkalk 4.4.1. Rock 4.4.2. Artesian aquifer 4.5. Niedersachsen and Altena 4.6. North Sea Supergroup 4.7. Near-surface formations 4.7.1. Rocks 4.7.2. Shallow aquifers 4.7.3. Soils	These FEPs describe hydrogeological properties associated with the geological formations overlying the cavern zone. (See below for processes associated with these domains, and for general categories of waters that might be specifically relevant to each of these formations). In each case, the hydrogeological properties could be sub-divided to give more detailed FEPs for each formation (porosity, density etc.). FEPs 4 "Hydrogeological properties" covers both the present properties of the rock and the future evolution of these properties.
5. Chemical properties 5.1. Salt 5.2. Anhydrite 5.3. Claystone 5.4. Muschelkalk 5.5. Niedersachsen and Altena 5.6. North Sea Supergroup 5.7. Near-surface formations 5.7.1. Rocks 5.7.2. Shallow aquifers 5.7.3. Soils	These FEPs describe chemical properties associated with the geological formations overlying the cavern zone. (See below for processes associated with these domains). In each case, the properties could be sub-divided to give more detailed FEPs for each formation. In general the chemical makeup of each rock will need to be matched to different classes of water (see below) to define the likely chemical conditions in waters held within these formations. FEP 5 "Chemical properties" covers both the present properties of the rock and the future evolution of these properties.
6. Mechanical properties 6.1. Salt 6.2. Anhydrite 6.3. Claystone 6.4. Muschelkalk 6.4.1. Rock 6.4.2. Artesian aquifer 6.5. Niedersachsen and Altena 6.6. North Sea Supergroup 6.7. Near-surface formations	As above, except these FEPs reflect mechanical properties of each formation, and again could be appropriately sub-divided if required. FEPs 6 "Mechanical properties" covers both the present properties of the rock and the future evolution of these properties.

Overlying Geological Formations FEPs	Notes
6.7.1. Rocks 6.7.2. Shallow aquifers 6.7.3. Soils	
7. Formation boundaries	General FEP reflecting all the boundaries between formations.
8. Structures (faults and fractures) 8.1. Intra-formation structures 8.2. Inter-formation structures	Reflects structural features that might occur across or within formations. Note, in particular for the latter case, these can be considered to be applicable to each formation noted above; each FEP is noted once here, rather than subdivided into other FEPs for each formation, in order to limit the overall length of the list.
9. Aquifers 9.1. Saline (deeper) aquifers 9.2. Fresh water (near-surface) aquifers	As for structures, this is a general category capturing the range of aquifers that might exist in relevant domains. Particularly important may be the Muschelkalk aquifer, and those associated with near-surface formations; hence, relevant properties of these domains are explicitly highlighted under other FEPs. Other aquifers (of uncertain presence) may also be relevant considerations. However, the Muschelkalk and near-surface aquifers represent the main known environmental receptors for the impact/risk assessment, as they reflect the main domains that might be exploited in a manner which could lead to impacts to humans, and are receptors in their own right, as defined by the Groundwater Directive.
10. Other formation fluids 10.1. Gas 10.2. Water 10.3. Hydrocarbon liquids	Covers fluids that might exist in the formations noted above that are not explicitly recognised as aquifer waters.
11. Change in geometry due to creep	A process that might act on or within one or more of the formations identified that will tend to deform geometry.
12. Change in geometry due to dissolution/precipitation	Processes that could lead to changes in geometry and/or structure of formations of interest.
13. Fracturing	
14. Induced seismicity **15. Self-healing**	
16. Hydraulic gradients and pressures	Characterising driving forces for fluid migration
17. Advective flow/transport (inc. contaminant transport) 17.1. Waters (inc. brine) 17.2. Gas	Processes that might lead to fluid flow and/or contaminant migration.

Overlying Geological Formations FEPs	Notes
17.3. Other fluids (e.g. hydrocarbons)	
18. Diffusive transport (inc. contaminant transport) 18.1. Waters (inc. brine) 18.2. Gas 18.3. Other fluids (e.g. hydrocarbons)	
19. Contaminant retardation 19.1. Sorption/de-sorption and cation exchange 19.2. Contaminant solubility / co-precipitation 19.3. Rock-matrix diffusion	Processes that might act to limit contaminant mobility.
20. Contaminant release from rocks due to leaching / chemical changes	Recognises the potential for other contaminants to be leached or otherwise released from rocks into waters, for example in response to changes in chemistry/pH.
21. Temperature gradients	

Table 7-4: High-level FEPs Associated With Boreholes

Borehole FEPs	Notes
21. Borehole bores 21.1. Water-filled component 21.2. Gas-filled component 21.3. Contaminant/waste transport within bores	Concerns the central bore associated with each borehole.
22. Borehole casings 22.1. Steel casings 22.2. Steel casing perforations (design or through corrosion) 22.3. Cement bonding 22.4. Contaminant/waste transport within an annulus associated with the casing/ outside the casing (e.g. due to a failed/incorrectly placed packer)	Reflects the physical status of each component of the borehole, its casing, and the surrounding zones, noting the potential for contaminant transport associated with those zones.
23. Borehole seals	
24. Physically/chemically disturbed zone around borehole (inc. breakouts, remedial cement jobs etc.)	
25. Contaminant/waste transport within the disturbed zone	
26. Chemical (inc. biochemical)/physical evolution 26.1. Corrosion of steel casings	Represents some of the key mechanisms by which different components of each borehole may evolve with time.

Borehole FEPs	Notes
26.2. Evolution of cement bonding 26.3. Evolution of the borehole seal 26.4. Physical deformation due to external stresses (e.g. rock creep) 26.5. Physical deformation due to chemical processes 26.6. Gas pressurisation within bores (due to corrosion, mechanical effects etc.) 26.7. Pressure gradients across seals	
27. Residual contamination from drilling and other operational activities (e.g. drilling fluids)	Recognises that some historical contamination may still be present.
28. Induced Seismicity	Borehole drilling could act to induce small-scale seismicity.

7.4 EFEPs

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** (inc. 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).
5. **Accidents and unplanned events.**

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 e.g. contact with wastes during borehole exploration for resources. This scenario is also, however, considered relatively unlikely to occur.

7.5 Expected Evolution Scenario

On the basis of the current system understanding, including best estimates of the status of the above FEPs, the following expected evolution scenario description has been defined.

- Backfill will be injected successfully and fill the majority of all the caverns, to the level currently estimated.
- Backfill will "cure" and then consolidate over the timescales defined above. The backfill will not migrate out of the intended zone within the caverns during this process.

- Post-curing chemical evolution of the backfill will not compromise the mechanical or containment performance of the backfill. Backfill will thus provide mechanical safety functions to design performance levels.
- There will be some residual cavern migration due to the remaining head-space in the caverns. However the overlying formations provide the expected resistance to deformation. That is, the effect of the migration will be attenuated by formations between the caverns and the ground surface.
- It is assumed that none of the cavern roofs penetrate the anhydrite layer at time zero.
- It is assumed that pillars between caverns will not fail – that is, there will be no significant interaction between caverns for this scenario.
- However, there will be some continuing roof and wall collapse during and after the main phase of residual cavern migration.
- There will be limited interaction with the Solling Formation through the base of the caverns.
- There will be some diffusion of contaminants, and possibly advective transport, of contaminants out of the wastes within the backfill. However releases rates from the backfill are expected to be low.
- Borehole seals and materials will all be sealed, will then perform as designed, and will then undergo slow degradation with time, with no major failures until the medium to longer term; the scenario recognises a more significant probability of some failure after 1000+ years.
- Released contaminants may diffuse to other formations including the Solling formation. There may also be some transport within faults and fractures, but this will be limited. There may be some migration along boreholes, but again this will be limited. Fluxes to receptor domains of interest e.g. aquifers are expected to be low.
- It is assumed that the topography and use of the surface environment will not evolve significantly; climate change will cause limited change in surface land use e.g. agricultural practices.
- Density differences between backfill and salt will not have a substantial impact long-term.
- There will be no substantial temperature changes anywhere in the system throughout the assessment timeframe.

7.6 Safety Functions

The expected evolution scenario recognises the following key safety functions provided by the system.

- Structural stability, provided by the backfill.
- Resistance to deformation, provided by geological formations.
- Contaminant containment, provided by the backfill and the borehole components (including seals, casing etc.), which prevents contaminants from migrating to

shallower levels, recognizing that the main potential source of the contaminants will be the backfill itself.
- Isolation of contaminants from receptors, by the overlying geological formations.

7.7 Alternative Evolution Scenarios

Alternative scenarios have been defined on the basis of:

- Potential for action of EFEPs on the system to alter its evolution from that expected.
- Potential for failure of key safety features and related FEPs, exploring key “failure mode” scenarios whereby the above safety functions are not provided.
- Plausible alternative assumptions for other FEPs that are not critical to the prime safety functions, but have an important if secondary role in estimating impacts.

Subsequently, additional uncertainty and sensitivity cases may be defined, based upon the scenarios identified, exploring the importance of key parameters / conceptual representations within mathematical models.

A list of alternative evolution scenarios defined on the above basis is provided in Table 7-5, together with a description of how each one is treated in the assessment.

Table 7-5: Alternative evolution scenarios.

No.	Alternative Evolution Scenario	Description	Treatment in the Assessment
1.	Do nothing	Caverns are not backfilled. The risk of cavern collapse is higher than for the expected evolution case (exploration of how much higher is an aim of the scenario).	Explicit treatment by scoping calculations and qualitative arguments.
2.	Interaction between caverns	Pillar failure could lead to two caverns becoming one; partial pillar failure might also be relevant; hydraulic connections associated with partial failure might occur.	Explicit treatment by scoping calculations and qualitative arguments.
3.	Collapse of roof within residual headspace	Benefit of anhydrite beam for deformation resistance is bypassed. The effects of this scenario would be similar to those that would occur if the backfill does not provide the required structural support.	This scenario is subsumed within the base case. Roof collapse is assumed to occur in all the variants of the base case.
4.	Backfill doesn't provide required structural support	Backfill placement, curing and/or consolidation does not proceed as expected and as a result, caverns are not filled to the extent designed, or caverns are filled but the backfill does not have the expected mechanical strength.	Explicit treatment by scoping calculations and qualitative arguments.
5.	Overlying formations provide greater / lower levels of deformation resistance than expected	For example, "beam failure" occurs much more quickly, or alternatively, beams last for much longer.	This scenario is subsumed within the scenario "Backfill doesn't provide required structural support". In an alternative case of this latter scenario the backfill doesn't provide required structural support and therefore collapse of the overlying formations becomes a key factor controlling release of contaminants.
6.	Backfill migration	Encompassed here is the possibility that, due to a lack of curing and thus support from the backfill, vertical cavern migration results, and the unsolidified backfill migrates vertically into the migrating void.	Explicit treatment by scoping calculations and qualitative arguments.

No.	Alternative Evolution Scenario	Description	Treatment in the Assessment
7.	Less contaminant retardation by backfill than expected	Backfill does not effectively contain waste contaminants – contaminant release is unretarded by waste matrix or chemistry.	Explicit treatment by scoping calculations for an alternative case of the expected evolution scenario and qualitative arguments.
8.	Borehole seal/materials fail	Boreholes either are not sealed correctly OR materials degrade much more quickly than expected, providing a conduit for contaminant (or indeed waste, for uncured backfill scenario) transport.	Explicit treatment by scoping calculations and qualitative arguments.
9.	Faults/fractures provide transport pathway to receptor (aquifer)	Faults/fractures provide conductive feature linking cavern with aquifer.	Explicit treatment by scoping calculations and qualitative arguments.
10.	Multiple barrier failure	Combination of the above, testing the cautious case whereby a source-pathway-receptor connection clearly exists. NB might be through multiple linked pathways, e.g. borehole connecting with a fracture.	Explicitly treated by qualitative arguments based on outputs from calculations designed to explore other scenarios.
11.	Transport pathway via Solling Formation	Recognises possibility that floor of the caverns is mechanically fractured or otherwise dissolved / compromised, such that there is a flow path between the cavern and the Solling.	This scenario is subsumed in the “Interaction between caverns” scenario.
12.	Permeable interbeds in salt formations provide hydraulic connection between caverns	Maybe enhanced possibility of lateral contaminant transport in such cases.	This scenario is subsumed in the “Interaction between caverns” scenario.
13.	Human intrusion	Accidental human intrusion directly into a backfilled cavern (e.g. during exploration drilling) is unlikely but cannot be ruled out. In any case material that would be intruded into is not particularly hazardous on contact.	The effects of this scenario are bounded by other failure scenarios (borehole seals / materials fail; collapse of roof within residual headspace; backfill doesn’t provide required structural support; less contaminant retardation by backfill than expected; multiple barrier failure). However, human intrusion is recognized to be potentially important and therefore needs to be considered explicitly.

No.	Alternative Evolution Scenario	Description	Treatment in the Assessment
			Consequently, the scenario is treated by discussing it explicitly in the light of results from calculations designed to explore the above-mentioned failure scenarios.
14.	Exploitation of natural resources	This scenario is similar to the accidental human intrusion scenario except that exploitation of natural resources covers human activities to exploit resources that are adjacent to a backfilled cavern. These activities may include pumping of potable groundwater from shallow aquifers above a backfilled cavern and development of new caverns adjacent to the backfilled cavern during brine extraction. This scenario is treated in a similar fashion to the Human Intrusion scenario.	The effects of this scenario are bounded by other failure scenarios (borehole seals / materials fail; collapse of roof within residual headspace; backfill doesn't provide required structural support; less contaminant retardation by backfill than expected; multiple barrier failure). However, exploitation of natural resources is recognized to be potentially important and therefore needs to be considered explicitly. Consequently, the scenario is treated by discussing it explicitly in the light of results from calculations designed to explore the above-mentioned failure scenarios.
15.	Climate and landscape change	This scenario concerns temporal changes in surface environments caused by climate change and on-going atmosphere – hydrosphere – solid earth interactions (i.e. recognizing that even under constant climatic conditions the landscape will evolve), other than those changes that would be caused by glaciation. While glaciation is a particular manifestation of climate change, if it occurred glaciation could potentially impact upon surface and deep sub-surface environments more significantly than other kinds of climate-related variations. Hence glaciation is considered as separately below. In this scenario climate change refers to variations in atmospheric temperature and quantities, patterns and characteristics of meteoric precipitation (i.e. whether precipitation is in the form of liquid water, or snow/ice). The scenario also covers changes in the characteristics of surface water bodies (i.e. whether they are free water or	Climate and landscape changes are not expected to fundamentally change the processes by which leachate might escape from a backfilled cavern. Over the 10,000 year timescale of the assessment general weathering and erosion in the Hengelo area are not predicted to cause the land surface to regress significantly towards a backfilled cavern. Similarly changes in landscape are not expected to have a significant direct effect upon a backfilled cavern or the overburden at depths of more than a few tens of metres. Climate and landscape changes would probably cause receptors to change (e.g. the size and spatial distribution of the human population). However, the receptors of primary interest to the Phase 1 PSCT assessment are the shallow groundwater aquifers, which would be impacted before even shallower subsurface (to a few tens of metres) and surface receptors are impacted. Consequently the effects of climate and landscape changes on the shallower subsurface

No.	Alternative Evolution Scenario	Description	Treatment in the Assessment
		ice) and sea level changes. Landscape change here refers to all variations in topography, surface habitats, vegetation, spatial distributions of surface water bodies (lakes and rivers) and buildings that will occur as a result of: • the present atmosphere – hydrosphere – solid earth interactions; • climate variations that change these interactions; • anthropogenic activities (noting that changed anthropogenic activities will be coupled to climate change and landscape change).	and surface receptors are not considered explicitly. Changes in the shallow aquifers due to climate and landscape changes are expected to be related only to changing hydrogeology. Hydrogeological changes due to climate and landscape change could be more significant than changes in landscape and surface and shallow subsurface water. However, it is considered that the effects of these hydrogeological changes will be within the uncertainty ranges of impacts that are consistent with hydrogeological parameter uncertainties. For these reasons changes in landscape, shallower subsurface receptors (to a few tens of metres) and surface receptors are screened out. Changes in the deeper groundwater system (shallower aquifers and deeper formations) due to climate and landscape change are addressed by a combination of qualitative discussion and by subsuming them within the failure scenarios (borehole seals / materials fail; collapse of roof within residual headspace; backfill doesn't provide required structural support; less contaminant retardation by backfill than expected; multiple barrier failure).
16.	Glaciation	Glaciation concerns the development of glaciers and ice sheets and is here taken to include related phenomena such as permafrost development. Were the site of a backfilled cavern to be glaciated the cavern and its backfill would be subjected to increased loading (effectively the overburden thickness would be increased). Isostatic depression and uplift would occur during glacial loading / unloading. There would be associated changes in topography that might be substantial. Groundwater flow patterns would change as a result of variations in recharge, development of permafrost (which would decrease the	Glaciation is unlikely over the next 10,000 years, especially taking into account the effects of global warming caused by anthropogenic activities. In any case, the impacts of glaciations would be much more significant than impacts due to wastes. Screened out.

No.	Alternative Evolution Scenario	Description	Treatment in the Assessment
		permeability of the rock) and pressurisation of the rock / groundwater system by glacial loading.	
17.	Seismicity	Seismicity here covers natural energy releases within the solid earth due to rapid releases of accumulated strain. In non-volcanic areas these energy releases are caused by sudden displacements along faults.	The effects of seismicity are greatest near the un-restrained surface of the solid earth, except near to the site of fault displacement that causes an earthquake. Remote from such a site the effects of seismicity diminish steadily with increasing depth. The Hengelo area is not considered seismically active (it is remote from tectonic plate boundaries) but some seismicity cannot be ruled out over 10,000 years. Since this seismicity will originate in fault movements that are remote from Hengelo (there are no active faults in the Hengelo area), there will be insignificant rock displacements at the depths of the backfilled caverns. Overall, the effects of seismicity are likely to be small and would not result in a containment breach. Screened out.
18.	Industrial accident	This scenario concerns accidents that occur at the surface and shallow sub-surface, such as fires or explosions.	Industrial accidents covered by this scenario could damage near-surface borehole completions, but are very unlikely to substantially influence subsurface environments at depths of more than a few tens of metres. Hence, most potential impacts of industrial accidents are outside the scope of the assessment. In the unlikely event that significant sub-surface impacts were to occur, these would be within the ranges of the failure scenarios that are considered explicitly (borehole seals / materials fail; collapse of roof within residual headspace; backfill doesn't provide required structural support; less contaminant retardation by backfill than expected; multiple barrier failure). Near-surface effects are screened out; subsurface effects are subsumed into other scenarios.

8 Conceptual Models

8.1 Conceptual Model for the Expected Evolution Scenario

The conceptual model describes our understanding of the system (caverns, geology, hydrogeology, etc.) and how the system will evolve. The Expected Evolution Scenario described in Section 7 is based on our understanding of the system and the design performance of the backfilling process and long-term performance of the backfill. There are uncertainties and natural variability which might lead to the system behaving or evolving in a different way to the Expected Evolution Scenario. This is explored in the risk assessment through a comprehensive suite of Alternative Evolution Scenarios.

A large suite of documents are available that describe the caverns, geology, hydrogeology, material properties etc. Much of this information has already been "brought together" to form an overall system description as part of the risk assessment of gas and oil storage in salt caverns in the Twente region (van Duijne et al., 2011a). This system description forms the starting point for the conceptual model described below. It is anticipated that the conceptual model described below will be further developed as the PSCT project progresses, to the extent that is required to support the risk assessment.

8.1.1 Geology

Figure 8-1 shows the major geological strata of the Twente region. It is noted that the thicknesses and continuity of the strata vary across the area in which the salt caverns have been developed. Therefore the precise stratigraphy is cavern specific, and this may be important for cavern specific assessment calculations. The geology is described by van Duijne et al. (2011a,b) and is summarised below. The geography and main structural elements in the Twente region are shown in Figure 8-2.

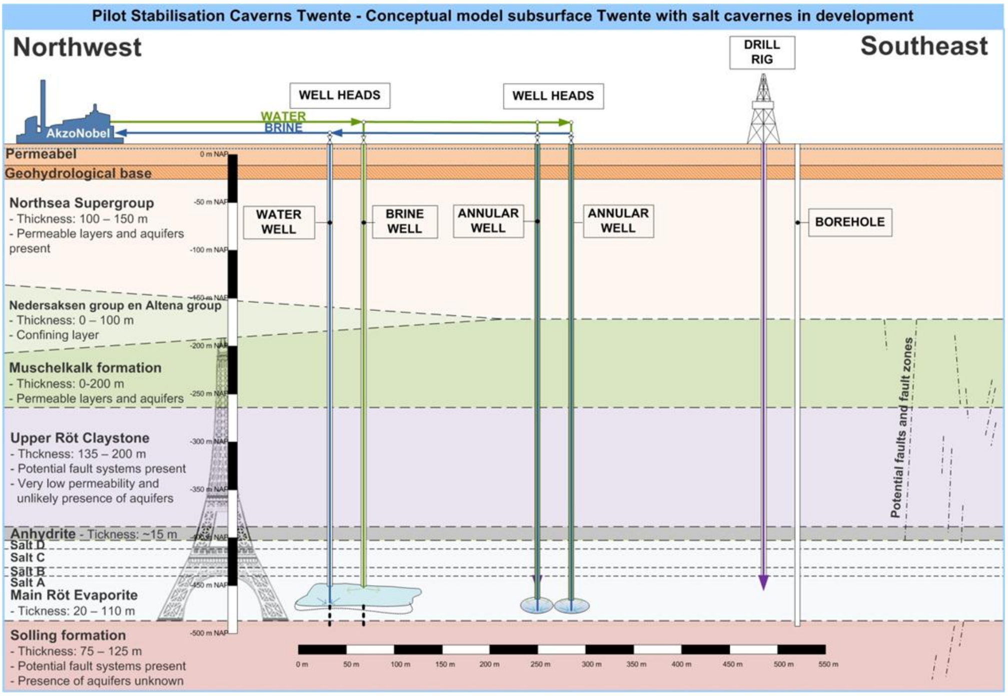


Figure 8-1: Geology of the Twente Region.

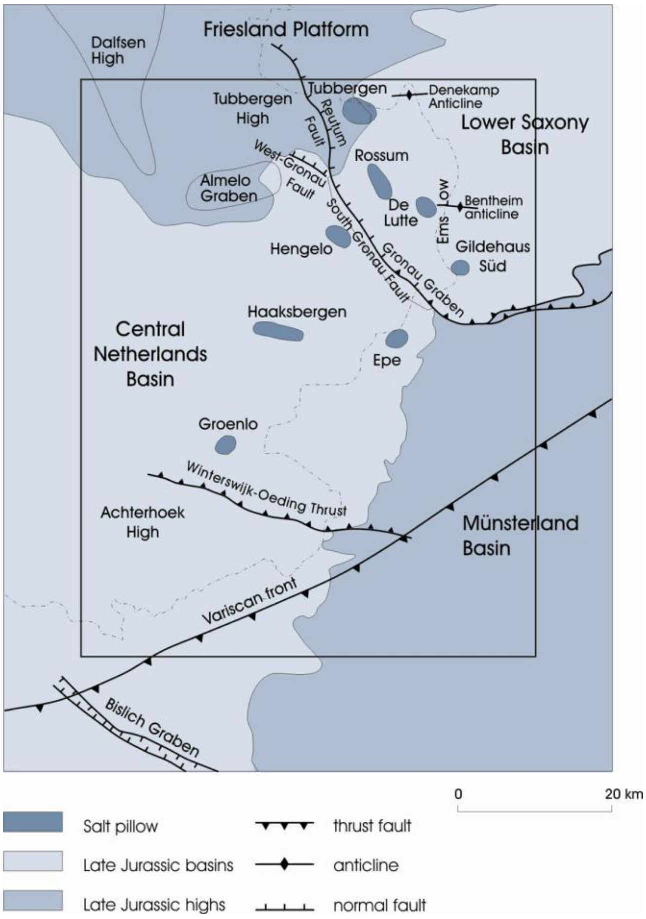


Figure 8-2: Overview of the main structural elements in the Twente region and the location of the study area considered by van Duijne et al. (2011a).

Solling Formation

The Solling Formation is subdivided into the Basal Solling Sandstone Member and the Solling Claystone Member. The Basal Solling Sandstone Member has a thickness of a few meters at most and consists of fine-grained calcareous sandstone. The Solling Claystone Member consists of dolomitic silty claystone. The unit is thickest in the Ems Low (over 120 m) and decreases in thickness to approximately 70 m towards the west.

Röt Formation

The Röt Formation is subdivided into the Main Röt Evaporite Member, the Middle Röt Claystone Member, the Upper Röt Evaporite Member and the Upper Röt Claystone Member. The Upper Röt Evaporite Member is not always present. The total thickness of the Röt Formation varies between 225 m in the north and 300 m in the central part of the area and decreases in southern direction to slightly less than 200 m.

The Main Röt Evaporite Member consists primarily of halite, with a thick anhydrite layer at the base, and with intercalated clay layers of 10 to 15 m thickness at the top. The largest thickness of the Main Röt Evaporite Member is 110 m in the Ems Low. Southeast of the Gronau Fault zone, located north of the AkzoNobel concession, thicknesses of more than 100 m have been encountered.

The salt member of the Main Röt Evaporite (in which the salt caverns are located) is subdivided into four salt layers by the presence of four claystone intervals (which include dolomite and anhydrite) that can be correlated across the area. In the Twente area, the four salt layers have been named A, B, C and D from bottom to top.

The Middle Röt Claystone Member consists of claystone with a relatively constant thickness of 25 to 35 m. The Upper Röt Evaporite Member has alternating anhydrite and claystone layers. The thickness of the Upper Röt Evaporite Member varies between 5 and 15 m. The Upper Röt Claystone Member often contains a silt or sand fraction and gypsum nodules are present. In the upper ~50 m, the claystone alternates with marl and thin claystone layers. The Upper Röt Claystone has a thickness of approximately 135 m, while in the Ems Low thicknesses of up to 200 m have been encountered.

Muschelkalk Formation

The Muschelkalk Formation is subdivided into four geological units: the Lower Muschelkalk Member, the Muschelkalk Evaporite Member, the Middle Muschelkalk Marl Member and the Upper Muschelkalk Member. The Muschelkalk Evaporite Member and the Middle Muschelkalk Marl Member together are informally known as the Middle Muschelkalk. The Muschelkalk Formation has a maximum thickness of 200 m in the Twente area.

The Lower Muschelkalk Member consists of marly to clayey limestone, with inclusions of dolomite, marl and claystone. The Muschelkalk Evaporite Member only occurs in the northeast of the Twente area, and locally west of the Gronau Fault zone. It consists of alternating anhydrite and dolomitic marl and has a thickness of approximately 25 m. The Middle Muschelkalk Marl Member has approximately the same distribution area as the Muschelkalk Evaporite Member. It consists of dolomitic marl in which the clay content increases towards the top. The thickness varies between 25 and 30 m. The Upper Muschelkalk Member is found only sporadically in the Twente area. It consists of alternating dolomite and marl.

Altena Group

The Altena Group consists mainly of claystones. The group is subdivided into five formations. Only the Sleen Formation and the Aalburg Formation occur in the area. The thickness of the Altena Formation varies between 0 to 200 m in the Twente area, and is up to 500 m near the Gronau Fault zone. The Aalburg Formation consists of claystone, which is sometimes calcareous, with thin limestone layers. The entire section of the Aalburg Formation contains ammonites, belemnites, molluscs and iron oolites.

The Sleen Formation consists of black, sometimes bituminous, claystone and clayey shale. The Formation is divided in two parts by a thin sandstone layer. The Sleen Formation has a thickness of 5 to 30 m in the Twente area.

Niedersachsen Group

The Niedersachsen Group consist of fine clastic sediments with intercalations of limestone and evaporite. In the Twente area the Niedersachsen Group consists of the Weiteveen Formation and the Coevorden Formation. Its occurrence is limited to the Lower Saxony Basin, while in the Central Netherlands Basin it occurs only locally and is very thin. In the graben west of Hengelo the thickness of the Niedersachsen Group is over 200 m.

The Weiteveen Formation consists of alternating fine grained claystone, marl, fine grained sandstone and intercalations of anhydrite and limestone. East of the study area, halite layers also occur in the Formation. The Lower Coevorden Member consists of a sequence of claystones and limestone layers. The Middle Coevorden Member consists of silty to sandy claystones and can be distinguished by the relatively high calcareous content. The Upper Coevorden Member consists of sometimes fine-grained sandy deposits that contain shell horizons as well as layers with iron oolites and bituminous deposits.

North Sea Supergroup

The North Sea Supergroup (NSG), of Tertiary age, is predominantly composed of clays and sands. It is subdivided by intra-formational hiatuses into the Lower North Sea, Middle North Sea and Upper North Sea Groups. Different groups may be encountered at the base of the Tertiary owing to unconformities within the NSG.

The Lower North Sea Group comprises the Landen and Dongen Formations. The group is found throughout the area with the exception of the east of Twente and the Achterhoek. The Landen Formation, of Late Paleocene age, has a limited aerial extent and is restricted to the Reutum Graben and the southwest of the area. The Formation consists of moderately to substantially sandy clays, with scattered occurrences of quartz pebbles. The deposits are glauconitic, with a few cemented horizons. The thickness reaches a maximum of 45 m in the Reutum Graben and almost 40 m in the west of the map sheet area indicated in Figure 8-2.

The Dongen Formation forms the basal part of the Tertiary in the majority of the area. It is widespread with the exception of parts of the Twente and Achterhoek regions and adjacent parts of Germany. The Formation is subdivided into five members. The Basal Dongen Sand (thickness 15 m) comprises a sequence of mud-bearing sand and sandy clay, with sporadic occurrences of glauconite. The Leper Member (thickness 1 to 80 m) is composed of glauconite-bearing sandy clays and argillaceous sands. The Brussels Sand (thickness 30 to 90 m) consists of fine to moderately coarse sands. The Asse Member (few meters thick) comprises clay, with a fluctuating sand content. The most complete succession is found in the northwest; elsewhere in the map sheet area (Figure 8-2) only the lowermost members were unaffected by erosion.

The deposits of the Middle North Sea Group are found in a large part of the Twente area, and comprise the Rupel Formation and the Veldhoven Formation. The Rupel Formation is subdivided into the Vessem and the Rupel Clay Members. The thickness of the Formation increases from 0 m in the east of Twente and the Achterhoek to over 100 m in the northwest of the map sheet area (Figure 8-2). The Formation is unconformably overlain by the Veldhoven Formation or by deposits of the Upper North Sea Group. The Vessem Member (thickness 10 to 25 m) consists of glauconite-bearing, non-calcareous, poorly sorted sand at the base; succeeded by argillaceous, fine sands. The Rupel Clay (formerly the Boom Clay) consists of heavy clays, with several septaria beds. In the uppermost part of the sequence, sandy intercalations are found. The thickness pattern is strongly determined by the degree of erosion and is up to around 100 m in the northwest of the map sheet area.

The Veldhoven Formation is found locally in the Reutum Graben and in the western part of the map sheet area. It is up to 110 m thick in the Reutum Graben and the northwest of the Twente area. The Formation comprises sandy clays and moderately coarse sands.

Deposits of the Upper North Sea Group, are found in the Reutum Graben and the western part of the map sheet area.

Quaternary

The Quaternary deposits occur throughout the Twente area. Within the group, the Breda, Oosterhout and Peize Formations can be identified. The Breda Formation comprises a complex mixture of sands and clays. A high percentage of glauconite is characteristic of the Formation. The Formation thickens in a north-westerly direction to over 200 m. The Oosterhout Formation is composed of well sorted argillaceous, very fine sands, containing little glauconite. The Formation occurs in the Reutum Graben and in the western part of the map sheet area. The Formation achieves a thickness of 50 m.

In the northwest of the map sheet area the marine Oosterhout Formation passes laterally into the predominantly fluvial and near shore Peize Formation, which occurs in the Reutum Graben and the northwest of the Twente area. The Formation consists predominantly of sands. The lowermost part comprises well-sorted, fine sands, whereas upward the sorting becomes poorer and the grain size coarsens. The thickness of the formation is irregular, with the maximum thickness locally exceeding 30 m. The remaining Quaternary formations consist of sand, clay and gravel, deposited in predominantly terrestrial and glacial conditions. Their thickness increases in a north-westerly direction from a few meters to over 160 m.

Faults and Fractures

The Gronau Fault Zone (Figure 8-2) is a major tectonic element with a long history. The orientation of the stress-field dictated the degree of activity of various elements during the course of geological history. Major movements along the Gronau Fault Zone occurred during all the tectonic phases in the period spanning Carboniferous to the present time. The fault zone extends into the deposits of the North Sea Supergroup.

A smaller tectonic element in the Twente area is the Boekelo Fault zone which is located just southwest of the area with the salt concessions. The Boekelo Fault Zone is oriented NW-SE and runs parallel to the South Gronau Fault. The fault zone affects the stratigraphy from below the Solling Formation up to (and into) the deposits of the North Sea Supergroup. The minimum distance from a salt cavern to the disturbed zone of the Boekelo Fault Zone is 100m.

In the area with the salt concessions some smaller faults occur that are probably related to the Boekelo Fault Zone (mainly normal faults) with a maximum displacement of 10 m. A detailed study of the fault structures in the Marssteden area indicates that the integrity of the salt caverns is unlikely to be affected by these faults.

8.1.2 Caverns and Boreholes

There are about 200 caverns in the Twente area, 16 of which are candidates for possible stabilisation during the PSCT project. The caverns were all constructed by dissolution of halite, but two different approaches were used, resulting in different cavern geometries. The first stage was to drill a borehole to the base of the halite. Typically the borehole was continued for a few metres into the Solling Formation to confirm the base of the halite had been reached.

Tubing was passed down the borehole such that freshwater could be pumped down the annulus and brine could be extracted through the tubing at the base of the forming cavern. A thin layer of “blanket” oil was used to force the cavern to develop sideways first, i.e. to develop a sump. Once the desired diameter had been reached, the blanket oil was removed and the cavern would grow vertically while maintaining the diameter.

The salt production permit granted by the Ministry of Economic Affairs, Agriculture and Innovation limits the volume of blanket oil that may be used for cavern development to 100 m^3. Once the cavern has reached the desired diameter the layer of blanket oil is only a few centimetres thick. The amount of blanket oil recovered is highly variable: little to almost all the oil might be recovered, because variations in the cavern roof height of only a few cm can easily trap significant proportions of the blanket oil.

Two or three wells, spaced at a regular distance (about 40 m) from each other, were developed simultaneously. At some point when these single-well caverns had reached a certain size, there would only be limited pillars of salt remaining between them, and if necessary (i.e. if hydraulic connection between the caverns had not already been established through regular leaching), a connection would be forced by putting some overpressure on the caverns to force the leaching away of the pillars by fracturing them hydraulically (hydrofracking).

The freshwater injection point was some distance above the top of the Solling Formation, such that the base of the cavern would be formed by a layer of halite. Although the boreholes penetrate this layer, they only provide very limited hydraulic connection, since their area is small compared with the footprint of the cavern. However, the integrity of the cavern bases is uncertain. They may, for example, have been subject to some dissolution by waters from the Solling Formation or stress cracking in response to pressure differences between the Solling Formation and the cavern. Hydrofracking might have also led to hydraulic connection with the Solling Formation.

Early caverns were developed slightly differently resulting in caverns that are narrow at the bottom and wide at the top. However, the majority of these early caverns have already collapsed and hence they are not being considered as part of the PSCT project.

The halite contains some insoluble minerals and shale layers. Following creation of the cavern these insoluble minerals remain in the sump. There may be minor collapses from the roof of otherwise stable caverns, and any insoluble material is also deposited in the sump.

Cavern stability is influenced by a number of factors. In an effort to improve stability, a permanent oil blanket was applied after production in wells 75 and 77 and during production in wells 81 and 90. An oil blanket has been also present in well 58 since the exploration well was drilled in 1996 (Bekendam, 2009). Only well 90 is associated with one of the caverns potentially to be backfilled as part of the PSCT project (see below).

The area of direct interest to the PSCT project and the associated caverns are shown in Figure 8-3. Caverns that will potentially be backfilled as part of the pilot project (i.e. PSCT project) are shown in red. Only 3 of the highlighted caverns will be selected for backfilling as part of the pilot project. All the caverns of potential interest to the PSCT project were developed by using an oil blanket to control their widths and consequently have approximately constant radii perpendicular to their vertical axes.

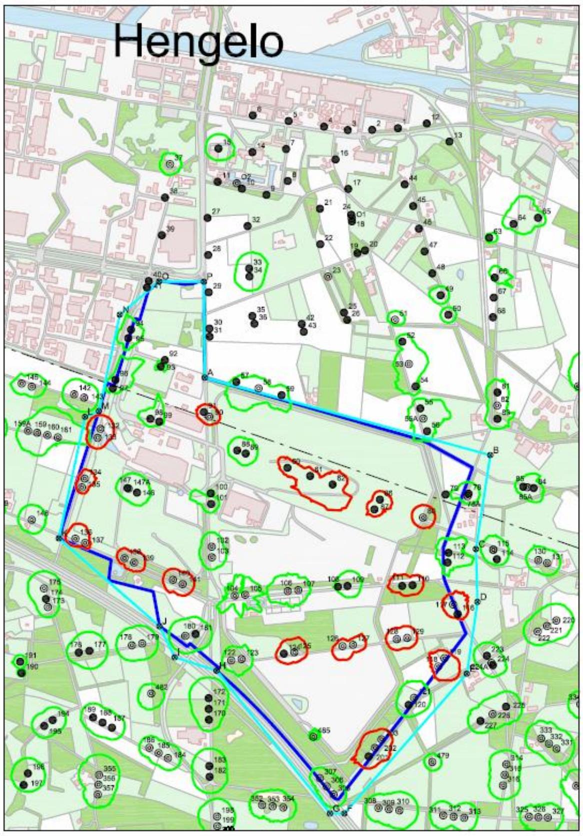


Figure 8-3: Area of direct interest to the PSCT project, and associated caverns. Caverns potentially to be backfilled as part of the PSCT project are shown in red.

8.1.3 Hydrogeology

In the Twente area the shallow hydrogeological system is isolated from the underlying deep hydrogeological system, as illustrated in Figure 8-4. The base of the shallow hydrogeological system lies at 10 to 60 m below the surface (10 to 20 m in the study area) and is formed by a layer of marine clay deposits of the Dongen Formation, the Rupel Formation and the Breda Formation (all North Sea Supergroup). While the shallow hydrogeological system has been studied in detail the deep hydrogeological system is poorly characterised. Hydraulic properties of the geological strata are shown in Table 8-1.

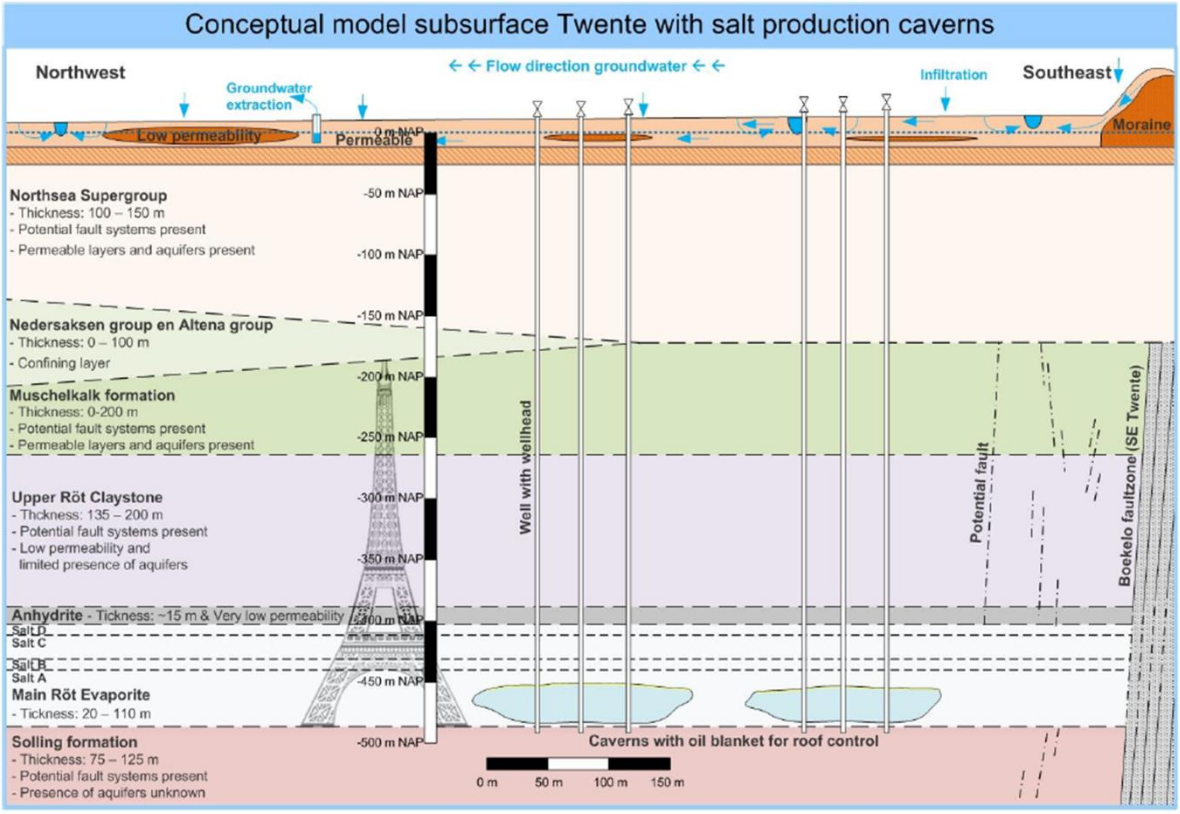


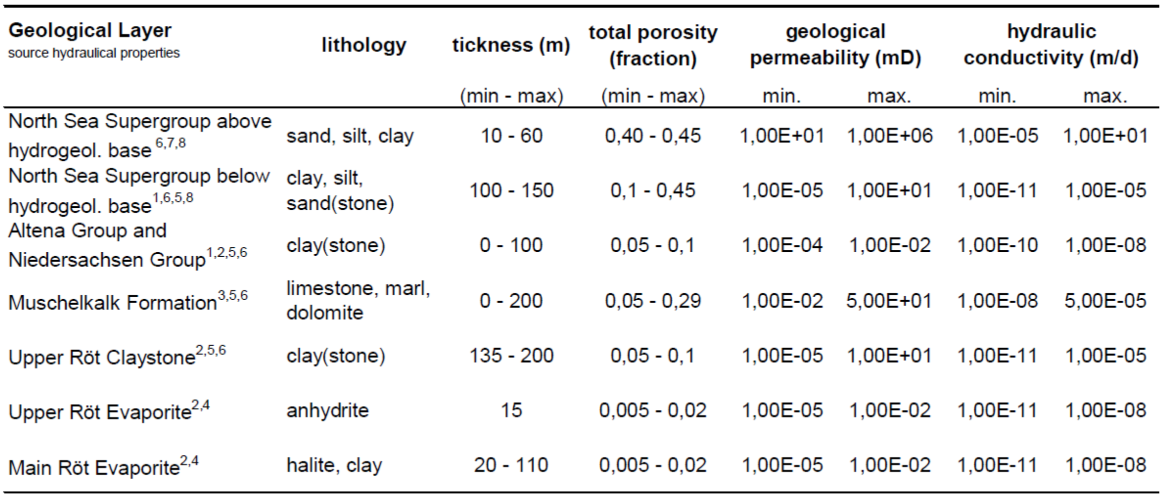
Figure 8-4: Conceptual model of the geology and hydrogeology (after van Duijne et al. 2011a).

Flows in the shallow groundwater system are gravity driven, with recharge draining to streams, ditches, etc. Groundwater is abstracted from the shallow system for drinking water and irrigation.

There is not thought to be significant flow in the deep hydrogeological system since the regional topography is too flat to drive flows at such depth, and in general the rocks are of very low permeability.

It is known that there are hydraulic overpressures in the Muschelkalk formation, since some of the more permeable horizons exhibit artesian conditions. The cause and hence the long-term sustainability of the overpressures is unknown. The overpressures are unlikely to be topographically driven, although it is possible they might be due to the geometry of dense saline waters at the basin scale, for example as observed in the Michigan basin (NWMO, 2011). Alternatively, the overpressures might reflect conditions that are still re-equilibrating following rapid melting of the last ice sheets circa 10,000 y ago.

Table 8-1. Hydraulic Properties of the Geological Strata (after van Duijne et al. 2011a).



Geological Layer source hydraulical properties	**lithology**	**tickness (m)**	**total porosity (fraction)**	**geological permeability (mD)**		**hydraulic conductivity (m/d)**	
		(min - max)	(min - max)	min.	max.	min.	max.
North Sea Supergroup above hydrogeol. base [6,7,8]	sand, silt, clay	10 - 60	0,40 - 0,45	1,00E+01	1,00E+06	1,00E-05	1,00E+01
North Sea Supergroup below hydrogeol. base [1,6,5,8]	clay, silt, sand(stone)	100 - 150	0,1 - 0,45	1,00E-05	1,00E+01	1,00E-11	1,00E-05
Altena Group and Niedersachsen Group [1,2,5,6]	clay(stone)	0 - 100	0,05 - 0,1	1,00E-04	1,00E-02	1,00E-10	1,00E-08
Muschelkalk Formation [3,5,6]	limestone, marl, dolomite	0 - 200	0,05 - 0,29	1,00E-02	5,00E+01	1,00E-08	5,00E-05
Upper Röt Claystone [2,5,6]	clay(stone)	135 - 200	0,05 - 0,1	1,00E-05	1,00E+01	1,00E-11	1,00E-05
Upper Röt Evaporite [2,4]	anhydrite	15	0,005 - 0,02	1,00E-05	1,00E-02	1,00E-11	1,00E-08
Main Röt Evaporite [2,4]	halite, clay	20 - 110	0,005 - 0,02	1,00E-05	1,00E-02	1,00E-11	1,00E-08

It is not known whether these overpressures only occur within the Muschelkalk Formation, or if there is an upward hydraulic gradient from the Solling Formation (and potentially deeper) to the shallow hydrogeological system. Available data regarding the hydraulic conditions at depth are further discussed in Appendix B.

Faults present in the deep hydrogeological system might form local hydraulic connections between geological strata. However, there are no data as to whether the faults are open (i.e. permeable) or closed (i.e. sealed). Faults are not thought to connect the deep and shallow hydrogeological systems.

8.1.4 Hydrochemistry

Van Duijne et al. (2011a) describe the groundwater quality. Water in the Röt and Muschelkalk Formations has very high sulphate concentrations and hardness, which is probably due to dissolution of the anhydrite layers in these deposits. The deposits of the Niedersachsen Group contain groundwaters with high chloride concentrations. These may be connate waters, or they might be due to migration of salt water from deeper deposits, for example by diffusion over geological timescales.

The transition from fresh to saline water is found in the Tertiary deposits of the Upper North Sea Group. The Peize Formation and younger, shallower formations were deposited in a continental environment, whereas the older formations were deposited in a marine environment. Originally, the transition of fresh to salt water therefore lay between these two formations. However the precipitation that has fallen on the region following deposition, and potentially also glacial meltwater injection, has resulted in fresh water penetrating towards the deeper formations.

Consequently, the groundwater up to a depth of approximately 100 m below the surface currently consists of fresh water. In the shallower, younger, Quaternary deposits the variation of groundwater quality is low with chloride concentrations of 35 mg/l to 50 mg/l. Below ~100 m the groundwater in the Tertiary deposits is brackish or saline (chloride concentrations of 1500 to 15,000 mg/l and sulphate concentrations of 250 to 1400 mg/l). The water in the artesian formations in the Muschelkalk Formation is known to be under-saturated with halite because it has historically been used as a source of water for cavern development.

Mixing between shallow fresh groundwater and deeper saline water is limited by the density contrast.

8.1.5 Collapse and Stabilisation

The anhydrite layer overlying the caverns has a very important influence on the mechanical stability of the caverns. This layer provides the greatest resistance to formation of a collapse zone of all the overlying formations. The anhydrite is postulated to act as a beam (Bekendam, 2009), and consistent with this conceptual model, when failure of the anhydrite occurs the full thickness of overburden fails rapidly. In caverns where collapse has been initiated, the time to beam failure has been 4 to 18 years, but in other caverns the anhydrite has retained its integrity for longer times (Bekendam, 2009). The causes of failure of the anhydrite are uncertain. The beam concept implies that larger diameter caverns should be more susceptible to collapse. This is not observed in reality, but this may just be because a statistically valid number of collapses have not yet been observed (Bekendam, 2009).

Once the Anhydrite layer has failed, the overlying formations collapse relatively rapidly (compared with the anhydrite) despite their significantly greater thickness. Where the collapse column has reached the ground surface, the total time for collapse has been 7 to 26 years (Bekendam, 2009).

As the collapse column develops the overlying formations are also conceptualised to act as a beam, which bends resulting in some subsidence at the ground surface. It has been calculated that if the collapse zone extends above 40 m below the base of the Tertiary North Sea Supergroup (Akzo Nobel, 2012), the beam is expected to fail and the collapse zone will rapidly extend to the ground surface resulting in sinkhole formation. The main objective of backfilling is to prevent sinkhole formation.

8.1.6 Backfilling

For the PSCT project only caverns that have not started to collapse will be selected for backfilling. This prevents the risk that unconsolidated backfill and associated bleed water will enter aquifers via a collapse column that has already developed. It also means that the amount of backfill added can be controlled and the extent to which the cavern is filled can be monitored.

Backfilling is essentially the reverse of cavern creation. Brine will be pumped from the cavern via a borehole. The brine will be evaporated, forming salt slurry. Supernatant liquor from the slurry, which is fully saturated with salt minerals, will be mixed with the backfill materials to form the backfill mix. The mix will then be pumped into the cavern via a second borehole. The existing boreholes can be re-used so long as they are not blocked. The backfill mix is fully saturated with salt minerals so it will not cause further dissolution of the halite.

The backfill has good flow properties and is denser than the brine in the cavern. It will sink to the bottom of the cavern and will spread laterally. Injection of the backfill will push more brine out of the cavern via the abstraction well. Therefore, only minimal pumping will be required to initiate the process and the differential pressures generated during backfilling will be small, thereby minimising the risk to cavern stability.

Salt slurry, which contains only a few per cent free water, will be stored during the backfilling process. When the cavern is nearly full, injection of the backfill mix will cease, and backfilling will be completed using the salt slurry. Therefore there should be little or no salt slurry to dispose of at the end of the process. Similar to the backfill, the slurry has good flow properties and is denser than the brine in the cavern, so it will also spread laterally towards the cavern perimeter.

Eventually the slurry will reach the cavern roof and the backfilling process will cease. It is expected that there will be some residual voidage in the cavern due to:

▲ incomplete filling around debris in the cavern sump;

▲ incomplete filling of any complex geometries around the cavern perimeter and in the roof; and

▲ incomplete filling around the cavern perimeter at the top of the cavern.

The latter will occur because there will be a shallow slope on the top of the slurry / backfill from the injection borehole to the cavern perimeter. Once the slurry / backfill reaches the cavern roof at the injection point there will still remain residual voidage around the cavern perimeter. It might be possible to further reduce the residual voidage by injecting slurry (or backfill) at higher pressures, but such injection would increase the likelihood of uncontrolled slurry, backfill and bleed water migration, and enhance the possibility of cavern failure before the backfill consolidates.

Alternatively, the salt slurry and backfill materials might be intimately mixed and introduced as a single phase.

Once backfilling is complete, and likely following a period of monitoring to confirm successful stabilisation of the cavern, the boreholes will be sealed with cement. Fresh and salt water cements have historically been used to plug/fill the wells. The formulation for sealing of the PSCT cavern boreholes is to be determined.

8.1.7 Contaminant Migration

Contaminants will be present in the backfill and in the bleed water. Residual blanket oil is also a potential contaminant, and brine is a potential contaminant in the context of the shallow (fresh) hydrogeological system. There is the potential for contamination of groundwaters with backfill while the backfill is being injected and before it sets. There is the potential for contamination of groundwaters with brine, residual blanket oil and bleed water during the backfilling process and after the backfill has set. In the long-term there is the potential for contamination of groundwaters due to advective and diffusive transport of brine that contains dissolved contaminants and blanket oil; and migration of free phase blanket oil due to buoyancy.

Potential pathways for contaminant migration include leaking borehole casings, fractures that intercept the caverns, and in the longer term, migration in the collapse column that is anticipated to form in response to the residual voidage in the cavern, and compaction and consolidation of the backfill. These pathways are not further described here but are detailed within the description of the Expected Evolution Scenario (see Section 7).

Many of the potential contaminants in the backfill, notably heavy metals, will be chemically retarded by solubility limitation and sorption onto substrates such as clay minerals in the overlying geological formations. Aqueous lead concentrations in backfill bleed water have been measured as part of the backfill development process. Analysis of the concentrations of Pb indicates equilibrium with metastable mineral phases (see Section 9). It is anticipated that over time, as the backfill cures, contaminant solubility limits will decrease as equilibrium with stable mineral phases is established.

Blanket oil might be slowly microbially degraded, resulting in the formation of gas. However, microbial activity, and hence degradation rates, might be low in the highly saline environment.

8.2 Conceptual Models for Alternative Evolution Scenarios

8.2.1 Do Nothing Scenario

The caverns are not backfilled. Although the caverns may be stable for several tens of years, ultimately the anhydrite layer will fail and collapse will be initiated. Failure of the anhydrite layer is expected to be instantaneous compared with the assessment timescale (10,000 y). The height of the collapse column will depend on the cavern height and the bulking factor (1.11 on average). There is naturally some uncertainty and variability in the bulking factor. For example it is likely to be different for the different rock types overlying the cavern.

If the height of the collapse column extends above 40 m below the base of the Tertiary, then rapid failure of the overlying rock will be initiated and a sinkhole will form at the ground surface. There is naturally some uncertainty and variability in this safety criterion.

In addition to sinkhole formation, there is the potential for contamination of shallow groundwater with brine from depth. This has not been observed for existing sinkholes. This is potentially because freshwater extends to depths of up to 100 m and therefore the brine was too deep to be displaced sufficiently far up the forming collapse column. However, brine contamination could potentially occur in the longer term due to migration of brine up the collapse column in response to the artesian conditions in the Muschelkalk.

Formation of a collapse column could also lead to residual blanket oil buoyantly rising to the shallow hydrogeological system. Contamination by blanket oil might make the shallow groundwater impotable. Cavern backfilling and stabilisation would prevent sinkhole formation therefore buoyant rise of residual blanket oil would be a very slow process due to the low permeability of the geological formations.

8.2.2 Cavern Interaction Scenario

In the Cavern Interaction Scenario contaminated water is considered to migrate into an adjacent cavern that has not been backfilled, and then finds a preferential migration pathway to the Muschelkalk Formation or the shallow hydrogeological system. This latter migration may occur either via the collapse column of the adjacent cavern, or via a fault, open borehole or leaky closed borehole associated with the adjacent cavern.

The backfilling process is designed such that it will only result in a small pressure increase in the cavern being backfilled. This small pressure increase is unlikely to drive significant flow of water through fractures in the pillar between adjacent caverns.

Larger driving pressures might be possible in the longer-term as the rock above the backfilled cavern collapses resulting in compaction of the backfill.

As the backfill is compacted by roof collapse, contaminated porewater will be squeezed out of the backfill. Much of the contaminated water will enter the forming collapse column, but some could potential pass through fractures in the pillar into the adjacent cavern.

It is assumed that the adjacent cavern is not backfilled. The worst case scenario is that the adjacent cavern collapses, resulting in the formation of a collapse column which extends to the shallow hydrogeological system. (This also means that a sinkhole will form). Contaminated water then migrates up the collapse column of the adjacent cavern to the shallow hydrogeological system via diffusion and in response to a vertical hydraulic gradient from depth (Figure 8-5).

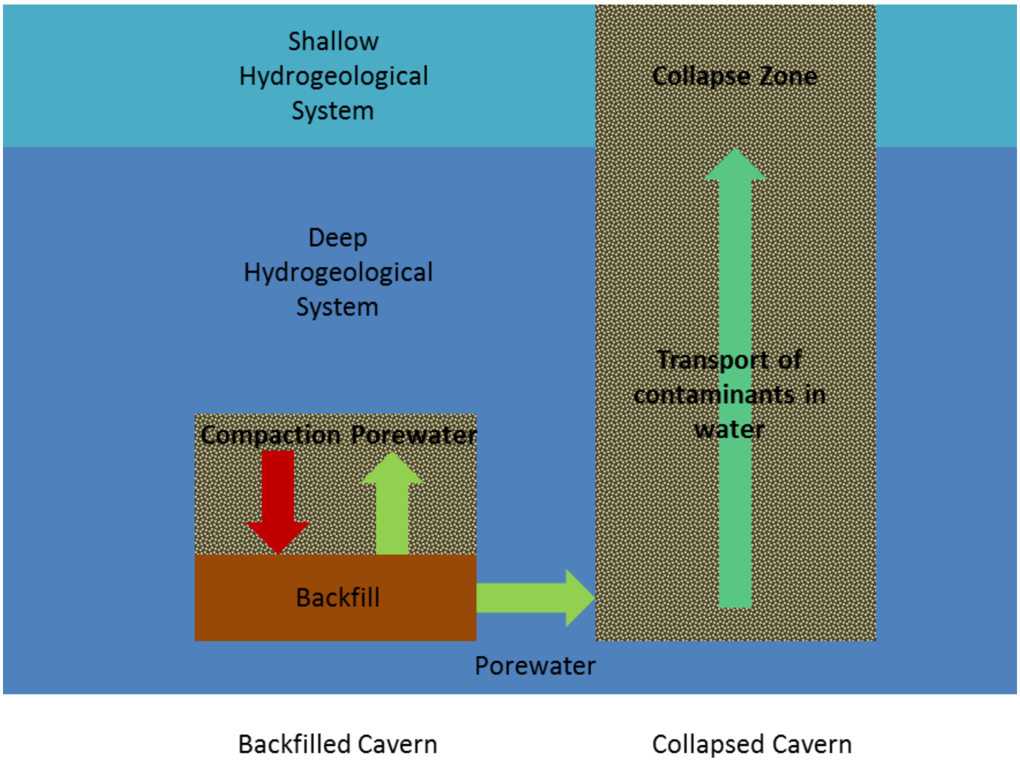


Figure 8-5: Illustration of the Cavern Interaction Scenario.

Where there is the potential for pillar failure between adjacent caverns, at this stage of development of the risk assessment, it is assumed that either the caverns will not be backfilled, or both caverns will be backfilled thereby preventing pillar collapse. However, this assumption needs to be reviewed in the context of the final criteria for cavern selection.

8.2.3 Backfill Doesn’t Provide Required Structural Support

This scenario encompasses a range of potential outcomes which all have the same consequence: the collapse zone that forms above the backfilled cavern extends further than the design intent. The processes that lead to the contaminant migration are the same as the Expected Evolution Scenario, but the barriers to migration are reduced.

This may result in contamination of waters in the Muschelkalk Formation, or shallow hydrogeological system, and in the worst case might also be accompanied by sinkhole formation. Sinkhole formation would only be possible if the cavern was backfilled to a very limited extent, for example if backfilling initiated roof collapse and could not be completed. However, the contaminant inventory would be smaller than in a cavern that had been successfully backfilled.

8.2.4 Backfill Migration

This scenario considers the possibility that the cavern roof fails before the backfill has cured and attained its design strength, resulting in backfill migrating up the collapse column. The height of the collapse zone will also be greater than the design intent, because collapse can continue until the backfill cures to the extent that it provides structural support. These two processes combine to reduce the thickness of the containment barrier above the backfill. Because the backfill is distributed within the collapse zone, which is self-supporting to an extent, there may be less compaction of the backfill compared with the EES, and this might counter (i.e. reduce) the increase in the height of the collapse zone to an extent.

The worst case assumes that the backfill is always able to flow. This would mean that a sinkhole forms, and potentially fluidic backfill could migrate all the way up the collapse column. This is treated as a pass/fail criterion in the risk assessment.

8.2.5 Contaminants Only Weakly Chemically Retarded

This scenario considers the possibility that contaminants are only weakly chemically retarded. In the worst case there is no chemical retardation, which tests the ability of physical barriers alone to provide the required performance. However, there is expected to be at least some solubility limitation due to equilibrium with metastable mineral phases.

8.2.6 Borehole Seal/Materials Fail

Once the cavern has been backfilled the boreholes will be sealed. However, potentially the sealing may not be successful, for example there may be an open interface between the casing and the cement backfill due to shrinkage of the cement. Similarly there could be an existing open interface between the cement outside of the casing and the casing and/or the wall rock.

Over time the steel casing will corrode. This will result in expansion of the casing. Although this expansion will tend to close any open interfaces, it may also result in cracking of the cement, both inside the casing and between the casing and the wall rock.

For simplicity it can be assumed that a “fracture” pathway always exists in the borehole, from the top of the collapse column to the shallow hydrogeological system. There is water flow up the fracture pathway in response to overpressures at depth. There may be some sorption of contaminants onto the corroded casing, borehole wall rock and borehole concrete, however this will be limited due to the saline conditions (competing ions) and relatively small surface area for sorption (compared with transport through a porous medium).

Transport up the borehole will result in a small, localised point source of contamination in the shallow hydrogeological system. It is possible that this contaminated water could be captured by an abstraction well in the shallow hydrogeological system. It should be noted that this abstraction well is a second borehole that is distinct from the leaky borehole that provides a pathway from the collapse column to the shallow hydrogeological system. However, because the contaminant plume is small, the probability this interception will occur is low compared with the probability that an abstraction well will intercept the much larger plume of contamination associated with transport through a collapse column which is of the same diameter as the cavern.

If the small plume of contaminated water associated with the leaking borehole is captured by a water abstraction well, it is likely that the entire plume will be captured. The contaminated water will be diluted by clean water which forms the majority of water abstracted from the well.

8.2.7 Faults/Fractures Provide Transport Pathway to Receptor (Aquifer)

This scenario has a number of similarities to the “Borehole seal/materials fail” scenario described above. Contaminants are assumed to be transported by water flow up the fracture pathway in response to overpressures at depth. There is only limited sorption of contaminants onto the fracture surfaces.

There are two different calculation cases. The first case considers a fracture that connects the collapse column to the base of the North Sea Supergroup (Figure 8-1, Figure 8-4). The second case is more cautious, and considers a fracture that connects the collapse column to the shallow hydrogeological zone.

In both cases it is unlikely that the fracture intercepts the maximum diameter of the collapse column. It is therefore assumed that the fracture intercepts half the diameter of the collapse column. The fracture is likely to result in a much larger contaminant plume than a leaky borehole. Therefore, it is cautiously assumed that contaminant concentrations in water abstracted from the shallow hydrogeological system are the same as the contaminant concentrations in the shallow hydrogeological system.

8.2.8 Multiple Failure Scenario

This scenario cautiously explores the possibility that a combination of the above scenarios results in enhanced contaminant transport. It is intended that this scenario will be explored by examining the results of scoping calculations for the other scenarios.

8.2.9 Transport Pathway via Solling Formation

This scenario is very similar to the Cavern Interaction Scenario. Roof collapse is considered to result in compaction of the backfill, which provides a driving force for flow of contaminated water. In the Cavern Interaction Scenarios the contaminated water is considered to enter an adjacent cavern that is not backfilled via fractures in the pillar. In this scenario the contaminated water is considered to enter an adjacent cavern that is not backfilled via flow through the Solling Formation. Contaminants can then migrate through the collapse column associated with the adjacent cavern.

8.2.10 Permeable Interbeds in Salt Formations Provide Hydraulic Connection Between Caverns

This scenario is identical to the Cavern Interaction Scenario, except that contaminated groundwater flows into an adjacent cavern that is not backfilled via permeable interbeds in the pillar, as opposed to through fractures in the pillar.

8.2.11 Climate and Landscape Change

Changes in climate and landscape are expected to occur within the assessment timeframe. Climate changes are anticipated to be those associated with greenhouse warming and development of cooler conditions is not anticipated within the assessment timeframe (BIOCLIM, 2004). Climate change, geomorphological processes and anthropogenic activities will all influence the shallow hydrogeological system and demands placed on the system as a source of fresh water for drinking, irrigation and other uses. However, such changes are considered to be within the bounds of uncertainty associated with the present day system; whether any potentially contaminated water will be captured by a future abstraction well; and how much dilution will occur through mixing with clean water in the well.

Climate and landscape change are not expected to affect the deep hydrogeological system, however overpressures at depth will tend to decrease with time as the system evolves towards equilibrium with the surface conditions.

8.3 Mathematical Models

8.3.1 Expected Evolution Scenario

This section describes the mathematical models for the key processes described in the conceptual model.

Height of the Collapse Zone

The voidage in the collapse column and hence the height of the collapse column are determined by the bulking factor of the rock.

The voidage in the collapse column, V_z, is equal to:

$(B_f-1)/B_f$

where B_f is the bulking factor (Figure 8-6).

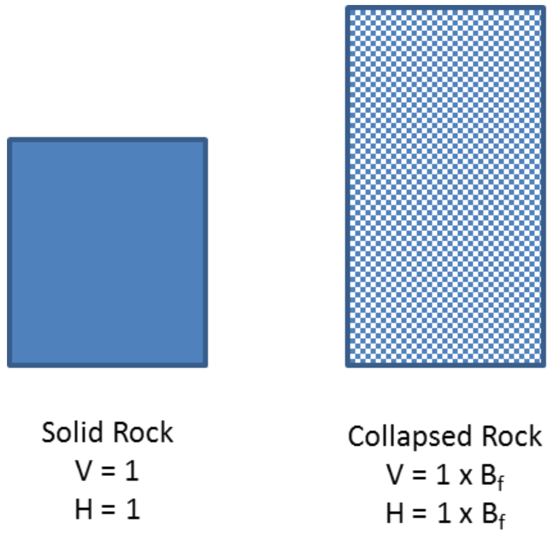


Figure 8-6. Definition of Bulking Factor

The height of the collapse zone can be calculated from a volume balance:

Void volume prior to collapse = Void volume following collapse (Figure 8-7)

$H_cV_c = (H_z + H_c)V_z$

where:

H_c is the height of the cavern;

V_c is the voidage in the cavern;

H_z is the height of the collapse zone above the original cavern; and

V_z is the voidage in the collapse column.

This is assumes there is no compaction of rock in the collapse column.

$V_c = 1$, and therefore,

$H_z = (H_c/V_z) - H_c$

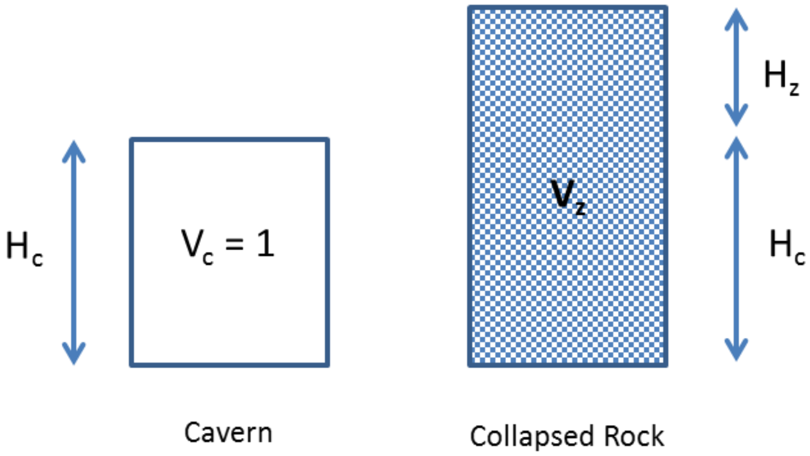


Figure 8-7. Volume Balance

Compaction and Consolidation of Backfill

It is anticipated that the backfill will gradually compact and consolidate under its own weight, but also in response to loading from the rock due to creep and formation of a collapse zone in response to the residual voidage immediately following backfilling. Ongoing formation and stabilisation of the collapse column will be coupled with compaction and consolidation of the backfill.

As the backfill compacts and consolidates its density will increase and its porosity will decrease. The height of the collapse zone will increase in response. The increase in the height of the collapse zone resulting from compaction and consolidation of the backfill can be calculated using the model described in the previous sub-section. To do so, the voidage associated with compaction and consolidation of the backfill needs to be calculated:

$V_b = (1-V_r)*B_c$

where:

V_b is the voidage associated with compaction and consolidation of the backfill;

V_r is the residual voidage in the cavern immediately following backfilling, so $1-V_r$ is the fraction of the initial cavern voidage that is backfilled, e.g. $1-V_r = 0.9$ or 90%; and

B_c is the fractional backfill volume reduction as the backfill compacts and consolidates, e.g. 0.1 or 10%.

Backfill compaction and consolidation is assumed to progress exponentially, such that a half-life for stabilisation can be specified. The half-life can be used to calculate the evolution of the total voidage with time:

$V_t = V_f + (V_b - V_b\exp(-B_r t))$

where:

V_t is the total voidage due to the residual voidage immediately following backfilling plus the voidage due compaction and consolidation of the backfill;

B_r is the backfill compaction rate (y^{-1}), which is equal to $\ln(2)/B_{0.5}$ where $B_{0.5}$ is the backfill stabilisation half-life (y); and

t is the time (y).

This leads to slightly different shaped stabilisation curve compared with the logarithmic model proposed by Bekendam (2009) for stabilisation of sink holes. However, it is considered to be appropriate for scoping calculations since relevant data are not available to parameterise a logarithmic model for the backfill.

8.3.2 Alternative Evolution Scenarios

The only additional process introduced by the Alternative Evolution Scenarios is fracture flow associated with the Borehole Seal/Materials Fail Scenario and the faults/fractures provide transport pathway to receptor (aquifer) scenario. In both these cases flow is assumed to be driven by overpressures at depth. The fracture flow rate can be calculated as the product of the hydraulic gradient and the fracture hydraulic conductivity, K_f (m s^{-1}).

$K_f = k_f \times 1E7\ m^{-1}\ s^{-1}$

where k_f is the fracture permeability for a 1 m long fracture (m^3) and 1E7 $m^{-1}\ s^{-1}$ is the conversion factor from permeability to hydraulic conductivity for water.

$k_f = a^3/12$

where a is the fracture aperture (m).

9 Scoping Calculations

9.1 Geochemical Scoping Calculations

9.1.1 Backfill Porewater Composition

Analyses of backfill and porefluids squeezed from recently mixed backfill formulations by K-UTEC, were supplied by AkzoNobel. Inventories of heavy metal contaminants in the backfill and bleed water are given in Table 9-1 and Table 9-2 respectively. An analysis of the major and minor constituents is given in Table 9-3.

Table 9-1: Contaminant inventories in the backfill.

Contaminant	Concentration (mg/kg)	Reference
As	3.87E+01	AN08, based on information in file "Präsentation BMC Development 28-03-2012_K-UTEC.PDF"
Cd	1.25E+02	As above
Pb	3.31E+03	As above
Sb	4.90E+02	As above
Zn	1.08E+04	As above

Table 9-2: Contaminant inventories in the bleed water.

Contaminant	Concentration (mg/l)	Reference
As	7.00E-02	AN08 in file "Porenfluid AN 08_An 14.pdf"
Cd	7.20E-02	As above
Pb	3.75E+01	As above
Sb	5.70E-02	As above
Zn	1.81E+01	As above
Cl	1.5E+03	van Duijne et al. (2011a)
SO_4	1.4E+02	As above

The reported porefluid for the "AN08" backfill composition (in supplied file "Porenfluid AN 08_AN 14.pdf") was taken as being broadly representative for the salt cavern stabilisation project. This porewater had a temperature of 50 ºC, reflecting the exothermic hydration reactions that occur upon backfill formulation.

In order to determine possible controls on the major element composition of this porewater, an aqueous speciation calculation was performed using the geochemical code "PHREEQC" (Parkhurst and Appelo, 1999). PHREEQC allows saturation indices to be calculated for measured water compositions and model water compositions to be produced by simulating the equilibration of solutes with solid phases at specified partial pressures of gases. The AN08 porefluid is highly saline and hence a Pitzer virial approach (Pitzer, 1987) was required for representing solute activity-concentration relationships and mineral solubilities. Most geochemical software packages include databases suitable for modelling dilute to brackish solutions, generally using the Davies equation or an extended Debye-Hückel equation to calculate the activity coefficients of solutes (e.g. Parkhurst and Appelo; Bethke, 2008). However, such approaches are unsuitable for very saline solutions, due to ion-pairing and ternary ion interactions (Langmuir, 1997).

Compared with the more standard approaches used for dilute to brackish waters, there are relatively few databases available that include Pitzer coefficients and relevant solids and aqueous species. One example is that developed for use in the Yucca Mountain Project, data0.ypf.R2 (US DoE, 2007). However, this database is comprehensive for modelling saline systems, but it does not include data for many of the heavy metals, such as lead. Nonetheless, this database can be used in speciation calculations to determine possible controls on major ion concentrations in the AN08 backfill.

Measured and modelled AN08 backfill porefluid compositions are given in Table 9-3. The model was carried out for a temperature of 25 ºC, approximating the temperature that would be attained in the long term, following emplacement and curing. Calculated saturation indices (0 = equilibrium solubility, >0 = oversaturation, <0 = undersaturation) suggest that at this temperature the AN08 porefluid is oversaturated with respect to calcite, gypsum, anhydrite and halite. However, major ion concentrations suggest that the solution has a composition that is approaching, or is at equilibrium with respect to hemihydrate (partially hydrated calcium sulphate, a common constituent of "plaster of Paris"), sylvite (potassium chloride), pirssonite (a sodium, calcium carbonate hydrate mineral) and zinc hydroxy sulphate. If the measured solution composition is equilibrated with these minerals ("Equilibrated 1" composition, Table 9-3), the solution composition remains broadly similar. There is a small charge imbalance, which has been left uncorrected, but this imbalance could be corrected by adjusting the concentration of a dissolved ion such as chloride. Note that the reported porefluid data do not include aluminium, magnesium or silica concentrations. Given the pH of the backfill porefluid and its similarity to that associated with low-pH cement blends (e.g. Lothenbach et al., 2011), a model composition ("Equilibrated 2", Table 9-3) was produced by adding hydrotalcite and a low Ca:Si calcium silica hydrate (C-S-H) gel composition to the solid phases set to be in equilibrium in the "Equilibrated 1" composition. In order to model these phases, equilibrium constants for C-S-H gel and hydrotalcite hydrolysis reactions were calculated using data from Matschei (2007) and incorporated into the Yucca Mountain Project database.

Table 9-3: Reported and modelled AN08 porefluid compositions (calculations undertaken using PHREEQC and the Yucca Mountain Pitzer Database).

AN08 Porefluid	Reported	Equilibrated 1	Equilibrated 2
pH	11.4	11.4	11.4
Ionic Strength (M)	10.05	9.92	9.92
Activity H2O	0.616	0.616	0.616
	meas conc.	calc. conc.	calc. conc.
	molal	molal	molal
C (total inorganic)	2.14E-02	1.60E-02	1.60E-02
Ca	1.10E+00	1.10E+00	1.10E+00
Cl	9.65E+00	9.66E+00	9.66E+00
K	1.23E+00	1.23E+00	1.23E+00
Na	6.09E+00	6.08E+00	6.08E+00
S	1.55E-02	1.59E-02	1.59E-02
Zn	4.37E-04	4.39E-04	4.39E-04
Al	-	-	8.71E-07
$SiO_{2(aq)}$	-	-	9.97E-07
Calculated Saturation Indices			
Calcite ($CaCO_3$)	3.44	3.32	3.32
Halite (NaCl)	0.52	0.52	0.52
Anhydrite ($CaSO_4$)	0.66	0.67	0.67
Gypsum (CaSO4 ·2H2O)	0.41	0.42	0.42
Portlandite (Ca(OH)2)	0.83	0.83	0.83
Zincite (ZnO)	6.31	6.31	6.31
$Zn(OH)_{2(beta)}$	5.37	5.36	5.37
$Zn_2SO_4(OH)_2$	-0.01	0	0
Sylvite (KCl)	0	0	0
Hemihydrate ($CaSO_4 \cdot 0.5H_2O$)	-0.01	0	0
Pirssonite ($Na_2Ca(CO3)_2 \cdot 2H_2O$)	0.26	0	0
Tobermorite-like C-S-H $(CaO)_{0.8333}(SiO_2)(H_2O)_{1.3333}$	-	-	0
Hydrotalcite ($Mg_4Al_2(OH)_{14} \cdot 3H_2O$)	-	-	0
charge error %	-3.47	-3.77	-3.77

9.1.2 Solubility of Heavy Metals

As noted in Section 9.1.1, the data0.ypf.R2 database used to investigate the stability of major mineral phases does not contain data for most of the heavy metals that are known to occur in the backfill. However, there are data for Zn phases and the calculations using the data0.ypf.R2 showed the porewater to be oversaturated with respect to several Zn-bearing phases (Table 9-4). Potentially, therefore, Zn concentrations could be solubility-controlled.

The solubility of potential heavy metal-bearing phases within the backfill were investigated further using PHREEQC together with a PHREEQC-formatted version of the ThermoChimie v.7.c (December 2010) thermodynamic database, termed “sit.dat”. This database was developed by Amphos 21, BRGM and HydrAsa for ANDRA, the French National Radioactive Waste Management Agency (Duro et al., 2011) and contains data for more heavy metals than does data0.ypf.R2. The saturation states of heavy metal-bearing minerals in porewater AN08, calculated using “sit.dat” are given in Table 9-4.

Table 9-4: Calculated saturation states of potential heavy metal-bearing phases. Over-saturated minerals (which could plausibly precipitate) are shaded yellow.

Mineral	SI	Formula	Mineral	SI	Formula
As and Zn Phases			**Pb Phases**		
As_2O_5(s)	-50	As_2O_5	Cotunnite	-5.04	$PbCl_2$
$Ca_3(AsO_4)_2$(s)	-0.34	$Ca_3(AsO_4)_2$	Galena	-89.02	PbS
Claudetite	-64.53	As_2O_3	Hydrocerussite	-0.81	$Pb_3(CO_3)_2(OH)_2$
Orpiment	-365.11	As_2S_3	Lanarkite	-5.73	$PbSO_4$:PbO
Realgar	-136.79	AsS	Laurionite	0.25	PbClOH
$Zn_3(AsO_4)_2$(s)	0.21	$Zn_3(AsO_4)_2$	Litharge	-0.94	PbO
			Massicot	-1.05	PbO
Cd Phases			Minium	-7.77	Pb_3O_4
$Cd(CO_3)$(s)	-3.03	$Cd(CO_3)$	Paralaurionite	0.25	PbCl(OH)
Cd(cr)	-32.6	Cd	Pb(cr)	-23.25	Pb
$Cd(OH)_2$(s)	-2.26	$Cd(OH)_2$	Pb(OH)2(s)	-1.93	$Pb(OH)_2$
$Cd(SO_4)$(cr)	-14.61	$Cd(SO_4)$	Pb3(AsO4)2(s)	-14.07	$Pb3(AsO4)_2$
$Cd(SO_4){:}2.67H_2O$(cr)	-11.55	$Cd(SO_4){:}2.67H_2O$	Phosgenite	-44.9	$Pb2(CO_3)Cl_2$
$Cd_3(AsO_4)_2$(s)	-16.79	$Cd_3(AsO_4)_2$	Plattnerite	-7.22	PbO_2
$CdCl_2$(s)	-9.17	$CdCl_2$	Plumbonacrite	-2.36	$Pb_{10}(CO_3)_6O(OH)_6$
$CdCl2{:}2.5H_2O$(s)	-8.21	$CdCl2{:}2.5H_2O$			
$CdCl_2{:}H_2O$(cr)	-8.25	$CdCl_2{:}H_2O$	**Sb Phases**		
CdO(s)	-3.39	CdO	Sb(cr)	-58	Sb
CdS(s)	-89.02	CdS	Sb_2O_5(s)	-21.97	Sb_2O_5
			Stibnite	-337.89	Sb_2S_3
			Valentinite	-38.79	Sb_2O_3

From this calculation is appears that concentrations of Zn, As and Pb could plausibly be solubility-limited. Additionally, $Cd(OH)_2(s)$ is only slightly undersaturated, raising the possibility, when account is taken of the uncertainties associated with thermodynamic modelling, that Cd concentrations too might conceivably be solubility-controlled. In the case of Sb there is no evidence for a solubility control on concentration.

9.1.3 Lead Behaviour and Solubility Limits

Among the heavy metals reported to occur in the backfill porewater, Pb has the highest concentration (Table 9-2). In order to determine which phases might control dissolved Pb concentrations in the AN08 backfill porefluid, an Eh-pH diagram was generated using Geochemist's Workbench (Bethke, 2008) and the thermo.com.v8.r6+ database (Figure 9-2). The diagram was generated so that major ion activities correspond to those calculated for the "Equilibrated 2" model porewater composition (Table 9-3).

The diagrams show that galena (PbS) is stable under very low redox conditions (under which sulphate would not be stable). Under higher Eh conditions and pH ~ 8-9, paralauronite (PbClOH) is stable. Above pH 9, $Pb_4Cl_2(OH)_6$ occurs with platnerite (PbO_2) only being stable under very high Eh conditions. Assuming that most of the sulphur present in the AN08 backfill is sulphate, $Pb_4Cl_2(OH)_6$ is the most stable lead phase that could form and act to control dissolved lead concentrations.

The variation in dissolved lead activities as a function of pH is demonstrated Figure 9-2. This suggests that at pH of 11.4, paralauronite solubility should give a dissolved Pb^{2+} activity of $\sim 10^{7}$ (activity is dimensionless). For a very dilute system, this would correspond to a concentrations of $\sim 10^{7}$ molal (activity = molal concentration for infinitely dilute solutions). It is generally the case that activity coefficients[2] for divalent cations decrease from a value of 1 for an infinitely dilute solution to values as low as 0.2 when the ionic strength of the solution (equal to half of the sum of ion concentrations, multiplied by the square of their charges) approaches 1. As ionic strength approaches a value more akin to hypersaline conditions (>5 molal), activity coefficients for divalent cations can become greater than 1 (Figure 4.5, Langmuir, 1997).

Given that the concentration of lead present in the AN08 porefluid is 1.8×10^{-4} mol l^{-1}, it appears that even accounting for activity-concentration relationships, the porefluid is oversaturated with respect to $Pb_4Cl_2(OH)_6$. If chloride-bearing solids are removed from the diagram calculations, $Pb_4Cl_2(OH)_6$ is replaced with the more soluble (but

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[2] The activity of an ion may be calculated by multiplying concentration (molal units) by a mean activity coefficient. These are usually calculated using models of activity-concentration relationships.

metastable) Pb_4SO_7 (Figure 9-3). If sulphate minerals are also removed, litharge (PbO) is present under porefluid conditions (Figure 9-4). Finally, if litharge is suppressed, Pb_2SiO_4 is observed (Figure 9-5). It may be the case that the measured concentrations of lead in the AN08 porefluid reflect the presence of metastable (and therefore relatively highly soluble) solids. It could be the case (depending on backfill aging and leaching) that over time, the lead-bearing solids undergo recrystallisation to more stable, and therefore less soluble, forms.

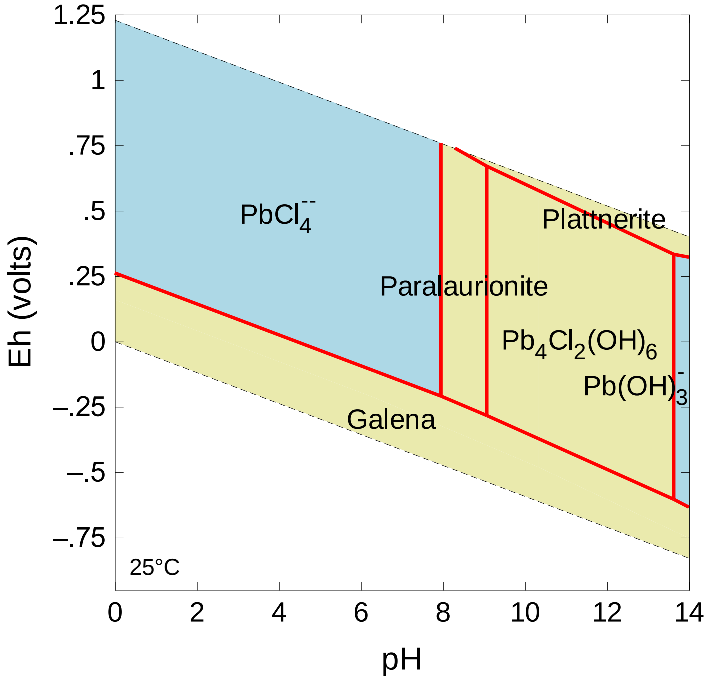

Figure 9-1: Eh-pH diagram for lead at 25 °C, 1 bar under saline conditions associated with AN08 backfill porefluid (calculated using Geochemist's Workbench and the database thermo.com.v8.r6+, log *a* Pb^{2+} = -3.7).

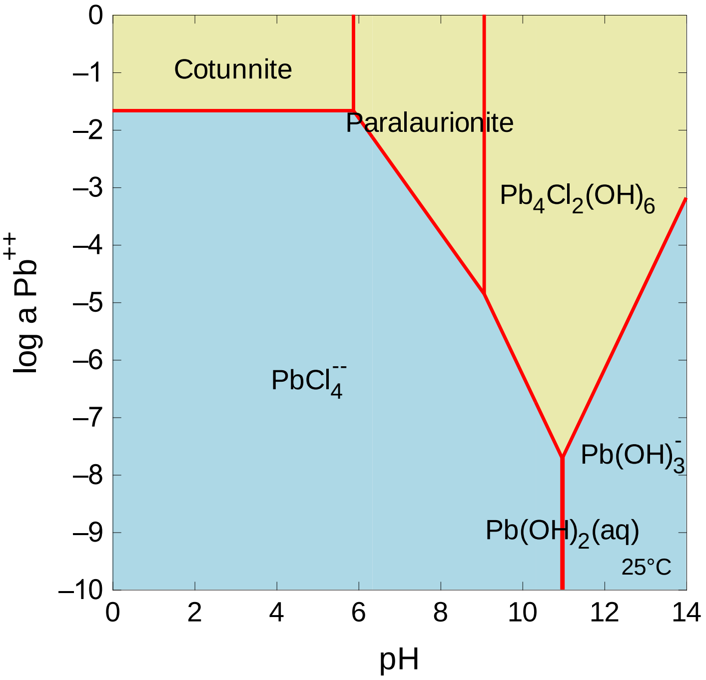

Figure 9-2: Solubility diagram for lead at 25 °C, 1 bar under saline conditions associated with AN08 backfill porefluid (calculated using Geochemist's Workbench and the database thermo.com.v8.r6+).

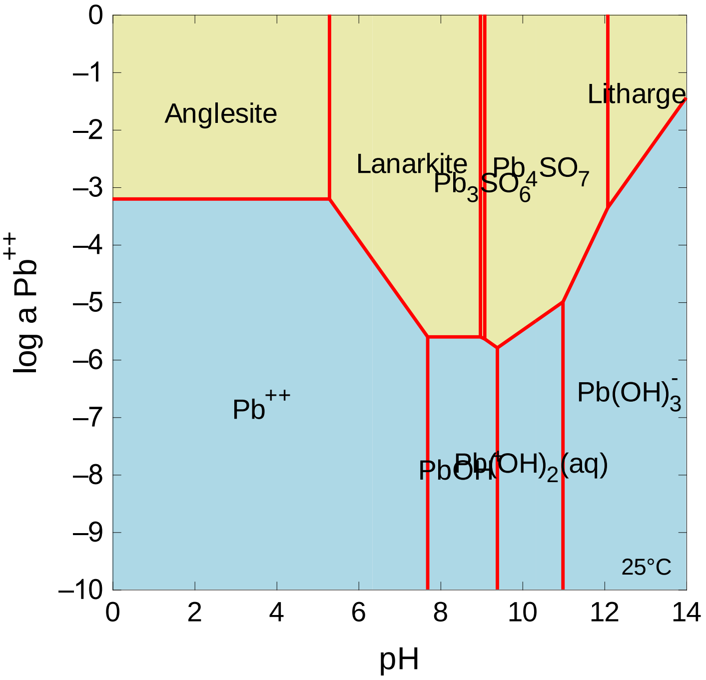

Figure 9-3: Solubility diagram for lead at 25 °C, 1 bar under saline conditions associated with AN08 backfill porefluid (calculated using Geochemist's Workbench and the database thermo.com.v8.r6+). Cl-bearing solids removed.

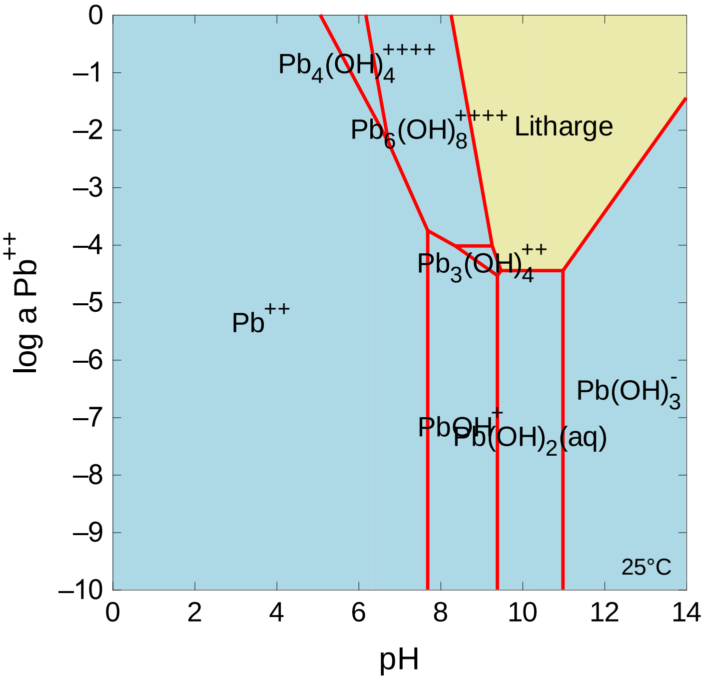

Figure 9-4: Solubility diagram for lead at 25 °C, 1 bar under saline conditions associated with AN08 backfill porefluid (calculated using Geochemist's Workbench and the database thermo.com.v8.r6+). Cl-and sulphate-bearing solids removed.

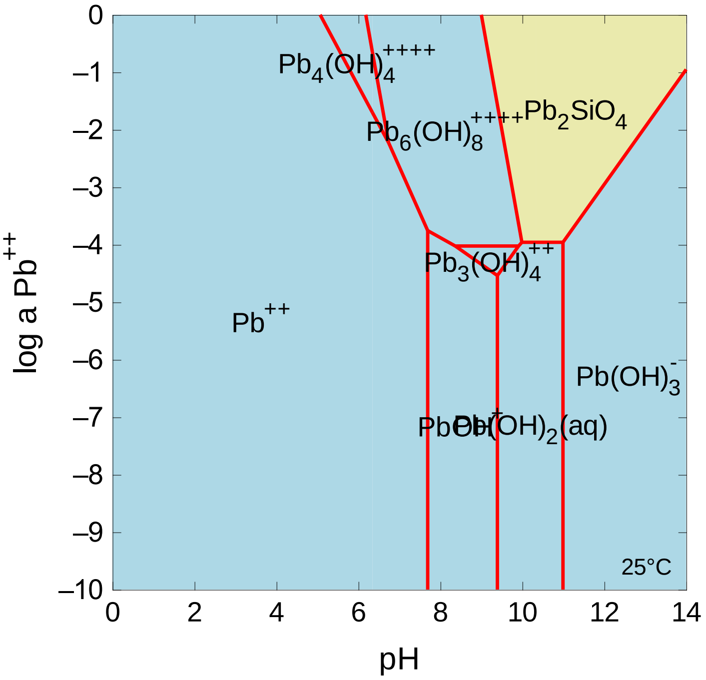

Figure 9-5: Solubility diagram for lead at 25 °C, 1 bar under saline conditions associated with AN08 backfill porefluid (calculated using Geochemist's Workbench and the database thermo.com.v8.r6+). All solids other than Pb_2SiO_4 are suppressed.

If lead is transported to shallower depths and pH / salinity decreases it is likely that a different phase may control dissolved lead concentrations, as Cl-bearing phases would be less likely to form. In solutions with low chloride activities and a lack of sulphate, cerrusite ($PbCO_3$) is a stable phase under near-neutral pH conditions (Figure 9-6). In dilute water compositions (log $f\,CO_{2(g)}$ = 3.5, i.e. ambient atmosphere) equilibrium with cerrusite would result in Pb^{2+} concentrations of ~10^{-7} molal (0.02 ppm). The solubility of lead carbonate phases varies as a function of $CO_{2(g)}$ fugacity (Figure 9-8) and therefore dissolved carbonate concentration. It should be noted that $f\,CO_{2(g)}$ values typically associated with crystalline "hard" rock groundwaters are ~10^{-6} to 10^{-4} bar (Coudrain-Ribstein et al., 1998) and that values more typical of sedimentary or soil environments are ≥10^{-2} bar.

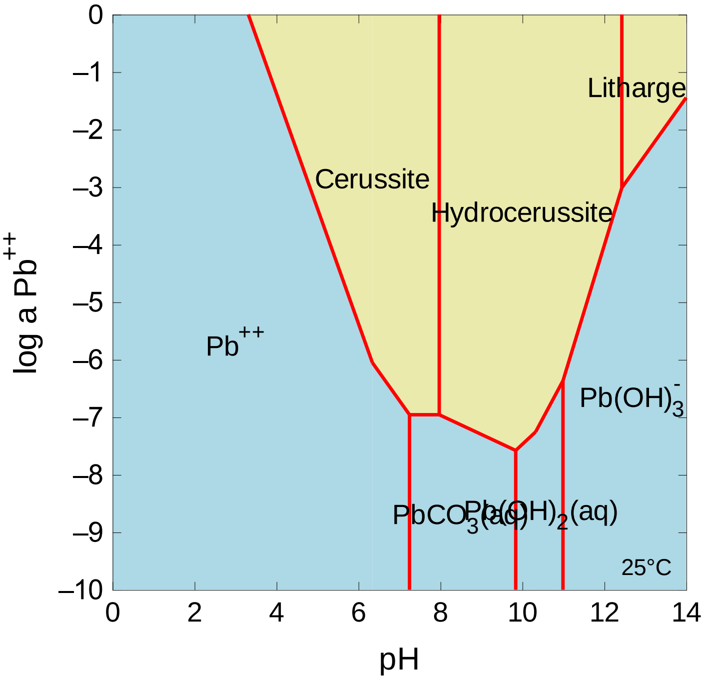

Figure 9-6: Solubility diagram for lead in the presence of dissolved carbonate (25 °C, 1 bar). Ca^{2+} activity is buffered by calcite ($CaCO_3$), log $f\,CO_{2(g)}$ = -3.5 (i.e. atmospheric).

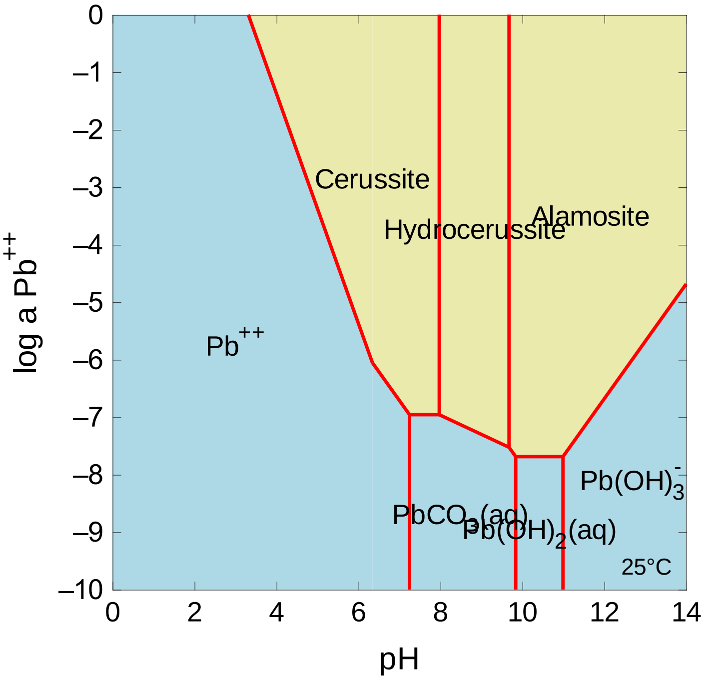

Figure 9-7: Solubility diagram for lead at 25 °C, 1 bar in the presence of dissolved carbonate. Ca^{2+} activity buffered by calcite ($CaCO_3$), SO_4^{2-} activity buffered by gypsum, $SiO_{2(aq)}$ activity buffered by chalcedony, log *f* $CO_{2(g)}$ = -4. Cerussite has the composition $PbCO_3$, hydrocerussite has the composition $Pb_3(CO_3)_2(OH)_2$, and almosite has the composition $PbSiO_3$.

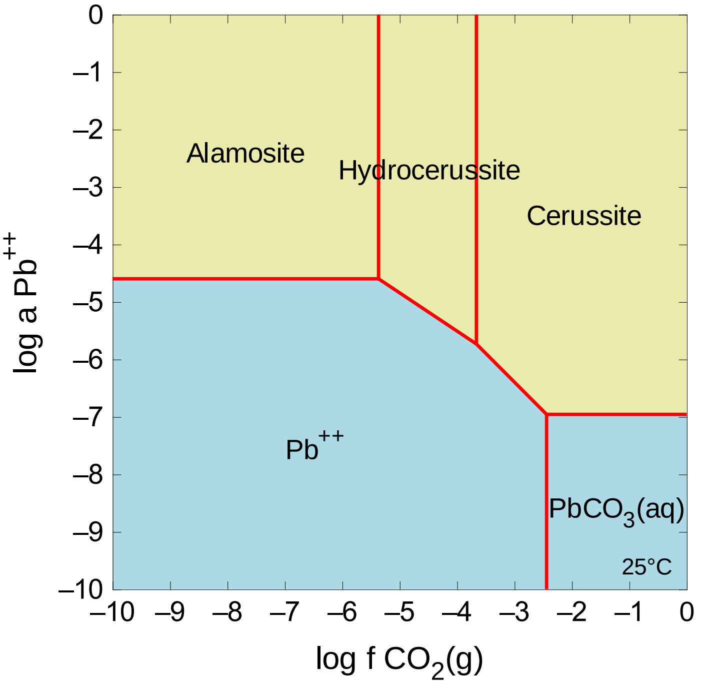

Figure 9-8: Solubility of lead phases as a function of *f* $CO_{2(g)}$ Ca^{2+} activity buffered by calcite (25 °C, 1 bar).

9.2 Calculations to Explore Scenarios

9.2.1 Scoping Calculations for the Expected Evolution Scenario

The Expected Evolution Scenario is quite complex as it includes evolving coupled hydro-mechanical-chemical processes. Consequently, relatively complex calculations are needed to represent these coupled FEPs at a sufficient level of detail that there will be confidence in the calculation results. The calculations also need to be at a sufficient level of complexity that they help to bring out key uncertainties that need to be managed, or addressed by future work.

Assessment Model

The mathematical model for the Expected Evolution Scenario was implemented in the GoldSim code (Version 10.50 (SP2), GoldSim Technology Group LLC). The model considers the cavern and a column of rock above the cavern, including the collapse zone that extends to the ground surface. It is illustrated schematically in Figure 9-9.

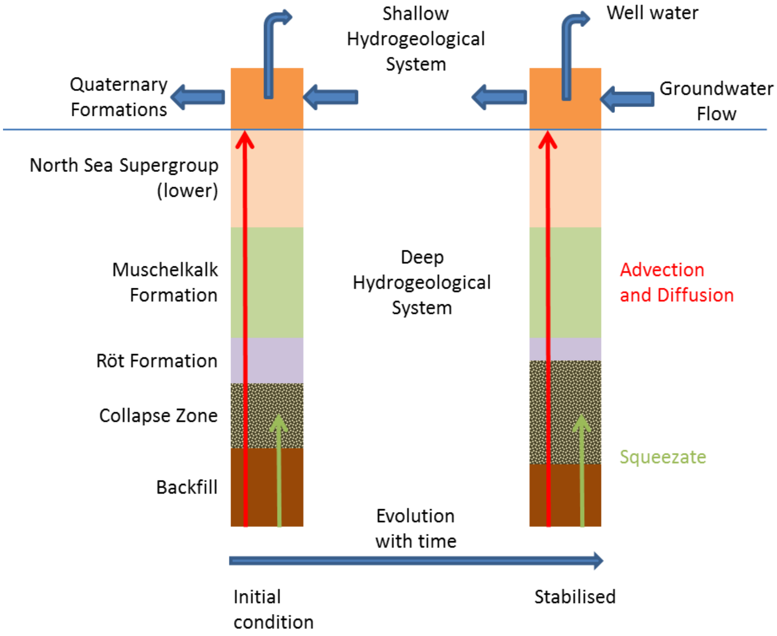

Figure 9-9: Schematic Illustration of the GoldSim Model.

The following features are represented in the (1D) column model:

- cavern backfill;
- collapse zone;
- Röt Formation;
- Muschelkalk Formation;

- North Sea Supergroup (lower part thereof); and
- shallow geological formations.

The shallow geological formations are those present in the shallow hydrogeological system, in which there is active flow of fresh groundwater. The shallow hydrogeological system is hydraulically isolated from the deep hydrogeological system, which is present in the lower formations of the North Sea Supergroup and the underlying geological formations. There is little flow in the deep hydrogeological system and the water is saline. The Niedersachsen group and the Altena group are not represented explicitly but for the purposes of the scoping calculations can be subsumed into the Muschelkalk or North Sea Supergroup (lower).

The model considers the contaminant inventory present in the backfill and in the bleed water from the backfill. Cautiously the entire void space remaining in the cavern after backfilling is assumed to contain undiluted bleed water. The following contaminants are included in the calculations based on the data available from the backfill development programme: As, Cd, Pb, Sb, Zn. Contaminant concentrations in the backfill were calculated based on the composition of the AN08 backfill development sample. Contaminant concentrations in the bleed water were specified based on the composition of AN08 squeezed porewater i.e. water extracted from the AN08 sample by squeezing the sample.

A collapse zone is assumed to form immediately after backfilling, with the height of the collapse zone being determined by the residual voidage following backfilling. That is, the anhydrite layer is assumed to fail immediately.

The backfill is assumed to compact with time, resulting in an increase in density and a reduction in volume and porosity. The backfill is simulated to stabilise according to an exponential decay model, therefore a “half-life” for stabilisation is specified in the model. As the backfill compacts, the height of the collapse column is simulated to increase, the thickness of undamaged rock correspondingly decreases, and contaminated water is squeezed out of the backfill and enters the collapse column.

Contaminants are transported up the column by advection and diffusion. It is assumed that there is a vertical hydraulic gradient (and hence vertical flow) from the underlying Solling Formation to the overlying shallow geological formations. Variant cases are used to explore the sensitivity to alternative assumptions. Since the model is 1-D, lateral diffusion and downwards diffusion into the Solling Formation, are not represented. Cautiously, this maximises the upwards diffusive contaminant flux.

The vertical advective flow must be supported by a supply of water. This may be due to water coming out of storage under confined conditions, due to the compressibility of the rock, or inflow of uncontaminated water. For simplicity, and consistent with the scoping nature of the calculations, there is assumed to be inflow of uncontaminated water. It should be noted that the rates and volumes involved are very small, consistent with the low permeability of the rock. As described in Section 9.2.3, for some calculation cases this may lead to slightly greater dilution than would be the case if the water was coming out of storage, but the difference will be small because the flow rates are small. The GoldSim code does not have the capability to calculate water fluxes through media of specified permeabilities under given head / pressure gradients (it lacks a flow solver). Hence, all water flows have to be determined separately, either using expert judgement or by means of "off-line" calculations, and then specified in the model input data.

Heavy metal concentrations are set equal to the contaminant concentrations measured in AN08 squeezed porewater. As described in Section 9.1.2, the concentrations of Pb, Zn and As could be controlled by the solubility of solid phases within the backfill. Sorption distribution coefficients have been specified for the backfill based on the ratio of liquid to solid contaminant concentrations for the AN08 backfill sample. However, these distribution coefficients will only affect transport if contaminant concentrations in the backfill fall below any solubility limit. Cautiously there is assumed to be no sorption in the overlying formations. Variant cases are used to explore the sensitivity to the more realistic assumption that there will be sorption in the overlying formations.

There is lateral groundwater flow in the shallow hydrogeological system, which results in dilution of the contaminants entering the shallow system. The cavern diameters are of the order 100+ m, and the plume of contaminated groundwater in the shallow hydrogeological system will be of similar or greater width. Therefore it is possible that a well in the shallow system might abstract only contaminated water. It is cautiously assumed that contaminant concentrations in the well water are the same as those in the shallow groundwater. Therefore calculated contaminant concentrations in the shallow hydrogeological system can be compared with Drinking Water Standards (DWS). In reality the well might only intercept part of the plume above the cavern, and contaminated water might be diluted with clean groundwater.

The model has been run for the Expected Evolution Scenario and a number of variant calculation cases, as described in Table 9-5. Cautious assumptions in the Expected Evolution, No Retardation in Rock Case are summarised in Table 9-6. The potential degree of caution is noted, and this informs the selection of Expected Evolution Scenario variant cases. Model data are presented in Section 9.2.2 and the model results are presented in Section 9.2.3.

Table 9-5. Expected Evolution Scenario and variant calculation cases.

Calculation Case	Description
No Retardation in Rock Case	No Retardation in Rock Case for the Expected Evolution Scenario. This provides a reference point for assessment of sensitivity to alternative assumptions. It is not the best estimate case at this stage of the risk assessment.
Variant 1 - Sorption onto Rock	Sorption distribution coefficients for the (undamaged) Röt and Muschelkalk Formations and the North Sea Supergroup are assumed to be the same as for the backfill.
Variant 2 - Vertical Flow in the Muschelkalk and Overlying Formations Only	There is no vertical flow through the backfill, collapse zone or Röt Formation, transport is by diffusion only. There is vertical flow in the Muschelkalk Formation and North Sea Supergroup.
Variant 3 - No Vertical Flow	There is no vertical flow. Transport through the deep hydrogeological system is by diffusion only.
Variant 4 - Chemical Barrier Safety Criteria	This case is used to help derive a chemical barrier safety criteria for the thickness of undamaged Röt Formation required to provide a barrier to contamination transport into the overlying Muschelkalk Formation. Transport is by diffusion only. There is no vertical flow.

Table 9-6: Cautious assumptions in the Expected Evolution Scenario, No Retardation in Rock Case.

Cautious Assumptions	Potential Degree of Caution
Contaminant concentrations measured in bleed water from fresh backfill samples are treated as solubility limits.	Potentially high as solubility limits are expected to decrease with time as the backfill cures and contaminant concentrations equilibrate with stable mineral phases.
Sorption onto rock occurs in the collapse column and the overlying formations.	Potentially high, particularly for clay rich formations such as the Röt Formation. However high salinity might limit sorption compared with freshwater environments due to the concentration of competing ions.
Vertical flow from the Solling Formation to the shallow hydrogeological system. Overpressures at depth don't diminish with time.	Potentially high. The chosen flow rates are an upper bound value. In addition, if peak overpressures occur in the Muschelkalk Formation, then flow might actually be downwards from the Muschelkalk Formation to the Solling Formation.
No lateral or downwards diffusion.	Likely low to medium degree of caution, depending on the significance of diffusion compared with upwards advection. Dilution by dispersion is underestimated.
The entire void space remaining in the cavern after backfilling contains undiluted bleed water.	Likely low degree of caution. Contaminant concentrations in the backfill are much higher than in the bleed water. Therefore it is anticipated that contaminant concentrations in the water in the void space will rapidly reach similar levels to those in the backfill, which are plausibly solubility-limited in the cases of As, Zn and Pb.

Cautious Assumptions	Potential Degree of Caution
Contaminated water is abstracted from directly above the cavern, without dilution.	The contaminant plume is likely to be of similar width to the cavern, and therefore of the order 100+ m. Therefore this is possible. However, the likelihood that a well will be drilled in the required location compared with elsewhere is low.
Residual voidage is evenly distributed across the footprint of the cavern.	This is optimistic because it tends to minimise the height of the collapse zone. However, it is also cautious because it maximises the upwards flux of contamination, the size of the resultant contaminant plume and the likelihood that contaminated water will be abstracted via a well without dilution.

9.2.2 Data

Key data used in the scoping calculations are detailed in the tables below.

Table 9-7: Cavern data.

Parameter	Value	Reference
Cavern diameter	125 (m)	Representative value suitable for scoping calculation
Cavern height	60 (m)	As above
Fraction backfilled	0.9	As above

Table 9-8: Backfill properties.

Parameter	Value	Reference
Grain density	2650 (kg/m^3)	Assumed based on quartz (Deer et al., 1993)
Uncompacted dry bulk density	1635 (kg/m^3)	AN08 in file Oedometerversuche AKZO_13-08-12_
Uncompacted porosity	0.38 (-)	Calculated from grain density and uncompacted dry bulk density
Backfill compaction factor	0.13	This is the fractional loss in backfill volume upon compaction. Estimated to give compacted dry bulk density that is similar to compacted ANO8 in file Oedometerversuche AKZO_13-08-12_
Backfill compaction rate	0.035 y^{-1}	Derived from a compaction 'half-life' of 20 y, which is consistent with the description of the Expected Evolution Scenario (Paulley and Metcalfe, 2012).

Table 9-9: Sorption distribution coefficients for the backfill.

Contaminant	Kd (m^3/kg)	Reference
As	5.52E-01	Calculated from ratio of squeezed porewater and solid concentrations for AN08.
Cd	1.74E+00	As above
Pb	8.84E-02	As above
Sb	8.59E+00	As above
Zn	5.97E-01	As above

Table 9-10: Contaminant concentrations.

Contaminant	Concentration (mg/l)	Reference
As	7.00E-02	Equal to concentration measured in squeezed porewater from AN08 – see Table 9-1
Cd	7.20E-02	As above
Pb	3.75E+01	As above
Sb	5.70E-02	As above
Zn	1.81E+01	As above

Table 9-11: Formation properties.

Formation	Thickness (m)	Bulking Factor (-)	Reference
Shallow geological formations	20	1.11	Typical thickness from van Duijne et al. (2011a). Bulking factor from Dimmie et al. (2012)
North Sea Supergroup (lower)	130	1.11	As above
Muschelkalk	135	1.11	As above
Röt	135	1.11	As above

Table 9-12: Rock properties.

Formation	**Porosity (-)**	**Dry Bulk Density (kg/m^3)**	**Reference**
Shallow geological formations	0.425	1524	Porosity – van Duijne et al. (2011a) Density calculated from an assumed grain density if 2650 kg/m^3 multiplied by porosity.
North Sea Supergroup (lower)	0.275	1921	As above
Muschelkalk	0.17	2200	As above
Röt	0.075	2451	As above

Table 9-13. Properties of the deep hydrogeological system.

Parameter	**Value**	**Reference**
Average vertical hydraulic conductivity	1E-10 (m/s)	Towler (2012) – note uncertain, chosen value is likely to be cautious
Vertical hydraulic gradient	0.153 (-)	Towler (2012)
Vertical Darcy flow rate	4.83E-4 (m/y)	Towler (2012)
Flow focussing factor for the collapse column	2 (-)	Assumed

Table 9-14: Properties of the shallow hydrogeological system.

Parameter	**Value**	**Reference**
Horizontal hydraulic conductivity	1E-5 (m/s)	Representative value suitable for scoping calculations based on van Duijne et al. (2011a)
Horizontal hydraulic gradient	0.01	Representative value suitable for scoping calculations

Table 9-15: Drinking Water Standards.

Contaminant	Value (µg l^{-1})	Reference
As	10	Target: Bijlage III. bij het Besluit kwaliteitseisen monitoring water 2009. wetten.overheid.nl/BWBR0027061/geldigheidsdatum_14-08-2012
Cd	1	As Above
Pb	30	As Above
Sb	20	WHO DW Guidelines, 3rd Edition.
Zn	200	As for As
Cl	1.5E5	As Above
SO_4	1.0E5	As Above

9.2.3 Results for the Expected Evolution Scenario

Expected Evolution Scenario No Retardation in Rock Case

In the No Retardation in Rock Case it is assumed that 90% of the cavern volume is filled with backfill and there is 10% residual voidage. The backfill compacts with a “half-life” of 20 years, eventually reducing to 0.87 of the original volume. This results in the density of the backfill increasing from 1635 kg/m^3 to 1879 kg/m^3 (Figure 9-10). This final density is consistent with compacted samples from the backfill development programme.

The height of the collapse column is initially 60m, associated with the 10% residual voidage, but increases to 131m as the backfill compacts (Figure 9-11). (The final height of the collapse zone above the roof of the cavern is 118 m). The thickness of the undamaged Röt Formation reduces from 80m to 17 m, compared with a formation thickness of 135 m.

Figure 9-12 shows contaminant concentrations in the Muschelkalk Formation compared with DWS. Since a DWS is not specified for Sb in the Netherlands, a WHO value has been used. Contaminants are able to migrate across the undamaged part of the Röt Formation, so that DWS are exceeded for all contaminants within the timeframe of interest (10,000 y), although it should be noted that the calculations include a number of cautious assumptions, not least that there is no sorption in the Muschelkalk Formation. In any case the waters in the Muschelkalk are saline and not potable.

Figure 9-13 shows contaminant concentrations in the shallow hydrogeological system compared with DWS. DWS are not exceeded within the timeframe of interest (10,000 y). Results are presented up to 1,000,000 y to capture the peak concentrations and therefore test sensitivity to process representations within the assessment timeframe. However, it should be noted that over such timescales the results are very uncertain and the near-surface environment will likely be subject to significant environmental changes which are not reflected in the calculations. The DWS is nearly reached for Pb, but only after 200,000 y.

Figure 9-14 shows the spatial distribution of Pb with time. Initially all the Pb is present in the backfill and in the bleed water in the collapse zone. As the backfill is compacted some contaminated water is squeezed into the collapse zone, but the amount of lead in solution is small compared with the solid inventory. Lead slowly migrates to the shallow hydrogeological system. After 10,000 y less than 0.1% of the inventory has migrated into the Röt and Muschelkalk Formations. After 1E6 y ~5% of the inventory has migrated into the shallow hydrogeological system.

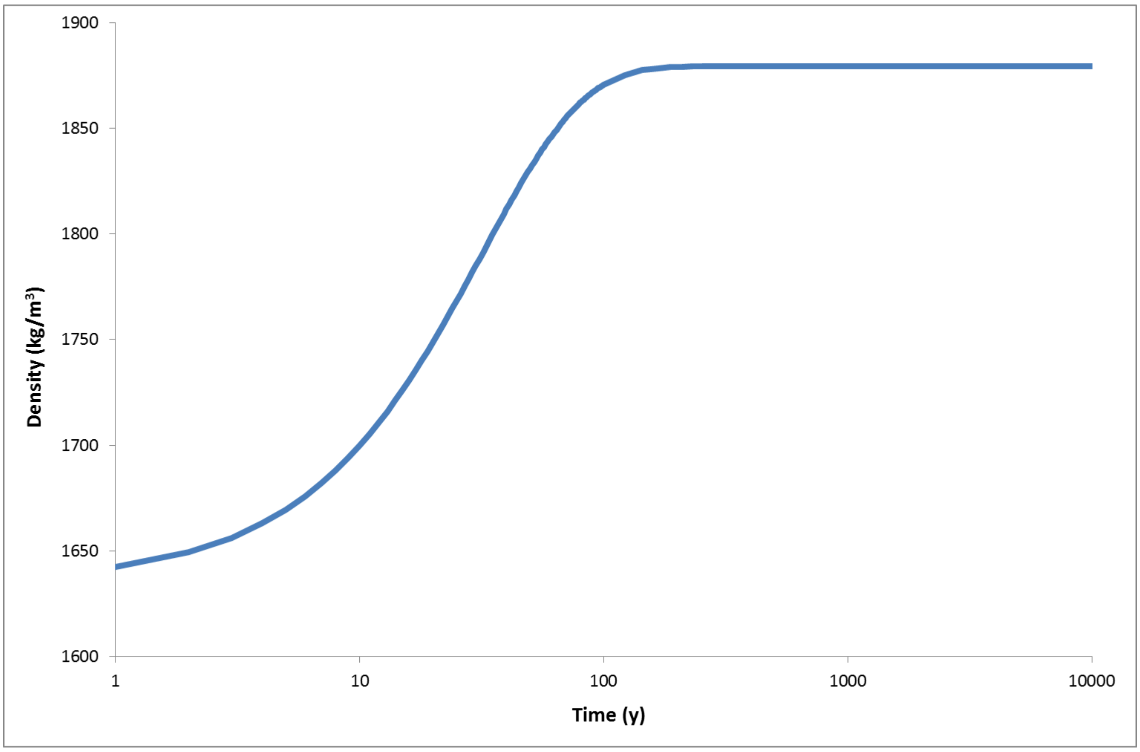

Figure 9-10: Evolution of backfill density for the Expected Evolution Scenario, No Retardation in Rock Case.

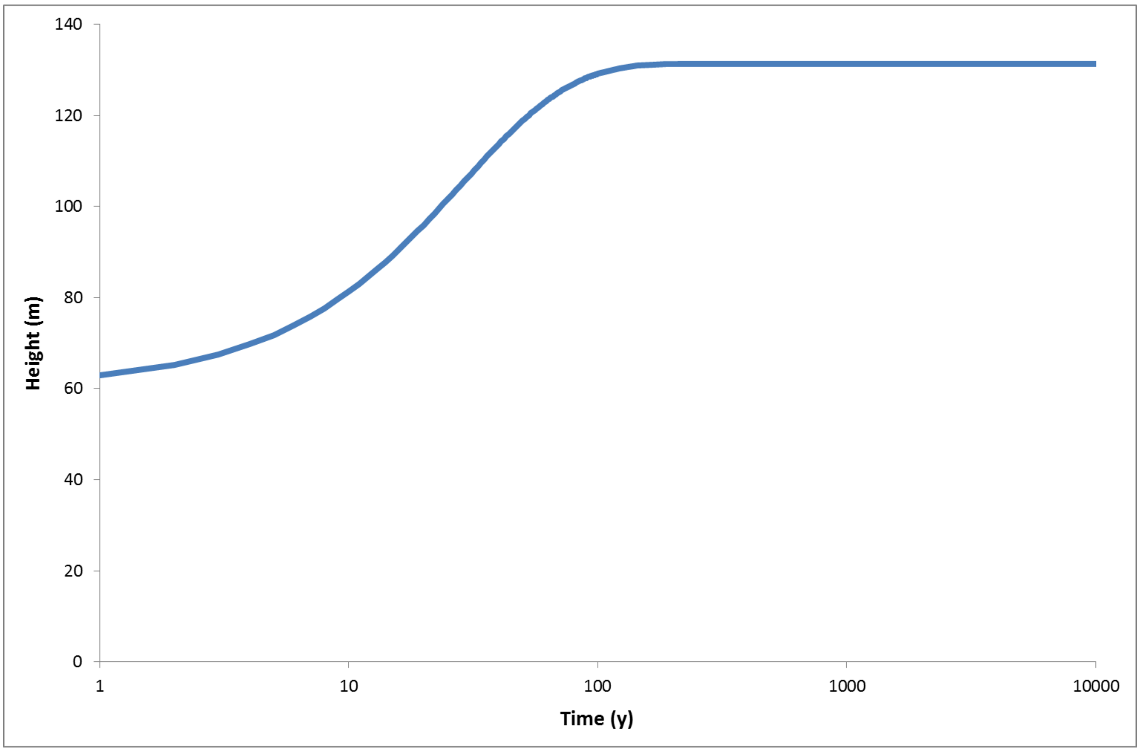

Figure 9-11: Evolution of the collapse column height for the Expected Evolution Scenario, No Retardation in Rock Case.

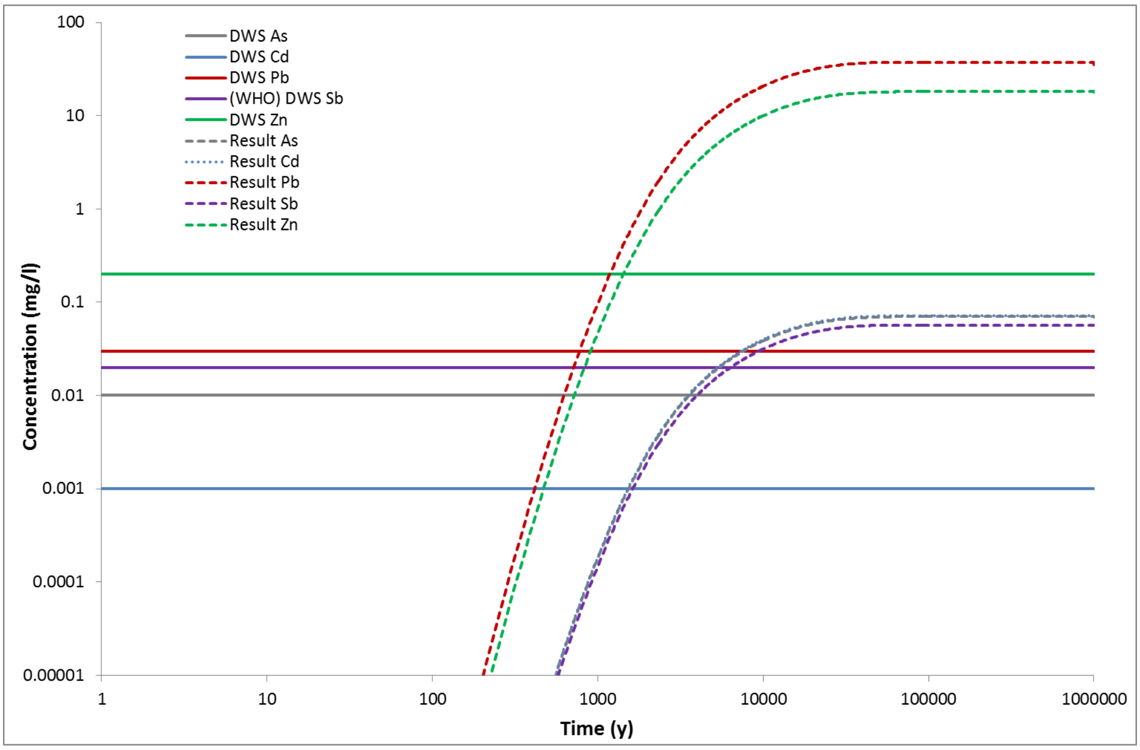

Figure 9-12: Calculated contaminant concentrations in the Muschelkalk Formation compared with DWS for the Expected Evolution Scenario, No Retardation in Rock Case.

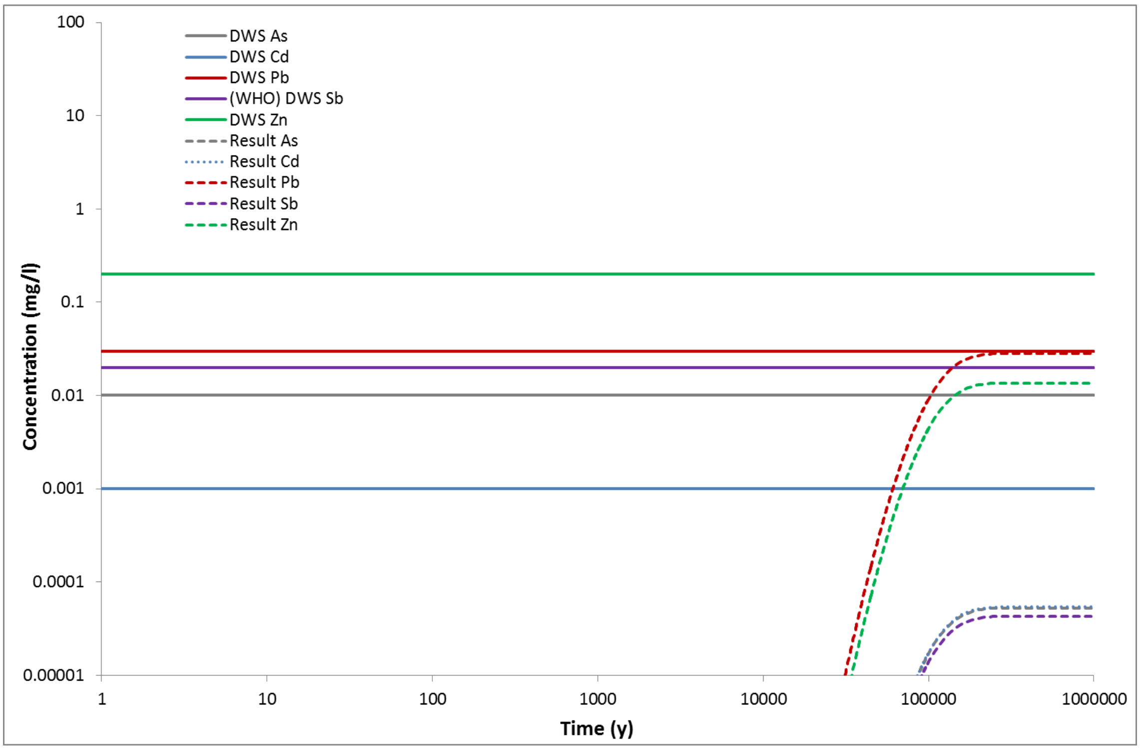

Figure 9-13: Calculated contaminant concentrations in the shallow hydrogeological system compared with DWS for the Expected Evolution Scenario, No Retardation in Rock Case.

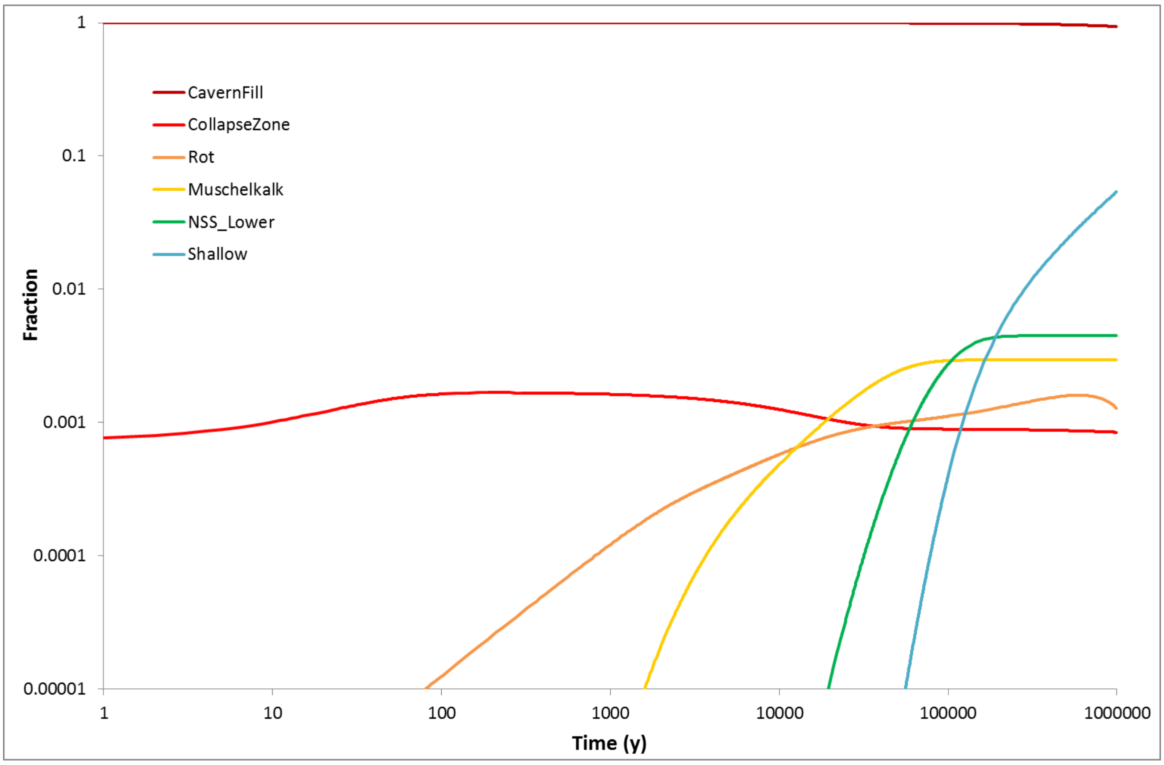

Figure 9-14: Spatial distribution of lead for the Expected Evolution Scenario, No Retardation in Rock Case.

Expected Evolution Scenario Variant 1 - Sorption onto Rock

In the No Retardation in Rock Case, only contaminant sorption onto the backfill was considered. In this variant case sorption onto the (undamaged) Röt Formation, Muschelkalk Formation and North Sea Supergroup is considered. There is no sorption onto the shallow geological formations or the rock in the collapse zone. There is assumed to be no sorption onto rock in the collapse zone since transport can occur through water filled voids, and the surface area for rock-water interaction is small compared with transport through the rock matrix.

Sorption distribution coefficients are not available for these rocks. Data are available from the literature for analogous rocks with relatively low-salinity water (seawater concentrations or lower), but only limited data are available for analogous rocks with highly saline water and brine. For these initial scoping calculations, the sorption distribution coefficients were set to be the same as for the backfill.

DWS were not exceeded in the shallow hydrological formations or the Muschelkalk Formation within the 1,000,000 model run time (Figure 9-15).

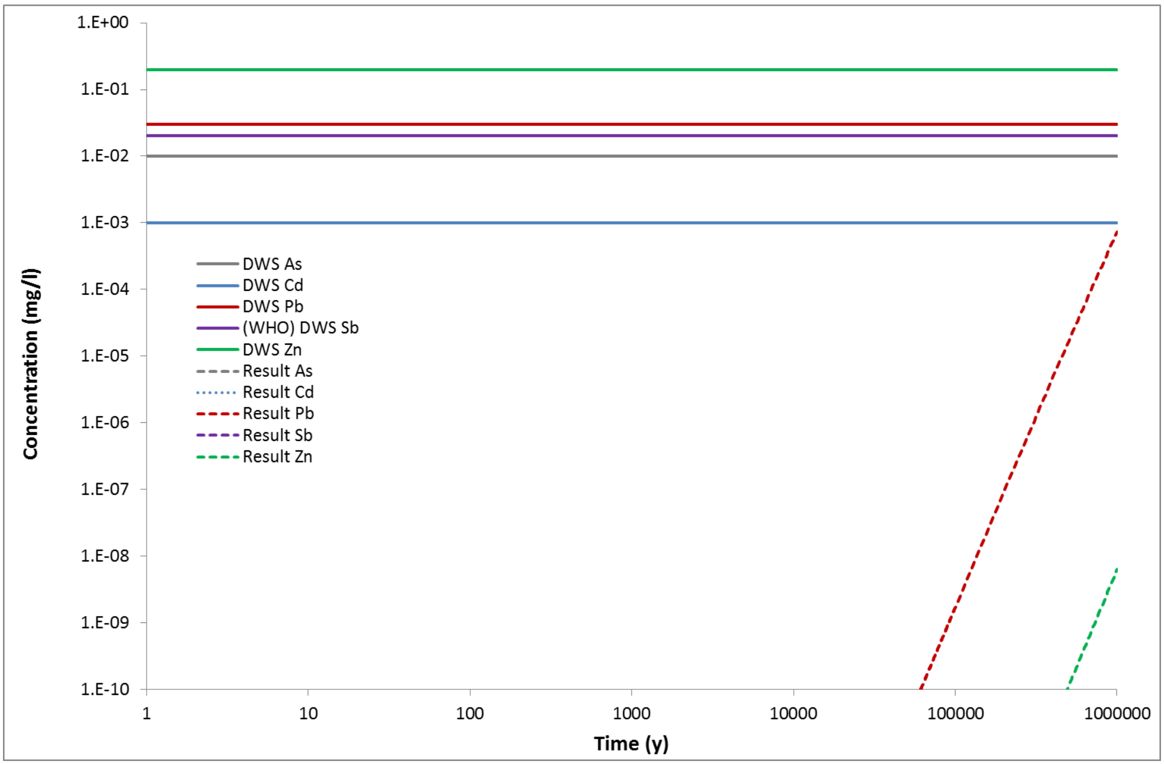

Figure 9-15: Calculated contaminant concentrations in the Muschelkalk Formation compared with DWS for the Expected Evolution Scenario Variant Case 1 (Sorption onto Rock Case).

Expected Evolution Scenario Variant 2 - Vertical Flow in the Muschelkalk and Overlying Formations Only

There are artesian conditions in some permeable beds within the Muschelkalk Formation. It is not known whether these overpressures only occur within the Muschelkalk Formation, or if there is an upward hydraulic gradient from the Solling Formation (and potentially deeper) to the shallow hydrogeological system. The No Retardation in Rock Case cautiously assumes that there is a hydraulic gradient from the Solling Formation to the shallow hydrogeological system, which leads to vertical flow through the backfill, collapse column and overlying formations. The vertical flow rate (Darcy velocity) is sensitive to the estimated vertical hydraulic gradient and estimated average vertical hydraulic conductivity. The value chosen for the estimated average vertical hydraulic conductivity is likely cautious.

In this variant case there is only vertical flow in the Muschelkalk Formation and overlying North Sea Supergroup. Transport through the backfill, collapse zone and undamaged Röt Formation is by diffusion only. The vertical advective flow must be supported by a supply of water. Since release of water from storage is not included in the mathematical model, it is assumed that there is lateral inflow of uncontaminated water from the adjacent rock in the Muschelkalk Formation.

Peak contaminant concentrations in the shallow hydrogeological system occur after approximately 250,000 y, and contaminant concentrations are more than an order of magnitude below the DWS. In the Muschelkalk Formation, DWS are exceeded for Pb, Zn and Cd but only after 12,000 y, 45,000 y and 60,000 y respectively.

Expected Evolution Scenario Variant 3 - No Vertical Flow

As described in the previous sub-section, the vertical flow rate (Darcy velocity) is sensitive to the estimated vertical hydraulic gradient and estimated average vertical hydraulic conductivity. In this variant case, there is no vertical flow in the deep hydrogeological system. Transport to the shallow hydrogeological system is by diffusion alone. This reflects the fact that the average vertical hydraulic conductivity might be much lower than assumed in the No Retardation in Rock Case; and for the average vertical hydraulic conductivity assumed in the No Retardation in Rock Case the flows may not be sustainable throughout the assessment timeframe.

Even after 1,000,000 y, contaminant concentrations in the shallow hydrogeological formations are all more than four orders of magnitude below the DWS. Figure 9-16 shows contaminant concentrations in the Muschelkalk Formation. DWS are eventually exceeded for all contaminants, but DWS are not exceeded within the 10,000 y timeframe. The DWS for Pb is exceeded shortly after the end of the assessment timeframe, i.e. after 11,500 y.

Contaminant concentrations in the Muschelkalk Formation are higher than in the preceding case (Variant 2). This is because transport to the Muschelkalk Formation is similar in the two cases, but contaminants are transported out of the Muschelkalk Formation more rapidly in the preceding variant case, due to vertical advective flow. There is also a small amount of dilution by lateral inflow of clean water.

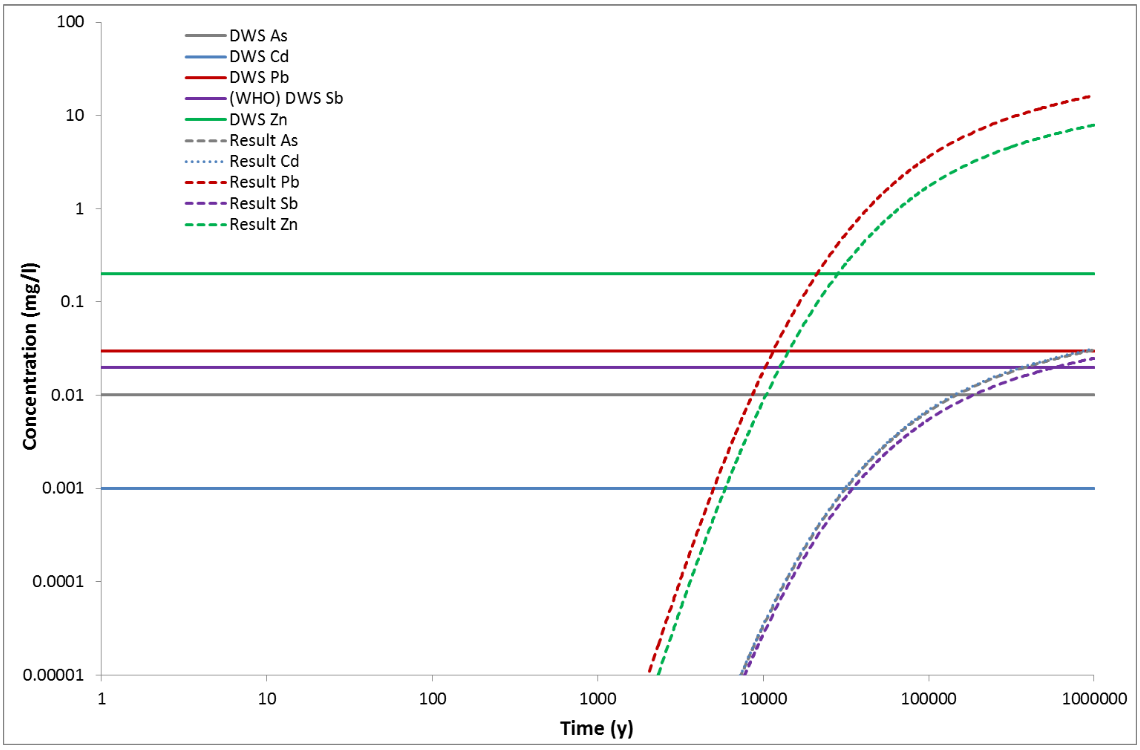

Figure 9-16: Calculated contaminant concentrations in the Muschelkalk Formation compared with DWS for the Expected Evolution Scenario Variant Case 3 (No Vertical Flow Case).

Expected Evolution Scenario Variant 4 - Chemical Barrier Safety Criteria

This case is used to help derive a chemical barrier safety criteria for the thickness of undamaged Röt Formation (Upper Röt Claystone) required to provide a barrier to transport of contamination into the overlying Muschelkalk Formation. In this variant case, the modelled thickness of the Röt Formation is increased from 135 m to 158.4 m, such that the thickness of undamaged rock is 40 m once the backfill has stabilised. The thickness of the North Sea Supergroup is correspondingly reduced to 106.6 m, such that the total thickness of rock is the same as in the No Retardation in Rock Case.

An assumption implied by the criteria is that there is insignificant advective transport in the Röt Formation, therefore it is assumed that no vertical flow occurs through the backfill, collapse zone or undamaged Röt Formation. Since the objective of the criteria is to protect the Muschelkalk Formation, taking into consideration the results of

Variant Cases 2 and 3, it was cautiously assumed that there is no vertical flow in the Muschelkalk Formation or overlying North Sea Supergroup. This maximises contaminant concentrations in the Muschelkalk Formation.

DWS in the Muschelkalk Formation are not exceeded within the timeframe of interest (10,000 y) (Figure 9-17). For calculations to 1,000,000 y, DWS are eventually exceeded for As, Cd, Pb and Zn. However, no DWS is exceeded until after 40,000 y, when Pb becomes the first element to exceed its DWS (Figure 9-17).

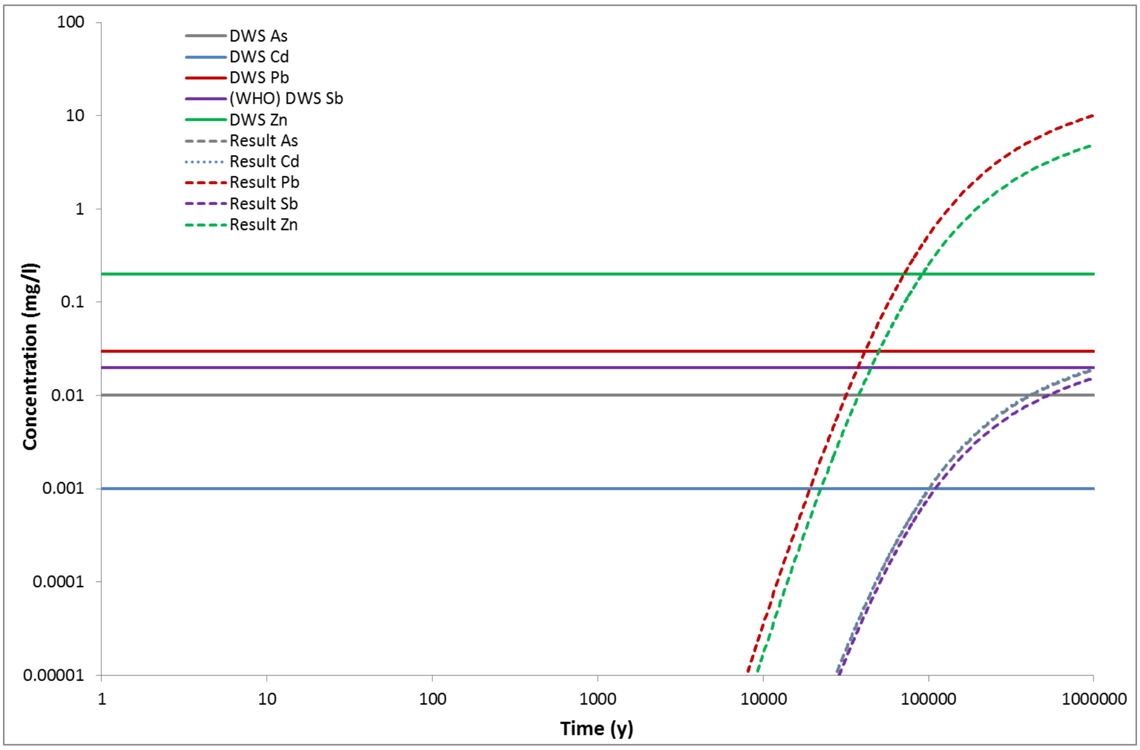

Figure 9-17: Calculated contaminant concentrations in the Muschelkalk Formation compared with DWS for the Expected Evolution Scenario Variant Case 4 (Chemical Barrier Safety Criteria case).

9.2.4 Scoping Calculations for Alternative Evolution Scenarios

Do Nothing Scenario

The caverns are not backfilled. Although the caverns may be stable for several tens of years, ultimately the anhydrite layer will fail and collapse will be initiated. For scoping calculations it is assumed that collapse occurs immediately, and the resulting collapse column extends to the shallow hydrogeological system. In practice this means that the collapse column will extend to the ground surface and a sinkhole will form. The collapse column forms a permeable pathway through the low-permeability formations that help to hydraulically isolate the shallow hydrogeological system from the deep hydrogeological system. The scoping calculations investigate the potential for brine contamination of the shallow hydrogeological system due to migration of brine up the collapse column in response to the artesian conditions in the Muschelkalk Formation.

For the scoping calculations, the Rot and Muschelkalk Formations are assumed to contain brine with chloride and sulphate concentrations of 15,000 mg l^{-1} and 1400 mg l^{-1} respectively. Chloride and sulphate are transported up the collapse column by diffusion and by advection in response to artesian conditions in the Muschelkalk Formation. For modelling simplicity, the North Sea Supergroup is assumed to contain freshwater, although in reality the fresh-saline interface lies within these strata. This simplification slightly delays the calculated time of arrival of saline water in the shallow hydrogeological system.

Peak concentrations in the shallow groundwater system for chloride and sulphate are 22.5 mg l^{-1} and 2.1 mg $^{-1}$ respectively, compared with DWS of 150 mg l^{-1} and 100 mg $^{-1}$ respectively. Therefore it is concluded that the no backfilling scenario is unlikely to result in brine contamination of the shallow hydrogeological system.

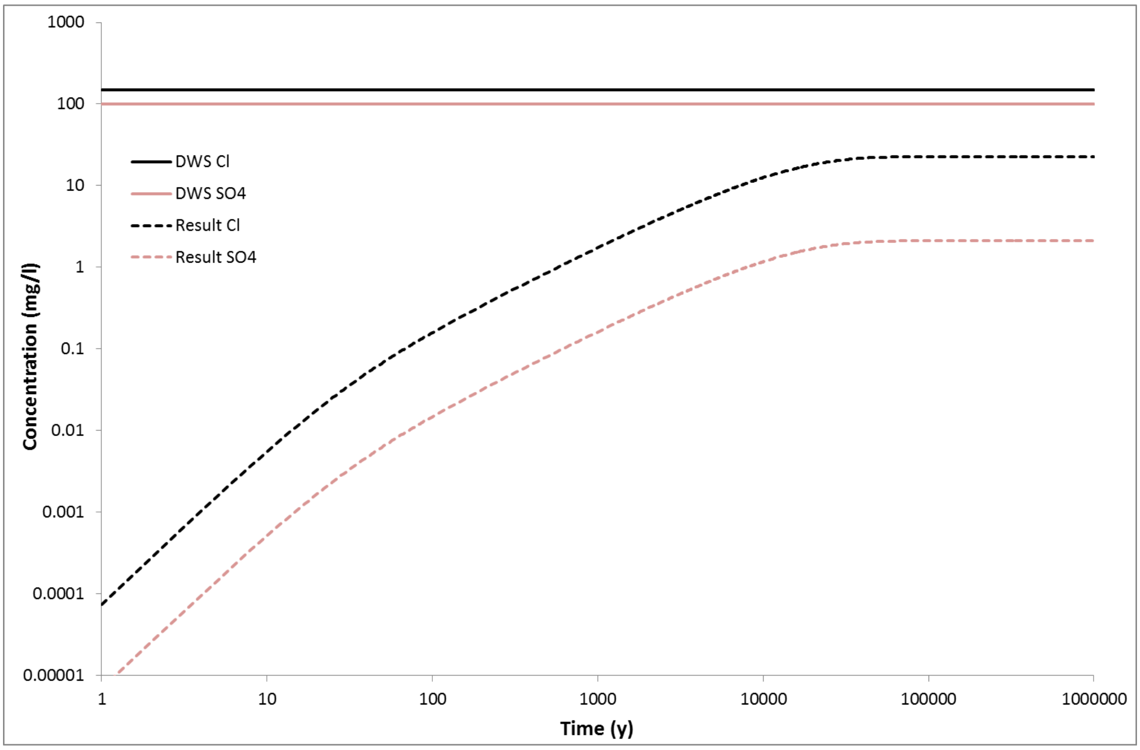

Figure 9-18: Brine concentrations in the shallow hydrogeological system compared with DWS.

Cavern Interaction Scenario

As the backfill is compacted by roof collapse, contaminated porewater will be squeezed out of the backfill. Much of the contaminated water will enter the forming collapse column, but some water could potentially pass into an adjacent cavern via fractures in the halite pillar.

It is assumed that the adjacent cavern is not backfilled. The worst case is that the adjacent cavern collapses, resulting in the formation of a collapse column which extends to the shallow hydrogeological system. This also means that a sinkhole will form. Contaminated water then migrates up the collapse column of the adjacent cavern to the shallow hydrogeological system via diffusion and in response to a vertical hydraulic gradient from depth.

This scenario is modelled using a combination of the models for the Expected Evolution Scenario, No Retardation in Rock Case and the Do Nothing Scenario. The amount of porewater that could migrate through fractures in the pillar into the adjacent cavern cannot be estimated reliably. It is assumed that 50% of water squeezed from the backfill migrates into the adjacent cavern. Figure 9-19 and Figure 9-20 below show contaminant concentrations in the Muschelkalk Formation and the shallow hydrogeological system respectively, above the adjacent cavern. There are two peaks in contaminant concentrations in the overlying formations, the most pronounced ones being in the shallower hydrogeological system (Figure 9-20). The smaller, earlier peak is caused by the initial compaction of the backfill squeezing porefluid into the adjacent cavern. The peak is relatively small owing to dilution of the contaminants by water already present in the collapse column above the adjacent cavern. The second, later peak reflects long-term flow of contaminated water from this cavern under the assumed natural upwards hydraulic gradient. This peak is larger than the earlier one because the water above the adjacent cavern becomes progressively contaminated.

DWS are exceed for Pb, Zn, As and Cd in the Muschelkalk Formation. Peak concentrations are several times lower than in the Expected Evolution Scenario No Retardation in Rock Case, but occur much earlier. DWS are not exceeded in the shallow hydrogeological system.

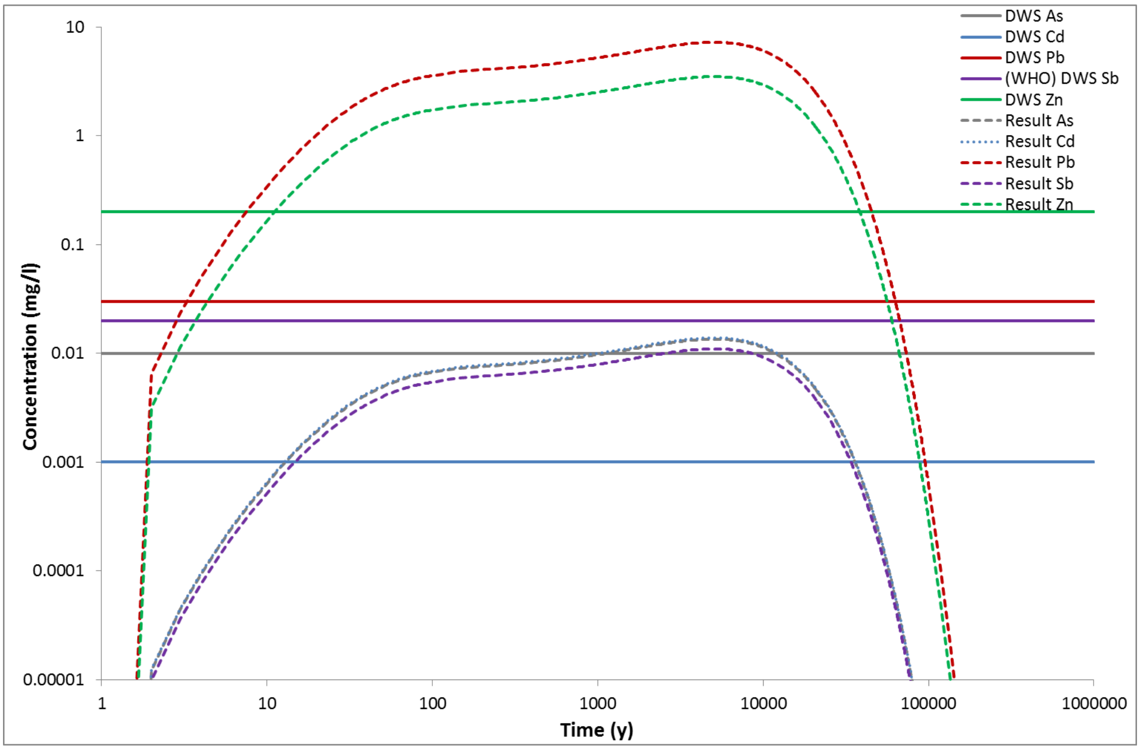

Figure 9-19: Contaminant concentrations in the Muschelkalk Formation for the Cavern Interaction Scenario (above the adjacent cavern).

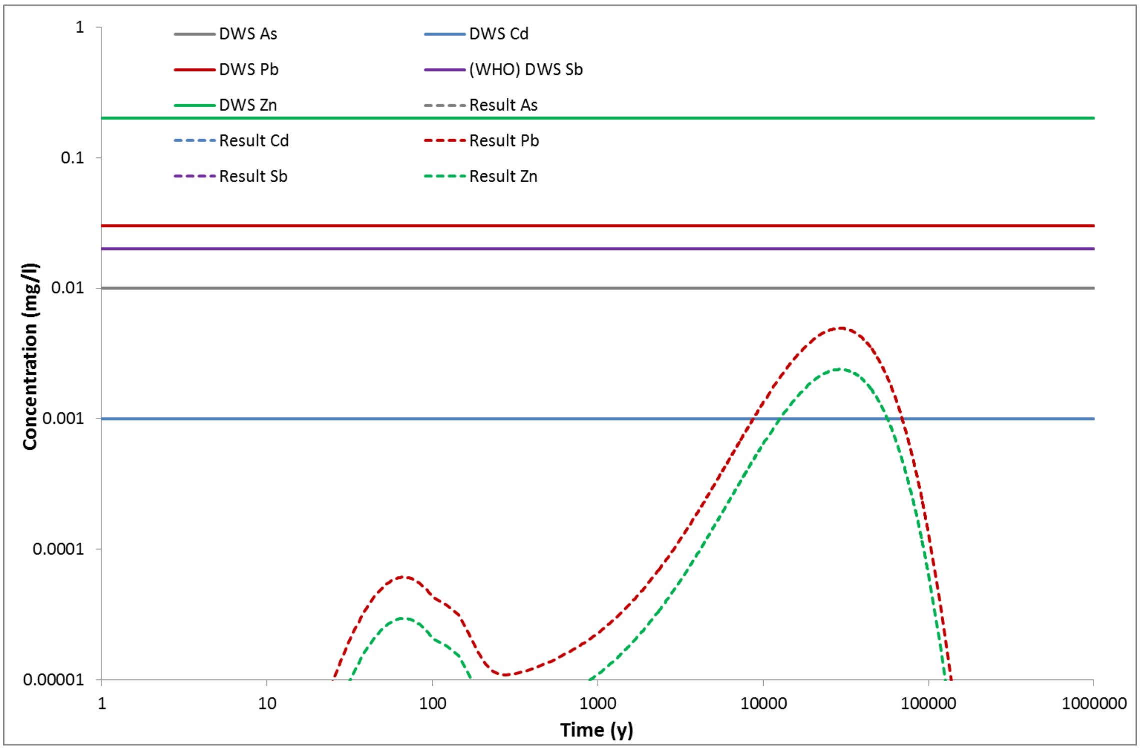

Figure 9-20: Contaminant concentrations in the shallow hydrogeological system for the Cavern Interaction Scenario (above the adjacent cavern). Cd, As and Sb concentrations are below the bottom of the scale.

Backfill Doesn't Provide Required Structural Support Scenario

This scenario encompasses a range of potential outcomes which all have the same consequence: the collapse zone that forms above the backfilled cavern extends further than the design intent. The processes that lead to the contaminant migration are the same as the Expected Evolution Scenario, but the barriers to migration are reduced.

If the backfill doesn't provide the required structural support, this may result in contamination of waters in the Muschelkalk Formation, or shallow hydrogeological system, and in the worst case might also be accompanied by sinkhole formation. Sinkhole formation would likely only be possible if the cavern was backfilled to a very limited extent, for example if backfilling initiated roof collapse and could not be completed. However, the contaminant inventory would be smaller than in a cavern that had been successfully backfilled.

Two calculation cases are assessed:

- ▲ Case 1. The collapse zone is assumed to extend into the Muschelkalk Formation. To simulate this, the model for the Expected Evolution Scenario reference case was re-run, but the residual voidage following backfilling was increased from 10% to 20%. Consistent the Expected Evolution Scenario, No Retardation in Rock Case, the remaining void space is assumed to be filled with bleed water from the backfill. The backfill volume is reduced by 13% by compaction and consolidation. The scoping model cannot simulate extension of the collapse zone beyond the top of the Röt Formation. Therefore, to simulate the reduced containment by the Muschelkalk Formation, the formation thickness was reduced from 135 m to 104 m, consistent with the calculated final height of the collapse zone.
- ▲ Case 2. Cavern collapse is initiated by backfilling. For this case it was assumed that 34% of the cavern voidage is filled with backfill when collapse occurs, and backfilling is abandoned. This is the maximum amount of backfill that will still result in sinkhole formation for the cavern dimensions and thicknesses of geological strata selected for the scoping calculations. Contamination from the backfill is able to migrate through the collapse column to the shallow hydrogeological system. Contamination in bleed water from the backfill was excluded from the calculation because there is only a limited amount of backfill, and hence the assumption that the residual voidage is filled with bleed water is not realistic. There is no compaction of the backfill in response to roof collapse.

For Cases 1 and 2, DWS are exceeded for heavy metals in the Muschelkalk Formation as the collapse zone migrates into the formation.

For Case 1 the peak concentrations in the shallow hydrogeological system are the same as the Expected Evolution Scenario, No Retardation in Rock Case, but occur earlier, although still beyond the 10,000 y assessment timeframe. This similarity is because in both cases the aqueous contaminant concentrations in the backfill and collapse zone are the same, and the transport processes are the same. Earlier contaminant "breakthrough" is due to the reduced barrier thickness.

For Case 2, concentrations of lead almost reach the DWS in the shallow hydrogeological system, but concentrations only approach the DWS beyond the assessment timeframe. For example lead concentrations reach 50% of the DWS at 39,000 y. DWS are not approached for other contaminants. Contaminant breakthrough occurs earlier than in the Expected Evolution Scenario No Retardation in Rock Case, and therefore contaminant concentrations are higher within the timeframe of interest. Contaminant breakthrough would have been earlier if bleed water was included in the model.

Backfill Migration Scenario

This scenario considers the possibility that the cavern roof fails before the backfill has cured and attained its design strength, resulting in backfill migrating up the collapse column. The height of the collapse zone will also be greater than the design intent, because collapse can continue until the backfill cures to the extent that it provides structural support. These two processes combine to reduce the thickness of the containment barrier above the backfill. Because the backfill is distributed within the collapse zone, which is self-supporting to an extent, there may be less compaction of the backfill compared with the Expected Evolution Scenario, and this might counter (i.e. reduce) the increase in the height of the collapse zone to some extent.

This case has been explored by modifying the scoping model for the No Retardation in Rock Case, by assuming that backfill porewater and water in the collapse zone are well mixed. This is equivalent to the backfill being present throughout the collapse zone. The scoping model does not include a relationship between the strength of the backfill and the height of the collapse zone. Therefore, an increase in the height of the collapse zone can only be simulated by increasing the residual cavern voidage, increasing the backfill compaction factor or decreasing the bulking factor. It was decided not to change any of these parameters from the values in the Expected Evolution Scenario, No Retardation in Rock Case. Hence, the height of the collapse zone is the same as the Expected Evolution, No Retardation in Rock Case. The half-life for backfill compaction and stabilisation was doubled from 20 y to 40 y.

It was found that contaminant concentrations in the shallow hydrogeological system are unchanged compared with the Expected Evolution Scenario, No Retardation in Rock Case, including the time of breakthrough. This similarity is because aqueous contaminant concentrations in the collapse column are at the solubility limit in the Expected Evolution Scenario, No Retardation in Rock Case. Therefore migration of backfill up the collapse column does not result in any additional aqueous contamination in the collapse zone. If the height of the collapse zone was greater than in the Expected Evolution Scenario, No Retardation in Rock Case, then backfill could potentially enter the Muschelkalk Formation and contaminant breakthrough to the shallow hydrogeological system would occur earlier, although the concentrations would be unchanged.

The worst case assumes that the backfill is always able to flow. This flow would mean that a sinkhole forms, and potentially fluidic backfill could migrate all the way up the collapse column. This process has not been modelled, but rather is treated as a pass/fail criterion in the risk assessment.

Contaminants Only Weakly Chemically Retarded Case

The Expected Evolution Scenario, No Retardation in Rock Case does not include sorption onto rock. Contaminant concentrations are considered to be solubility limited in the backfill. The solubility limits are taken from contaminant concentrations measured in bleed water from backfill development tests. The measured concentrations are high and are consistent with equilibrium with metastable minerals (Section 9.1). In the long-term, as the backfill cures, it is anticipated that contaminant concentrations will evolve to be in equilibrium with stable mineral phases, and consequently will be significantly lower than assumed in the scoping calculations. In addition, the measured concentrations are for elevated temperatures, which are caused by exothermic mineral hydration reactions in the backfill. Long-term in-situ temperatures will be lower, also contributing to reduced solubility. Therefore it is concluded that the Expected Evolution Scenario, No Retardation in Rock Case already includes the minimum credible chemical retardation.

Borehole Seal/Materials Failure Scenario

Once the cavern has been backfilled the boreholes will be sealed. However, potentially sealing may be unsuccessful. The following assumptions were made for the scoping calculation:

- There is a poorly sealed borehole, 15 cm in diameter, which connects the collapse column to the shallow hydrogeological system.
- There is a 0.1 mm aperture interface around the perimeter of the borehole.
- There is upwards flow through the interface in response to overpressures at depth.
- Contaminated water discharges into the shallow hydrogeological system, as a point source, and is captured by a drinking water well in the shallow system. It should be noted that this is a second well and not the poorly sealed borehole.

- The contaminated water is diluted by clean water, which forms the majority of the volume abstracted. A well abstraction rate of 1000 m^3 y is assumed, which is towards the lower end of the range given by van Duijne et al. (2011a). Therefore the calculation is quite cautious in terms of the amount of dilution assumed.
- There is no sorption onto the walls of the interface.

The DWS is exceeded for Pb throughout the assessment timeframe, but not for other contaminants (Figure 9-21). The flow rate is very sensitive to the interface aperture (a), since transmissivity increases with a^3. DWS may therefore be exceeded for other contaminants for larger fracture apertures. This possibility needs to be offset against the following conservative assumptions in the calculations:

- The small localised plume of contamination in the shallow system is captured by a drinking water well.
- There are hydraulic overpressures at depth to drive flow up the poorly sealed borehole.
- There is no sorption onto the walls of the interface.
- The amount of dilution assumed for the shallow system is towards the bottom end of the range.

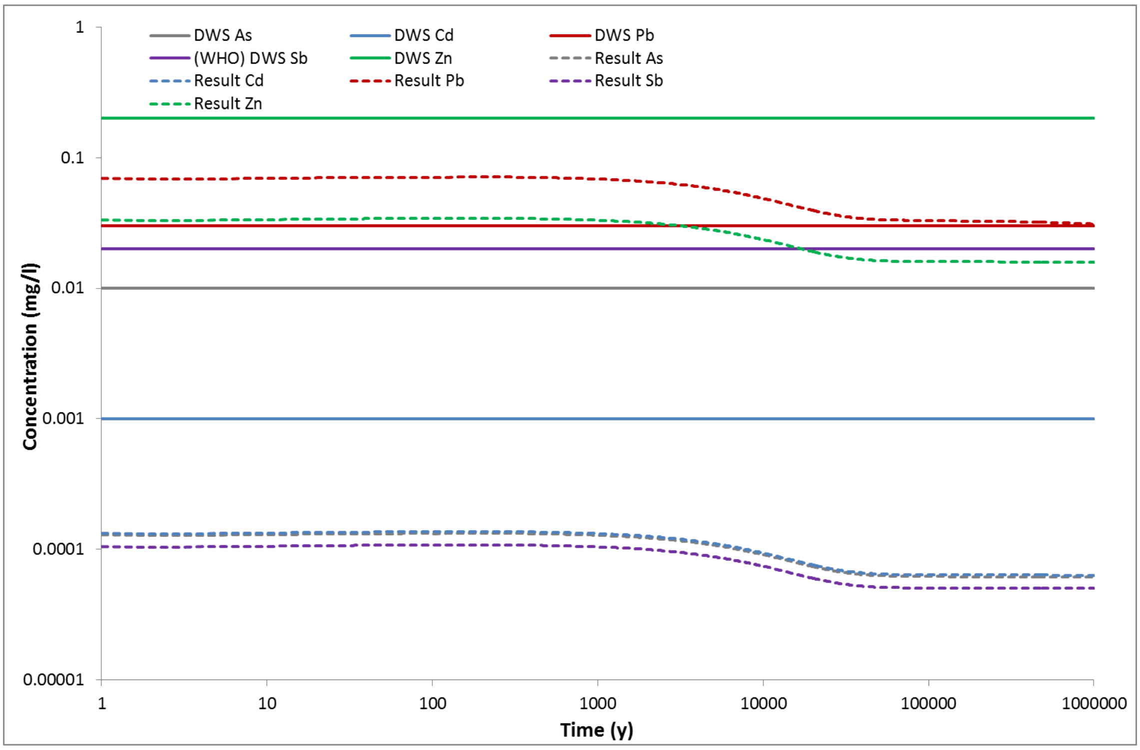

Figure 9-21: Contaminant concentrations in the well water for the Borehole Seal / Materials Failure Scenario.

Faults/Fractures Provide Transport Pathway Scenario

Two calculation cases are considered. The first case considers a fracture that connects the collapse column to the base of the North Sea Supergroup. The second case is more cautious, and considers a fracture that connects the collapse column to the shallow hydrogeological zone.

In both cases it unlikely that the fracture intercepts the maximum diameter of the collapse column. It is therefore assumed that the fracture intercepts half the diameter of the collapse column. The fracture is likely to result in a much larger contaminant plume than a leaky borehole. Therefore, it is cautiously assumed that contaminant concentrations in water abstracted from the shallow hydrogeological system are the same as the contaminant concentrations in the shallow hydrogeological system.

The mathematical model is the same as for the Borehole Seal / Materials Fail Scenario. The fault/fracture is assumed to have an aperture of 10^{-4} m, and there is no sorption onto the fault/fracture surfaces. Again, the results are very sensitive to the aperture assumed. However, an aperture of 10^{-4} m, with a fracture length of 62.5 m, results in a relatively high flow rate of 251 m^3 y^{-1}, which may not be sustainable in the long-term.

In Case 1, contaminant concentrations in the Muschelkalk Formation are reduced compared with the Expected Evolution Scenario, No Retardation in Rock Case, because contaminants bypass the formation. Unlike this case of the Expected Evolution Scenario, DWS are not exceed for As and Sb. Peak concentrations in the shallow hydrogeological system are the same as the Expected Evolution Scenario, No Retardation in Rock Case, but occur earlier, although still beyond the 10,000 y assessment timeframe.

In Case 2, concentrations in the Muschelkalk Formation are the same as in Case 1. DWS are exceeded in the shallow system for Cl, Pb, Zn and Cd between ~10 and 1,000 y due to migration of contaminated water up the fracture (Figure 9-22). However, there is no evidence that such conductive fractures exit present day.

The assumed fracture flow rate is sufficiently high that aqueous contaminant concentrations in the collapse zone fall below solubility limits because the rates of contaminant loss exceed the rates of contaminant release from the backfill. Therefore, beyond ~1,000 y contaminant concentrations fall to below the DWS for Cl, Zn and Cd, but remain at the DWS for Pb. This behaviour is unexpected and indicates that the assumed fracture flow rate is likely cautious. It is also noted that, even if the assumed fracture flow rate could be supported, the concentration of Cl in the collapse zone and hence shallow groundwater would not change with time, because water flowing into the collapse zone would be saline. However, this is not represented in the model.

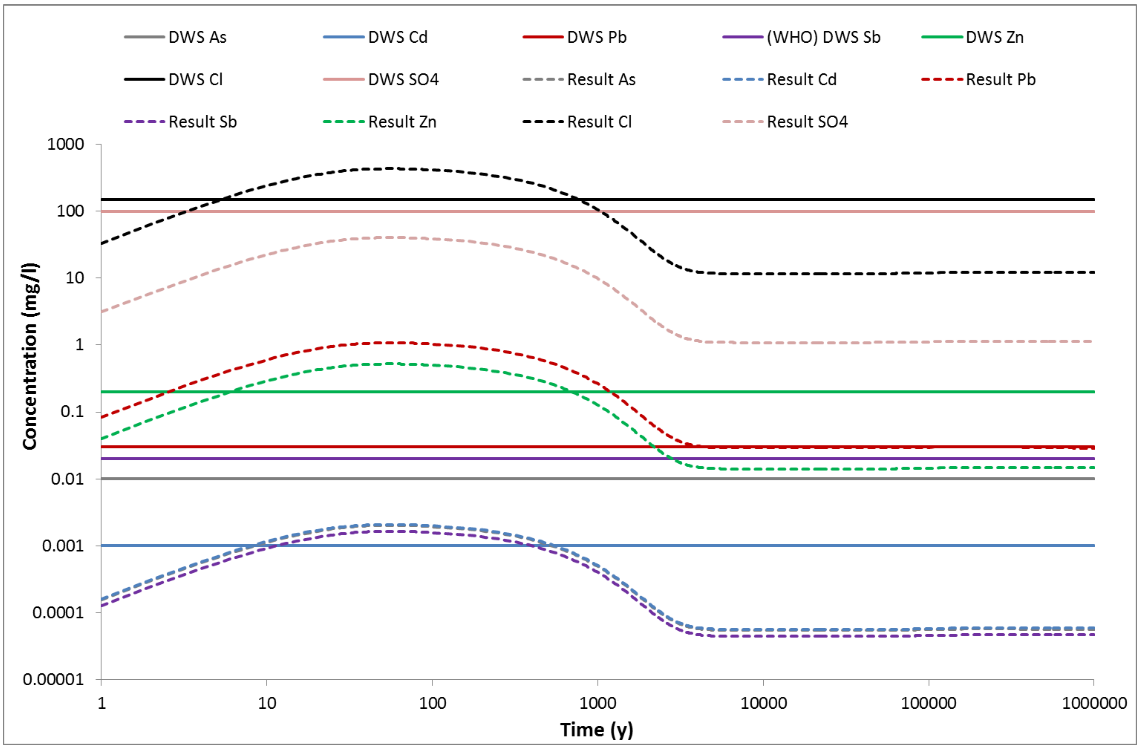

Figure 9-22: Contaminant concentrations in the shallow hydrogeological system for the Fault/Fracture Transport Pathway Scenario, Case 2.

9.3 Summary of Scoping Calculations

The Expected Evolution Scenario, No Retardation in Rock Case, includes many cautious assumptions. Despite these assumptions, calculated contaminant concentrations in the shallow hydrogeological system do not exceed DWS within the timescales of interest (10,000 y). Over long-timescales, when the nature of the near-surface environment is highly uncertain, Pb concentrations approach the DWS.

In this case, contaminant concentrations exceed DWS in the Muschelkalk Formation within timescales of interest. If less cautious assumptions are adopted then DWS might not be exceeded. It should be noted that the No Retardation in Rock Case is not intended to be a best estimate case at this stage of the risk assessment; currently it is just a reference for comparative purposes. Key uncertainties identified are:

- contaminant sorption distribution coefficients for the geological formations;
- the vertical head profile;
- the cause of overpressures in the Muschelkalk;
- vertical Darcy flow rates;
- permeability of the sump; and

- strength of the backfill.

The results of scoping calculations for alternative evolution scenarios indicate that interaction with a cavern that is not backfilled and has an associated collapse column to the shallow hydrogeological system, leaky boreholes, and open fracture connections to the shallow hydrogeological system are potentially important. The significance of these alternative pathways will be sensitive to the uncertainties in contaminant sorption and hydraulic conditions at depth, and cautious assumptions have been adopted for the scoping calculations.

The results of all the calculation cases and associated key cautious assumptions are summarised in Table 9-16. Note that contamination from residual blanket oil has not been considered at this scoping stage. Cases where contamination from residual blanket oil is most likely to be important are indicated in Table 9-16.

Table 9-16: Summary of calculation case results and key cautious assumptions. Red indicates that DWS are exceeded within the timeframe of interest; yellow indicates DWS approached within the timeframe of interest, or approached / exceeded beyond the timeframe of interest; green indicates DWS not approached within the timeframe of interest and significantly beyond. N/A = not applicable.

	Expected Evolution Scenario					**Alternative Evolution Scenarios**								
	No Retardation in Rock	**Sorption onto rock**	**Vertical flow only in the Muschelkalk & overlying formations**	**No vertical flow**	**Chemical barrier safety criteria**	**Do nothing**	**Cavern interaction (adjacent cavern)**	**Backfill failure 1**	**Backfill failure 2**	**Backfill migration**	**Contaminants weakly retarded**	**Borehole**	**Fracture 1**	**Fracture 2**
DWS shallow	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟥
DWS Muschelkalk	🟥	🟩	🟨	🟨	🟨	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Metastable solubility limits	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
No sorption on overlying formations	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vertical flow Solling to Muschelkalk	✓	✓	X	X	X	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vertical flow Muschelkalk to shallow	✓	✓	✓	X	X	✓	✓	✓	✓	✓	✓	✓	✓	✓
Residual blanket oil not considered	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	N/A	N/A	N/A	✓	✓	✓
Adjacent cavern collapses to surface	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cautious dilution by clean well water	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A

10 Application of Evidence Support Logic (ESL)

10.1 Overview

This section overviews the application of the Evidence Support Logic (ESL) methodology to develop an integrated assessment model that analyses confidence in project success. This methodology is implemented within the TESLA software developed by Quintessa (Egan, 2006; Quintessa, 2011).

The ESL approach structures the process for identifying all the key elements relevant to assessing confidence in a particular decision. It is based upon a logical hypothesis model or "decision tree" that breaks down the top-level or "root" hypothesis into supporting lines of reasoning. Appropriate parameterisation and logical operators reflect how those lines of reasoning together provide confidence in the root hypothesis. This is coupled with an independent analysis of the extent to which the supporting evidence base provides confidence "for" or "against" bottom-level "leaf" hypotheses.

This approach is based upon "three value logic", whereby the aim is to be clear about what is known, what is not known, and where there is remaining uncertainty. The level of confidence "for" and "against" leaf hypotheses is propagated through the tree to the root hypothesis, providing an overall assessment of confidence in the top-level judgement. In addition to the evaluation of confidence "for" the top level hypothesis on the basis of available evidence, an understanding of the confidence "against" the root hypothesis, and the remaining uncertainty at the top level, also indicates the level of risk to success, and provides a basis for prioritisation of any further work.

The TESLA software is designed to record the tree development process, and to facilitate analysis of the completed tree. The rationale for all key judgements on tree structure, parameterisation and evidence can be captured in the ESL model produced. Therefore, the model also provides an audit trail for all key aspects of the assessment.

Further details of the ESL methodology and the supporting TESLA tool are given in Appendix D.

A high-level overview of the application of ESL to the assessment of cavern stabilisation is provided in the following subsections. Details such as precise definitions of each hypothesis, success and failure criteria, and the audit trail associated with confidence judgements on the basis of evidence, are provided in the TESLA tree model reports included as Appendix E.

10.2 Aims

The aims of the ESL tree development process during Phase 1 were to:

- provide a structured analysis of all the key factors relevant to assessing performance, and thus provide a basis for ranking risks; and
- identify those significant factors that should be addressed by the risk management plan and monitoring plan to be developed during Phase 2 of the project.

Those factors that are deemed to be greatest contributors to risk, based upon this analysis, will be evaluated specifically to determine whether or not they are likely to call into question the safety and effectiveness of the proposed cavern stabilisation.

10.3 ESL Tree Structure

10.3.1 Approach

The ESL tree structure was derived based upon the following principles:

- The root hypothesis, and main supporting lines of reasoning, should reflect the main aims of the project, as set out in Section 3.
- The model should take into account evidence relating to all of the key FEPs identified in Section 7, to build confidence that its coverage is complete.
- Leaf-hypotheses should be formulated to facilitate appropriate analysis of available data. In particular, outputs from scoping calculations based on identified scenarios and conceptual models (Sections 7 to 9) need to be appropriately integrated.

In general, the logical structure of the tree and its parameterisation should be “cautiously realistic”. That is, the tree should be constructed to reflect the understanding of the system and associated decisions as accurately as is reasonable. However, where there are a number of plausible alternatives for the tree logic or parameterisation, a cautious approach is selected. Thus, sufficiency values for evidence “against” key hypotheses tend to be higher than equivalent parameters “for”. The impact of such judgements shall be considered in analysing the assessment outcomes, for example using sensitivity analyses to understand the implications of cautious judgements, prior to presenting the final outcomes of the assessment.

The tree was defined and parameterised by members of the project team, and then independently reviewed by separate experts from the project and client team. It was also presented to regulators and stakeholders in order to expose key logic and judgements and to obtain feedback. Comments have been considered and addressed within the updated tree presented in this document.

To describe the developed tree, a description of the logical hypothesis structure is first provided (Sections 10.3.2 to 10.3.4). Analysis of evidence and identification of the confidence for/against the root hypothesis is then described (Section 10.4).

10.3.2 Top-level Hypotheses

The top level hypotheses that reflect key lines of reasoning in the tree structure are shown in Figure 10-1 below.

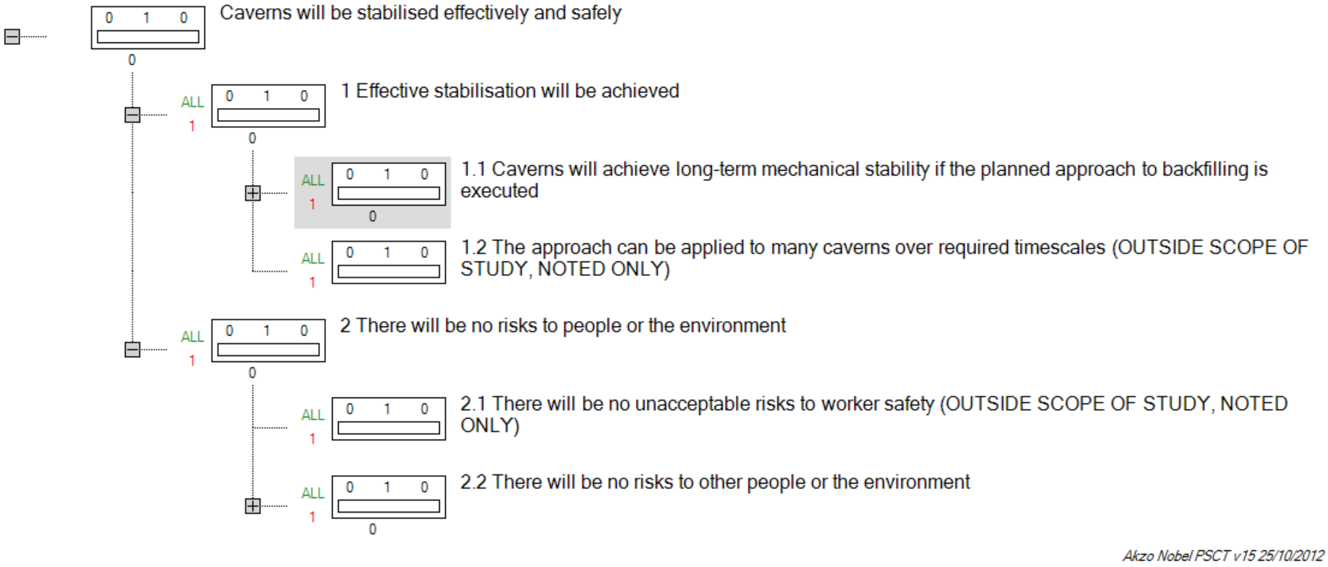

Figure 10-1: Top-level Logical Model Structure.

The root level hypothesis "Caverns will be stabilised effectively and safely" reflects the two main requirements of the study. These are assessed through the two main lines of reasoning "Effective stabilisation will be achieved" and "There will be no risks to people or the environment". Here:

- "Effective stabilisation" reflects the overall objective of backfilling, which is to achieve cavern stabilisation and thereby prevent unacceptable surface deformation. Full confidence in this hypothesis would indicate that:
    - There is no risk (i.e. extremely small likelihood) of sink-hole formation.
    - In addition, rates of general surface deflection that will not lead to sink holes would also be acceptable.
- "No risks to people or the environment" means there will be no risk (i.e. extremely small likelihood/consequence of impact) to humans or the environment as a result of backfilling. That is, there will be no unacceptable impact to sensitive receptors.

In both cases, the principle of demonstrating that risks are As Low As Reasonably Practicable (ALARP) is the key overall test of success.

For both lines of reasoning, the study timeframes are of relevance. Consistent with the timeframes discussed in Section 3, a cautious assessment time period of 10,000 years is considered. That is, full confidence in both of these two lines of reasoning will require evidence that there will be no unacceptable impacts over the entirety of the period.

The main element of proving “effective stabilisation” involves showing that “Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed” (Hypothesis 1.1). Hence, this hypothesis is “necessary” to success of the parent (indicated by the grey box). In addition, it is notable that to provide full confidence that the backfilling approach can be applied successfully to all caverns, Hypothesis 1.2 “The approach can be applied to many caverns over required timescales” is relevant. However, this hypothesis is out of the scope of the current study, which is focussed on the initial priority cavern set. This hypothesis is therefore only included for completeness, and full confidence “for” it assumed. In any case, the “ALL” parameterisation indicates that confidence “for” Hypothesis 1 can be no better than the “weakest link” of Hypotheses 1.1. and 1.2, so the confidence value of “1” set for this hypothesis by default is essentially irrelevant, which is appropriate for the current study.

Similarly, to be complete, proving “no risks to people or the environment” would include analysis of risks to workers during implementation / operation of the backfilling approach, to be complete. Again, this is outside the scope of the current study. A similar approach is therefore applied, with “There will be no unacceptable risks to worker safety” included as a hypothesis for completeness with full confidence assumed. However, the main line of reasoning of interest concerns showing “There will be no risks to other people or the environment”.

Environmental receptors (“sensitive domains”) of interest include, consistent with definitions elsewhere (see Section 7 and Section 8) potentially potable freshwater aquifers, and saline aquifers, that might present potentially exploitable resources. Human users of that water (e.g. for drinking or irrigation purposes) are also receptors of interest, but are not considered directly in the assessment as impacts to groundwater provide a suitable proxy for establishing risk to humans. However, surface human groups that might be directly exposed to risks e.g. from gas release are of relevance.

10.3.3 Lines of Reasoning Relevant to Assessing Long-term Mechanical Stability

Figure 10-2 shows the lines of reasoning that were identified as important to the assessment of long-term mechanical stability.

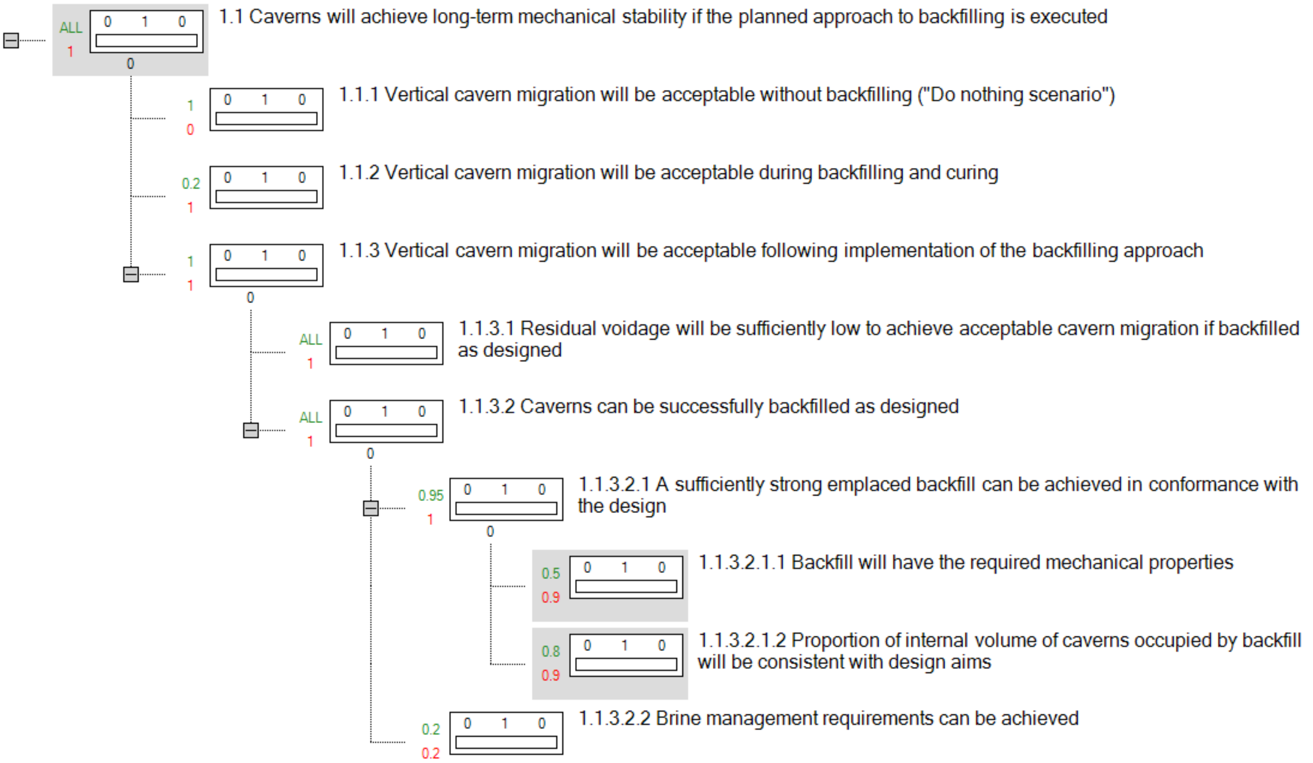

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Figure 10-2: Logical Model Structure: Lines of Reasoning Associated with Hypothesis 1.1.

The sibling hypotheses 1.1.1 to 1.1.3 explore, respectively, whether:

- cavern migration – and thus surface deflections – will be acceptable without backfilling (this will be sufficient alone to prove stability, but not sufficient to disprove, given the cavern backfilling plans);
- migration will be acceptable during the backfilling and curing process – i.e. whether critical failure will occur during that timeframe; and
- migration will be acceptable over the long term.

The latter judgement requires two further lines of reasoning, concerning:

- confidence that cavern migration will be acceptable if the backfill is emplaced and performs as designed;
- confidence in the first place that the backfill can be emplaced and that its post-emplacement properties will meet design criteria.

The potential relevance of ensuring effective brine management through the emplacement process is also noted.

10.3.4 Lines of Reasoning Relevant to Assessing Risks to Humans and the Environment

Figure 10-3 shows the lines of reasoning that were identified as important to the assessment of risks to humans and the environment. Key issues considered by the sibling hypotheses that together support Hypothesis 2.2 are risks associated with:

- fluid transport from the cavern zone;
- gas release from the cavern zone; and
- displacement of fluids outside the cavern zone.

The first of these is then broken down further to facilitate assessment. The logical structure under Hypothesis 2.2.1 therefore explores:

- whether there are any plausible pathways that could connect the source zone (i.e. the contamination associated with the backfill) to any sensitive domain;
- the extent to which there might be driving forces operating over any such pathways, sufficient to lead to interaction between contamination and receptors; and
- whether any such interaction could potentially lead to a risk to that receptor.

Note that the child hypotheses of 2.2.1.1.3 together consider whether it is plausible that any feature, on its own or in combination with others, could be part of a pathway connecting the source with a receptor. Meanwhile the child hypotheses of 2.2.1.1.4 consider evidence relating to the potential for a driving force across those pathways.

However, these judgements are made independently, and thus the largest confidence "against" no pathways of a particular type will be combined with the largest confidence 'against' no driving force existing. That is, it may be that the judgement of driving force for 2.2.1.1.4 concerns a pathway other than the "most likely" pathway from 2.2.1.1.3, as there is no direct on-to-one correspondence required by the logic. Thus, this aspect of the model parameterisation is cautious.

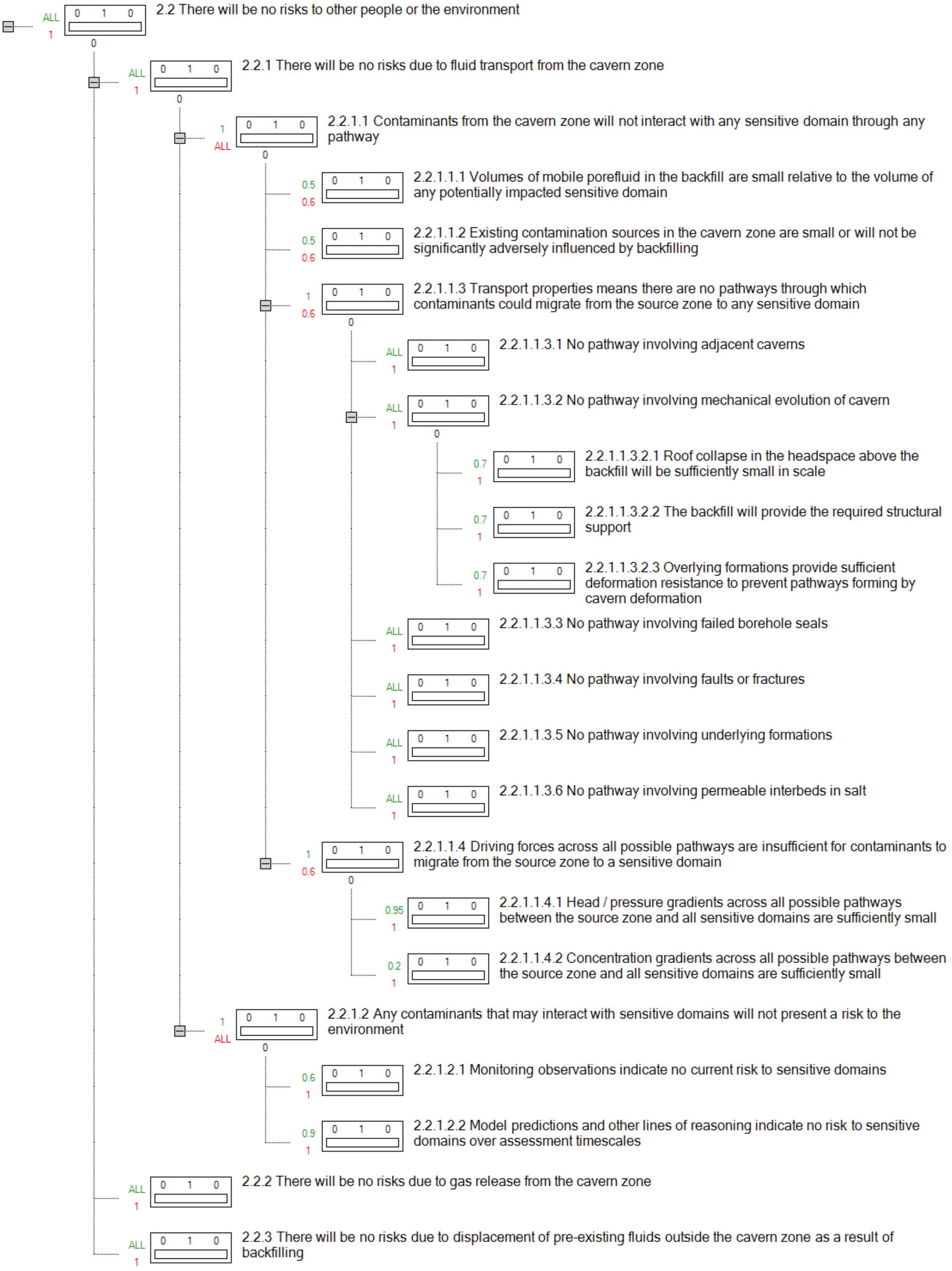

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Figure 10-3: Logical Model Structure: Lines of Reasoning Associated with Hypothesis 2.2

10.4 ESL Tree Confidence Judgements

10.4.1 Tree Overview

Figure 10-4 and Figure 10-5 together overview the outcomes of the assessment of evidence in terms of confidence in leaf-level hypotheses, and the related overall assessment of confidence in the root hypothesis.

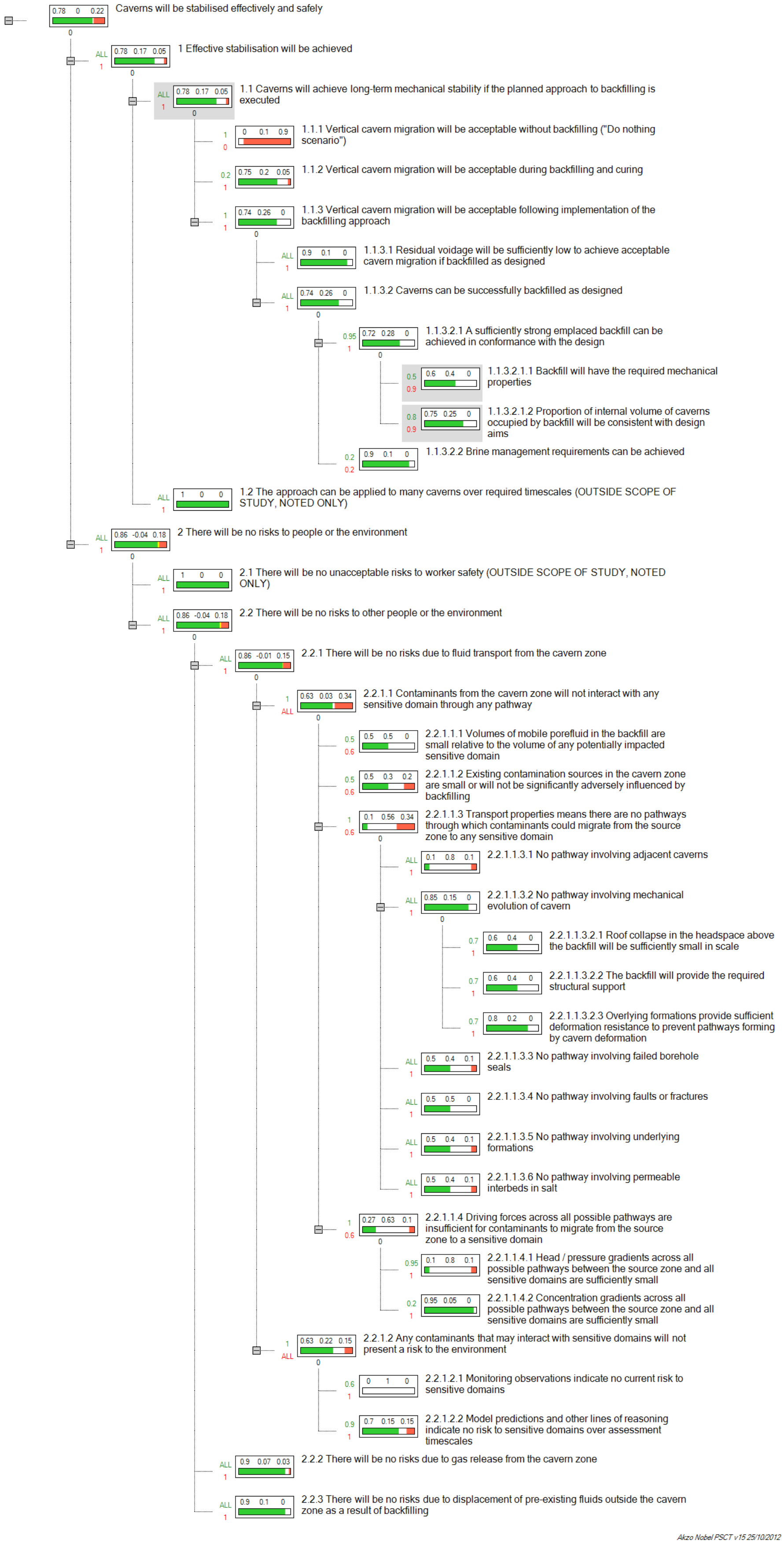
The main outcomes of the assessment show that there is a substantial balance of confidence in favour of successful stabilisation, but that there are some remaining risks. The reasons for this are outlines in subsequent sections (Sections 10.4.2 to 10.4.3). A full description of the implications of the assessment, including risk ranking and the identification of performance criteria, is then provided in Section 11.

10.4.2 Confidence Judgements Relevant to Assessing Effective Stabilisation

As noted above, Hypothesis 1.2 is included for completeness and, as parameterised, does not contribute to overall confidence in Hypothesis 1. Therefore, in considering effective stabilisation, it is relevant to focus on Hypothesis 1.1. Figure 10-6 shows the outcomes of confidence judgements for the main lines of reasoning associated with this hypothesis.

The main features of this aspect of the assessment are as follows.

There is substantial confidence that if the caverns are not backfilled or in some other way stabilised, then there will be an unacceptable risk of future sink-hole formation. This is on the basis of existing observations of sink-hole formation; indeed the expected unacceptable future migration without stabilisation is the reason for the current backfilling plans. However, there is some “white space”; whereas there is substantial confidence in future failure for the “do nothing” scenario, it is not possible to be completely sure that this will be the case.



- 0.78 0 0.22 | Caverns will be stabilised effectively and safely
  - ALL 1 | 0.78 0.17 0.05 | 1 Effective stabilisation will be achieved
    - ALL 1 | 0.78 0.17 0.05 | 1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed
      - 1 0 | 0 0.1 0.9 | 1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")
      - 0.2 1 | 0.75 0.2 0.05 | 1.1.2 Vertical cavern migration will be acceptable during backfilling and curing
      - 1 1 | 0.74 0.26 0 | 1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach
        - ALL 1 | 0.9 0.1 0 | 1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed
        - ALL 1 | 0.74 0.26 0 | 1.1.3.2 Caverns can be successfully backfilled as designed
          - 0.95 1 | 0.72 0.28 0 | 1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design
            - 0.5 0.9 | 0.6 0.4 0 | 1.1.3.2.1.1 Backfill will have the required mechanical properties
            - 0.8 0.9 | 0.75 0.25 0 | 1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims
          - 0.2 0.2 | 0.9 0.1 0 | 1.1.3.2.2 Brine management requirements can be achieved
    - ALL 1 | 1 0 0 | 1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)
  - ALL 1 | 0.86 -0.04 0.18 | 2 There will be no risks to people or the environment
    - ALL 1 | 1 0 0 | 2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)
    - ALL 1 | 0.86 -0.04 0.18 | 2.2 There will be no risks to other people or the environment
      - ALL 1 | 0.86 -0.01 0.15 | 2.2.1 There will be no risks due to fluid transport from the cavern zone
        - 1 ALL | 0.63 0.03 0.34 | 2.2.1.1 Contaminants from the cavern zone will not interact with any sensitive domain through any pathway
          - 0.5 0.6 | 0.5 0.5 0 | 2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain
          - 0.5 0.6 | 0.5 0.3 0.2 | 2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling
          - 1 0.6 | 0.1 0.56 0.34 | 2.2.1.1.3 Transport properties means there are no pathways through which contaminants could migrate from the source zone to any sensitive domain
            - ALL 1 | 0.1 0.8 0.1 | 2.2.1.1.3.1 No pathway involving adjacent caverns
            - ALL 1 | 0.85 0.15 0 | 2.2.1.1.3.2 No pathway involving mechanical evolution of cavern
              - 0.7 1 | 0.6 0.4 0 | 2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale
              - 0.7 1 | 0.6 0.4 0 | 2.2.1.1.3.2.2 The backfill will provide the required structural support
              - 0.7 1 | 0.8 0.2 0 | 2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation
            - ALL 1 | 0.5 0.4 0.1 | 2.2.1.1.3.3 No pathway involving failed borehole seals
            - ALL 1 | 0.5 0.5 0 | 2.2.1.1.3.4 No pathway involving faults or fractures
            - ALL 1 | 0.5 0.4 0.1 | 2.2.1.1.3.5 No pathway involving underlying formations
            - ALL 1 | 0.5 0.4 0.1 | 2.2.1.1.3.6 No pathway involving permeable interbeds in salt
          - 1 0.6 | 0.27 0.63 0.1 | 2.2.1.1.4 Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain
            - 0.95 1 | 0.1 0.8 0.1 | 2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small
            - 0.2 1 | 0.95 0.05 0 | 2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small
        - 1 ALL | 0.63 0.22 0.15 | 2.2.1.2 Any contaminants that may interact with sensitive domains will not present a risk to the environment
          - 0.6 1 | 0 1 0 | 2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains
          - 0.9 1 | 0.7 0.15 0.15 | 2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales
      - ALL 1 | 0.9 0.07 0.03 | 2.2.2 There will be no risks due to gas release from the cavern zone
      - ALL 1 | 0.9 0.1 0 | 2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling

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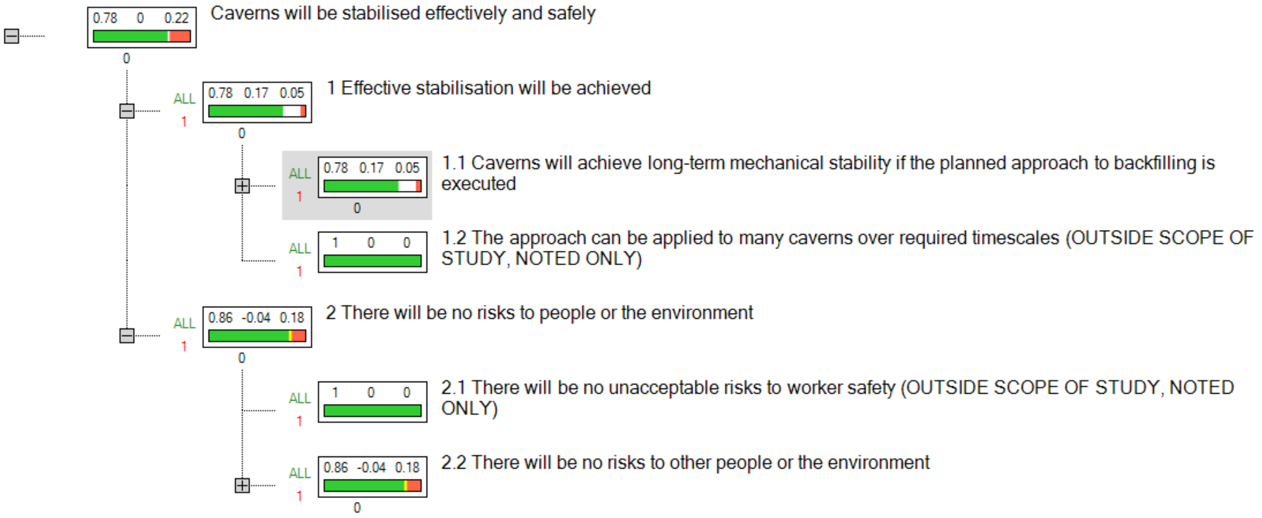
Figure 10-4: Full Tree including confidence judgements.



Caverns will be stabilised effectively and safely

1 Effective stabilisation will be achieved

1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed

1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)

2 There will be no risks to people or the environment

2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)

2.2 There will be no risks to other people or the environment

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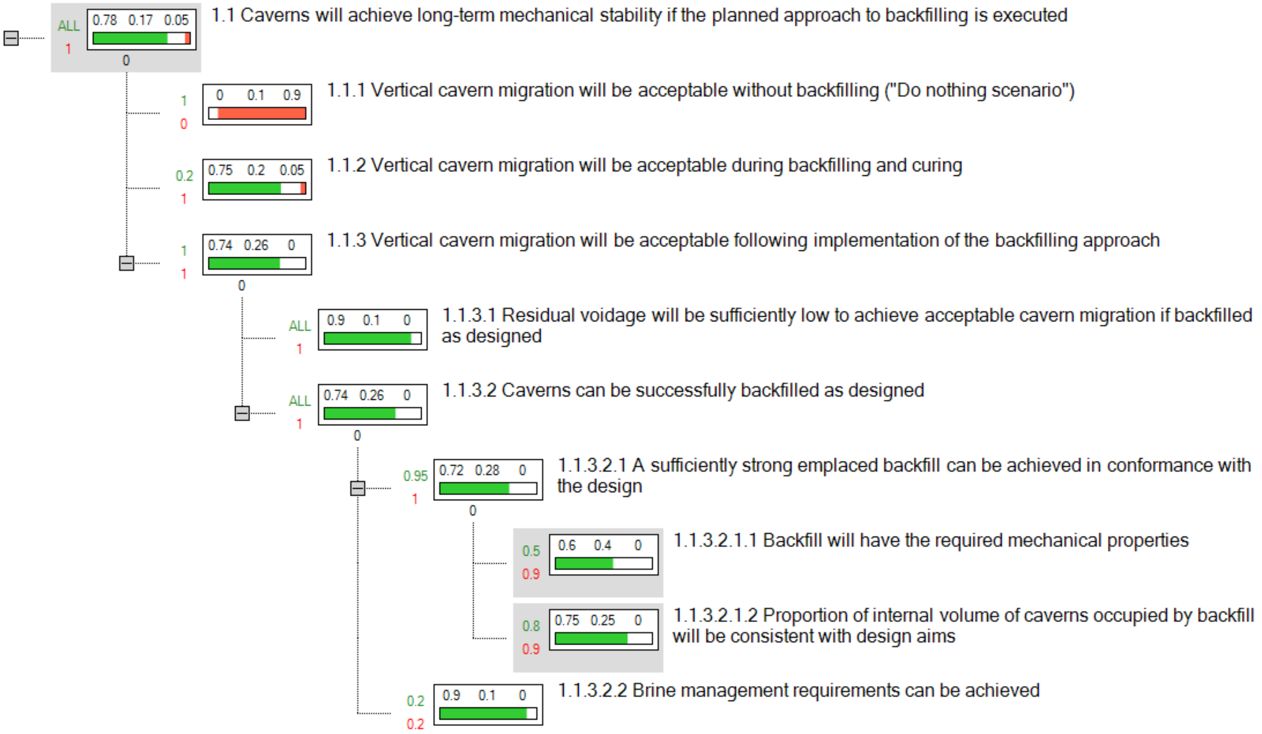
Figure 10-5: Confidence in Top-level Hypotheses on the basis of Leaf-level confidence judgements.



1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed

1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")

1.1.2 Vertical cavern migration will be acceptable during backfilling and curing

1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach

1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed

1.1.3.2 Caverns can be successfully backfilled as designed

1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design

1.1.3.2.1.1 Backfill will have the required mechanical properties

1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims

1.1.3.2.2 Brine management requirements can be achieved

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Figure 10-6: Confidence in Effective Stabilisation on the basis of Leaf-level confidence judgements.

There is considered to be **substantial confidence that vertical cavern migration will not be unacceptable during the period of backfilling and curing**. This is because:

- Observations on existing caverns show that it is reasonable to expect that even an unstable cavern will not collapse significantly during the timescale of a few years over which backfilling will occur.

- Geomechanical modelling shows that it is reasonable to expect that caverns will remain stable for a sufficient period to undertake backfilling.
- Caverns in salt in broadly similar geological settings elsewhere have been successfully backfilled without collapse during backfilling. However there is considered to be a small probability that, despite the above, an unstable cavern could fail and lead to faster migration than normally anticipated. Hence, there is some "white" space, and even some "red".

Moreover, there is considered to be **substantial confidence that vertical cavern migration will be acceptable following implementation of the backfilling approach.** The primary reasons for this include:

- There is a high confidence (90%) that **residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed**. This is because calculations show that for all reasonable bulking factors, once backfilling has been undertaken and the designed residual voidage attained, sinkhole formation or unacceptable surface subsidence rates will not occur. There is some uncertainty about bulking factors, which explains largely the white space.
- There is substantial confidence (74%) that **caverns can be successfully backfilled as designed.** Although confidence that **brine management requirements can be achieved** contributes, the main lines of reasoning are associated with establishing that **sufficiently strong emplaced backfill can be achieved in conformance with the design**:
    - Laboratory experiments and experience of preparing other backfills of relevance provides a balance of confidence that **backfill will have the required mechanical properties**. However, uncertainties concerning performance criteria and the variability in backfill characteristics lead to remaining uncertainty in this hypothesis.
    - There is a higher level of confidence that the p**roportion of internal volume of caverns occupied by backfill will be consistent with design aims.** This is informed by a similar set of information sources to those concerning mechanical properties, but reflects a different set of judgements on those data sources, reflecting in particular flow properties. As this hypothesis is considered more 'sufficient' to prove the parent than its sibling – filling the caverns with material will always help stabilisation, even if there is uncertainty in the exact properties of the material after emplacement – the overall confidence propagated to the parent from the siblings is weighted towards this hypothesis.

10.4.3 Confidence Judgements Relevant to Assessing Risks to Humans and the Environment

Again, Hypothesis 2.1 is included for completeness and, as parameterised, does not contribute to overall confidence in Hypothesis 2. Therefore, in considering effective stabilisation, it is relevant to focus on Hypothesis 2.2. Figure 10-7 shows the outcomes of confidence judgements for the main lines of reasoning associated with this hypothesis. The main features of this aspect of the assessment are as follows.

Firstly, the available evidence offers substantial confidence that **there will be no risks due to gas release from the cavern zone**. This is because it is considered highly unlikely that significant volumes of gas will be evolved during or following injection; any gas is most likely to be evolved during the process of backfill mixing. If any gas does evolve, it is unlikely that there will be significant build-up of gas in the cavern, as the boreholes will not be sealed during the operational/monitoring period, and in the longer term gas evolution is increasingly unlikely. The knowledge that there could be some residual gas evolution, however, indicates a very small amount of confidence ‘against’.

Similarly, it is considered very unlikely that the action of backfilling will lead to generation of a pressure/head gradient of sufficient significance to cause displacement of fluid bodies outside the cavern zone, and thus it is very unlikely that such an interaction will occur and lead to an impact to a sensitive domain. This, there is confidence that **there will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling.**

These factors mean that the main focus of this sector of the tree concerns whether **there will be no risks due to fluid transport from the cavern zone**. The analysis of evidence at the leaf-level provides confidence of 86% ‘for’ this hypothesis, and 15% ‘against’ (hence a small ‘conflict’ of 1%).

The judgements on impacts due to fluid transport reflect lines of reasoning associated with the potential existence of transport pathways, and also the potential for driving forces to operate across those pathways. They also take into account the use of related information in assessment calculations in order to assess risk. Overall, for there to be confidence ‘against’ no (that is, ALARP) risk, confidence against both (‘ALL’) there being no pathways and no associated risk is required. Conversely, confidence ‘for’ there being no pathways and there being no risk in any case contribute to overall confidence in this line of reasoning.

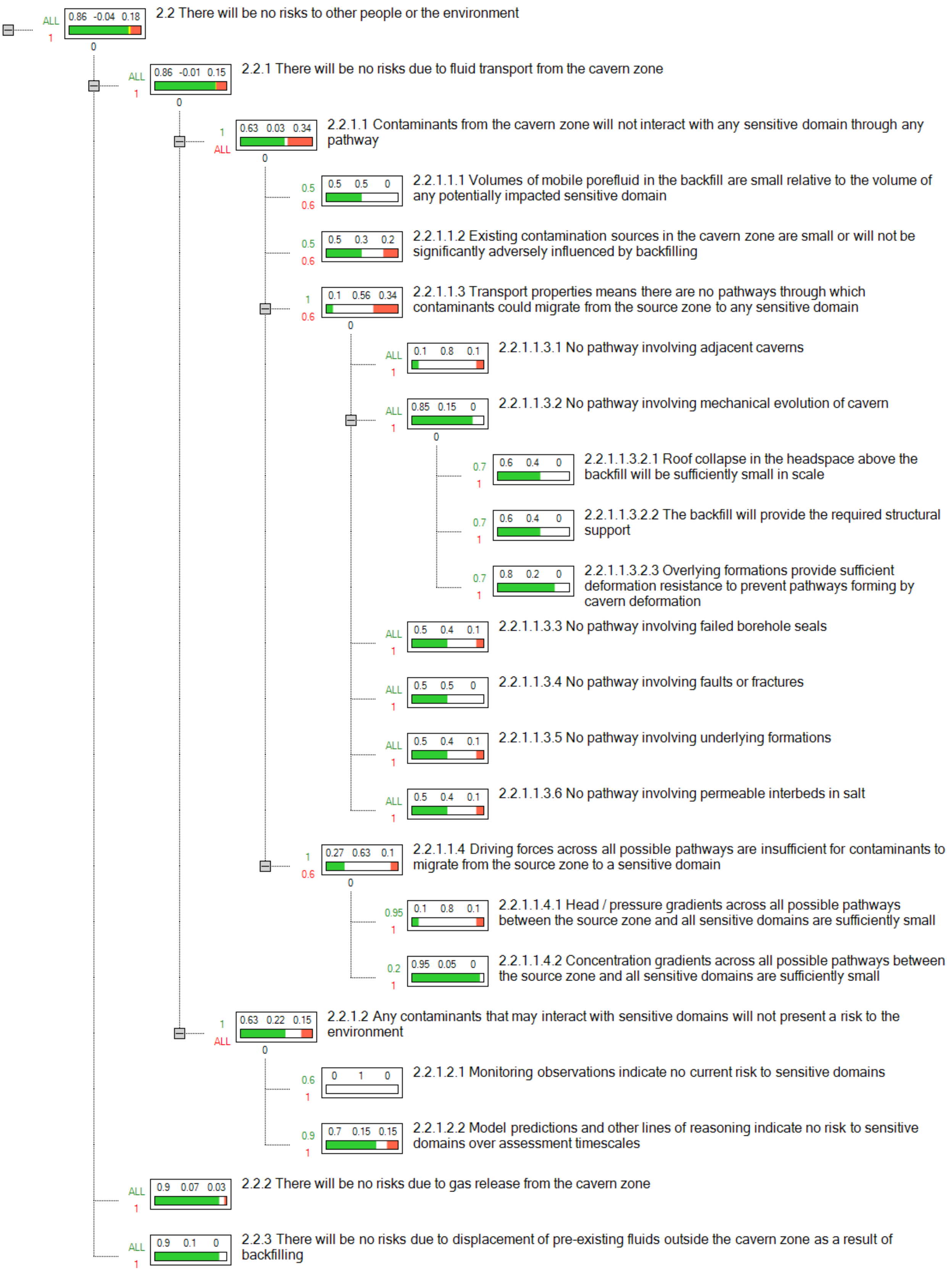

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Figure 10-7: Confidence in No Risks to Humans or the Environment on the Basis of Leaf-level Confidence Judgements

The evidence assessed indicates that there is a balance of confidence that **contaminants from the cavern zone will not interact with any sensitive domain through any pathway**, although there is notable level of evidence "against" also. This is because:

- ▲ There is no more than 50% confidence, with substantial remaining uncertainty, that there will not be a source due to either the backfilling process, or existing contaminants affected by backfilling (i.e. **volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain**, **existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling**). Confidence "for" these hypotheses reflects an understanding of the likely containment offered by the system; the remaining uncertainties reflect uncertain characteristics of the backfill, and of the sensitive domains being considered. In addition, there is some confidence "against" existing contamination sources being small, owing to the fact that residual diesel used in the oil blanket is buoyant and therefore relatively mobile and at the same time is potentially hazardous in small concentrations.
- ▲ There is substantial uncertainty concerning whether **transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain**. Although there is some confidence "for" there being no migration routes associated with most classes of pathway, and in particular there is substantial confidence that there will be **no pathway involving mechanical evolution of cavern** following backfilling (for similar reasons to those reflected in the assessment of effective stabilisation, discussed above), there is uncertainty concerning demonstrating there is and will be **no pathway involving adjacent caverns.** In addition, there remains a small degree of confidence "against" there being no pathways involving failed borehole seals, underlying formations, and/or permeable interbeds in salt.
    - The small amount of evidence "for" there being a pathway involving adjacent caverns reflects the argument that caverns are separated by low-permeability salt, which tends to support a lack of connection. On the other hand, some pressure responses have been measured in some caverns during activities in adjacent caverns. This provides some confidence against this hypothesis. However the nature of the response is unclear - it could be a mechanical response of the rock, or a response of the groundwater.
    - Overall there is substantial remaining uncertainty in this hypothesis, reflecting a lack of information coverage.
- ▲ While there is substantial confidence that **concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small** to not present a driving force of any note (as the path lengths

are large compared to the concentration differences), there is significant uncertainty concerning whether **head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small**.

  - There is however a small amount of confidence "for" this statement, as there is evidence of a high pressure in the Muschelkalk, which indicates a possibility that the pressure gradient might be away from the sensitive domains.
  - Conversely, there is the potential that the high heads in the Muschelkalk are reflective of upwards flows from depth, and thus there is a small amount of evidence that a driving force could exist.

Thus there is substantial uncertainty concerning the hypothesis that **driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain**. There is a small amount of confidence "for" this hypothesis propagated from its children, but also some confidence "against".

There is a balance of confidence (63%) supporting the statement that **any contaminants that may interact with sensitive domains will not present a risk to the environment**. There is some remaining uncertainty, and some confidence "against" (15%). Due to the model parameterisation approach described above, it is this confidence "against" value that is propagated to the parent, and dominates the confidence "against" the overall assessment of risks to humans and the environment.

The confidence "for" arises from judgements concerning whether **model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales**. In identifying 70% confidence "for" this hypothesis, it was noted that assessment calculations have been performed for a range of scenarios (see preceding sections). Of these, calculated impacts for the Expected Evolution scenario and a number of other plausible evolutions of the system are below targets over timeframes of interest. These scenarios together represent a reasonably high probability of occurrence. In addition, the calculations are cautiously parameterised, further building confidence "for" the results. Note that the targets identified reflect WHO drinking water standards.

The remaining uncertainty - and indeed the remaining confidence "against" this hypothesis - arises because a small number of the scenarios explored, that together have a lower probability of occurrence than the "expected" evolution and other scenarios, are associated with calculated impacts above targets during timeframes of interest. The probability of occurrence is low but not negligible, and so this outcome constitutes evidence "against". However, it is also noted that the calculations for these scenarios are cautiously parameterised.

10.5 Summary of Key Outcomes of the ESL Tree Development Process

The main messages from the ESL tree development process are summarised below.

- Based on the evidence available we have substantial confidence that stabilisation could be achieved successfully.
    - The evidence provides confidence that backfilled caverns are likely to migrate to a sufficiently small extent that unacceptable surface deflection will be avoided.
    - There is uncertainty concerning whether there will be pathways for fluid flow that could connect the backfill to locations that could be damaged ("sensitive domains"), but assessment calculations indicate that probably the risks associated with any contaminant transport would in any case be low.
- However, there are remaining risks.
    - There is a subset of low-probability scenarios that, if realised, could lead to impacts above drinking water standards in the longer term.
    - There is a smaller possibility that the mechanical behaviour of the backfilled caverns might deviate from the evolution expected on the basis of most available evidence.
- The tree is cautiously parameterised. This means there is a potential (intended) overestimation of risk at the top level of the tree.
- There is very little "white space" at the top level, which would represent uncertainty due to lack of information coverage – that is, "uncommitted belief". The lack of white space indicates that overall, the evidence coverage is good That is, there is evidence on which to base judgements of the impacts of all phenomena that could influence risk.

Noting the cautious nature of the tree parameterisation, the assessment outcomes can be regarded as providing a substantial level of confidence that cavern stabilisation will be successful, although risks remain.

11 Conclusions

11.1 Safety Criteria

The safety of backfilling will depend upon multiple factors. Just because a particular criterion is not met does not necessarily mean that backfilling would be unsafe. This follows from the fact that risks typically arise from multiple factors acting in concert. For example, the existence of an upwards head gradient does not necessarily constitute a significant risk if there are no pathways to support fluid flow. Indeed, the existence of an upwards head gradient could be interpreted as evidence to support the lack of such conductive pathways, since such pathways might lead to the dissipation of the head gradient.

With these caveats in mind, three kinds of safety-relevant criteria can be specified:

- criteria that if not met would show that backfilling to be almost certainly unsafe;
- criteria, or "favourable factors" that if met would favour, but not prove, the hypothesis that backfilling will be safe.

The first group of criteria is as follows:

- To prevent the development of a sink hole at the surface (or an unacceptable amount of general surface deflection), the collapse zone above a cavern must not extend upwards from the cavern to a level shallower than 40 m below the base of the Tertiary rock formations.
- To prevent DWS being exceeded in the Muschelkalk within a time frame of 10,000 years, the collapse zone above a cavern must not extend upwards from the cavern to a level shallower than 40 m below the base of the Muschelkalk.

The second group of criteria is as follows:

- No conductive pathways connect a backfilled cavern to rock bodies or other domains that might be exploited for groundwater resources. That is there are no unsealed boreholes, faults, permeable rock formations or adjacent un-stabilised caverns that individually or in combination with other conductive features form a pathway.
- There are no natural upwards head gradients to support flow.
- The backfill and cavern contain low levels of mobile contaminants (certainly not more than the levels of contaminants in the assessed backfill formulation).

11.2 Risk Ranking

Risk ranking has been achieved by analysing the tree developed in Section **Error! Reference source not found.**. The risks are deduced from:

- the sensitivity of confidence against the top-level, "root" hypothesis that "Caverns will be stabilised effectively and safely", to *changes* in confidence against the lowest level "leaf" hypotheses and intermediate hypotheses;
- actual confidence values against the lead hypotheses and intermediate hypotheses.

Mathematically, the approach was to determine for each hypothesis in the tree (both lowest level "leaf" hypotheses and intermediate hypotheses):

$R_f = C_A \times S$

where:

R_f is a "risk factor" that represents a risk;

S is the sensitivity of confidence against the top level "root" hypothesis that "Caverns will be stabilised effectively and safely" to confidence against the considered hypothesis; and

C_A is confidence against the considered hypothesis.

The "risk factor", R_f is analogous to the commonly used definition of risk as:

$R = P \times I$

where:

R is risk due to some phenomenon;

P is the probability that the phenomenon occurs; and

I is a numerical representation of the adverse impact of the phenomenon.

In the risk ranking here, the notation "R_f" is used rather than "R", since:

- R_f relates to a hypothesis, which is not in itself a *phenomenon* that could result in an adverse impact;
- C_A represents a numerical representation of confidence, rather than a probability in the strict mathematical sense; and
- S represents a *sensitivity* rather than an impact (which must include a value judgement).

The hypotheses were ranked in order of the magnitude of R_f and the risk-determining phenomenon corresponding to each one was identified. It should be noted that this approach gives an estimate of risk at the present time and that confidence against any of the hypotheses could increase or decrease as more information becomes available. That is, the risk ranking could change in future.

Those risks corresponding to hypotheses that gave positive values of R_f are the most important and are given in Table 6-11. By far the dominant risk is fluid transport (including contaminant transport) from the cavern zone into the overlying rocks.

However, this risk will only be important if the criteria in Section **Error! Reference source not found.** are not met. Furthermore, even this risk is rather low, as indicated by the relatively low level of confidence against the hypothesis.

Table 11-1: Ranking of risks to safe and effective cavern stabilisation.

Risk Rank	Risk	Corresponding Hypothesis	Confidence			Sensitivity and Risk Factor	
			Confidence For	Remaining Uncertainty	Confidence Against, C_A	Sensitivity, S %	R_f^*
1	Fluid transport from the cavern zone	There will be no risks due to fluid transport from the cavern zone	0.86	-0.01	0.15	92.0	13.8
2	Pre-backfill curing collapse	Vertical cavern migration will be acceptable during backfilling and curing	0.75	0.20	0.05	82.5	4.1
3	Gas release	There will be no risks due to gas release from the cavern zone	0.90	0.07	0.03	80.0	2.4

*Note: Sensitivity is a percentage, confidence is on a scale of 0 – 1. Hence, the maximum R_f is 100; all the values here are very much smaller.

In Table 11-1, pre-backfill curing collapse of the cavern is identified to be the second most important risk. However, it should be noted that the risk is judged to be very much smaller than the risk associated with fluid transport from the cavern zone. This risk arises because observed collapses of old, non-backfilled unstable caverns, and the predicted small degree of cavern disturbance that will be caused by backfilling, are interpreted as evidence against successful stabilisation.

The third most important risk shown in Table 11-1 is caused by gas release from the backfill. However, this risk is very small indeed and arises because a small quantity of gas is predicted to occur in the backfill, as a result of chemical reactions during curing.

Several hypotheses could potentially have significant negative impacts on the root hypothesis, should they be untrue, but there is presently no evidence that they are in fact untrue. These hypotheses correspond to *potential risks* and they can be ranked according to:

$PR_f = R_U \times S$

where:

PR_f is a potential risk factor; and

R_U is remaining uncertainty.

It should be noted that this approach ranks risk according to the *potential significance of the remaining uncertainty*. Furthermore, once again, the ranking is based on an appraisal of the evidence available at the time of writing. If future data acquisition and interpretation caused confidence in the truth of a hypothesis to decrease and at the same confidence in the falsehood of the hypothesis to increase, the ranking could change significantly.

The *potential* risks to safe and effective cavern stabilisation determined by this approach are given in Table 11-2. By far the greatest potential risk is the backfill not having sufficient mechanical strength. However, it should be noted that this and other potential risks are estimated by assuming pessimistically that all the remaining uncertainty (white space) in the decision tree is ultimately replaced by confidence against.

Table 11-2: Ranking of *potential* risks to safe and effective cavern stabilisation.

Risk Rank	**Risk**	**Corresponding Hypothesis**	**Confidence**			**Sensitivity and Risk Factor**	
			Confidence For	Remaining Uncertainty, R_u	Confidence Against	Sensitivity, S %	PR_f*
1	Insufficient mechanical strength of backfill	Backfill will have the required mechanical properties	0.6	0.4	0	70.0	28
2	Residual voidage too high	Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	0.9	0.1	0	77.5	7.8
3	There is displacement of pre-existing fluids	There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	0.9	0.1	0	77.5	7.8
4	Brine cannot be managed	Brine management requirements can be achieved	0.9	0.1	0	15.0	1.5

*Note: Sensitivity is a percentage, confidence in on a scale of 0 – 1. Hence, the maximum PR_f is 100; all the values here are very much smaller.

Table 11-1 and Table 11-2 show risks and potential risks respectively, corresponding to hypotheses in the decision tree that impact individually upon confidence in the root hypothesis that “Caverns will be stabilised effectively and safely”. There are also risks that potentially correspond to certain groups of hypotheses being collectively untrue. Of particular concern are those hypotheses that are connected with contaminant transport from the cavern zone, which is related to the overall risk to safe and effective cavern stabilisation caused by fluid transport from the cavern zone (judged to be the most significant direct risk; Table 11-1). However, contaminant transport would pose an actual risk to the safe and effective stabilisation of the caverns only if it resulted in some significant adverse impact.

Using the same approach as the one used to rank the direct risks to safe and effective cavern stabilisation (Table 11-1) the risk of contaminant migration from the cavern zone can be ranked. The ranking, shown in Table 11-3, indicates that contaminants initially in the cavern pose the most significant risk of contamination migrating from the cavern. However, based on the evidence available, this risk is still relatively small.

Table 11-3: Ranking of risks that contribute to the risk of contaminant migration from the cavern.

Risk Rank	Risk	Corresponding Hypothesis	Confidence			Sensitivity and Risk Factor	
			Confidence For	Remaining Uncertainty	Confidence Against, C_A	Sensitivity, S %	R_f*
1	There are significant existing contaminant sources in the cavern which will be influenced by backfilling	Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	0.5	0.3	0.2	45	9
2	There are significant upward groundwater head gradients	Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.1	0.8	0.1	42.5	4.3
3	There are pathways via adjacent caverns	No pathways involving adjacent caverns	0.1	0.8	0.1	36	3.6
4	There are pathways involving permeable interbeds in salt	No pathways involving permeable interbeds in salt	0.5	0.4	0.1	36	3.6
5	There are pathways via boreholes	No pathways involving failed borehole seals	0.5	0.4	0.1	36	3.6
6	There are pathways via underlying formations	No pathways involving underlying formations	0.5	0.4	0.1	36	3.6

*Note: Sensitivity is a percentage, confidence in on a scale of 0 – 1. Hence, the maximum R_f is 100; all the values here are very much smaller.

Should they be untrue, several hypotheses could potentially have significant negative consequences for the hypothesis that "Contaminants from the cavern zone will not interact with any sensitive domain through any pathway", but there is presently no evidence that they are in fact untrue. These potential risks were ranked using the concept of a Potential Risk Factor, PR_f described above. The ranking derived from this approach is shown in Table 11-4.

Table 11-4: Ranking of *potential* risks contributing to the risk of contaminant migration from the cavern zone.

Risk Rank	Risk	Corresponding Hypothesis	Confidence			Sensitivity and Risk Factor	
			Confidence For	Remaining Uncertainty, R_u	Confidence Against	Sensitivity, S %	PR_f*
1	Volumes of mobile porefluid in the backfill are large compared to the volume of the impacted domain	Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	0.5	0.5	0	39	19.5
2	There are pathways via faults and / or fractures	No pathways involving faults or fractures	0.5	0.5	0	32.5	16.3
3	There is significant roof collapse in the headspace above the backfill	Roof collapse in the headspace above the backfill will be sufficiently small in scale	0.6	0.4	0	32.5	13
4	The backfill does not provide the required structural support	The backfill will provide the required structural support	0.6	0.4	0	32.5	13
5	Overlying formations provide insufficient deformation resistance	Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	0.8	0.2	0	32.5	6.5
6	Concentration gradients are sufficiently large to drive significant diffusion	Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.95	0.05	0	37.5	1.9

*Note: Sensitivity is a percentage, confidence in on a scale of 0 – 1. Hence, the maximum PR_f is 100; all the values here are very much smaller.

It can be seen that the biggest potential risk is that volumes of mobile porefluid in the backfill are large compared to the volumes of potentially impacted domains.

In summary, in ranking risks a distinction is made between risk and uncertainty. A numerical risk implies that a probability of some phenomenon occurring, and a numerical representation of its impact should it occur, have been estimated. In contrast, uncertainty means that the probability and / or impact of a phenomenon are unknown. In these cases it is appropriate to rank only *potential* risks that would arise on the basis of certain defined assumptions. Here, when ranking *potential* risks the assumption is that the remaining uncertainty (white space in the ESL representation), if removed by further information acquisition and interpretation, becomes confidence against.

From the above analysis the main *risks* to safe and effective stabilisation are (in order of decreasing judged importance):

1. Fluid transport from the cavern zone (by far the most important), which, assuming that their impacts could be significant, is important by virtue of the risks of:
    a. significant existing contaminant sources occurring in the cavern which will be influenced by backfilling (the most important contaminant transport-related risk);
    b. significant upward groundwater head gradients (the second most important contaminant transport-related risk);
    c. pathways via adjacent caverns (equal third most important contaminant transport-related risk);
    d. pathways involving permeable interbeds in salt (equal third most important contaminant transport-related risk); and
    e. pathways via boreholes (equal third most important contaminant transport-related risk)
    f. pathways via underlying formations (equal third most important contaminant transport-related risk)
2. Pre-backfill curing collapse; and
3. Gas release.

However, based on the available evidence, risks arising from fluid transport are not judged to be high.

Potential risks to safe and effective cavern backfilling, for which there is presently no evidence but which could be important when account is taken of their associated uncertainties are (in order of decreasing judged importance):

1. Insufficient mechanical strength of backfill (by far the most significant);
2. Residual voidage too high;
3. There is displacement of pre-existing fluids; and

4. Brine cannot be managed.

The main potential contributors to risks from contaminant migration, assuming that such migration would cause a significant impact, are in order of decreasing importance:

1. Volumes of mobile porefluid in the backfill are large compared to the volume of the impacted domain;
2. There are pathways via faults and / or fractures;
3. There is significant roof collapse in the headspace above the backfill;
4. The backfill does not provide the required structural support;
5. Overlying formations provide insufficient deformation resistance; and
6. Concentration gradients are sufficiently large to drive significant diffusion

11.3 Overall Risk Statement

The work presented in this report is based on information available on 1st January 2013 and leads to the following statements about risks:

- ▲ Strong confidence exists that the proposed backfilling stabilisation methodology will be safe and effective.
- ▲ No issues have been identified that would definitely call into question the feasibility of the methodology, but uncertainties remain that can be addressed by additional investigations (e.g. assessment of actual backfill formulations, acquisition of hydrogeological information etc.).
- ▲ There is some evidence that suggests there are small remaining risks to performance. In the main this reflects the potential for contaminants to migrate from the backfill into the shallower water resources. These risks can be further reduced by:
  - − adopting more realistic assumptions in the numerical models that underpin the assessment based, for example, on additional information about the natural and engineered systems; and
  - − development of a risk management plan.
- ▲ Key uncertainties that remain concern:
  - − fluid flow driving forces (specifically head gradients);
  - − contaminant transport retardation parameters (specifically sorption coefficients);
  - − the existence or otherwise of flow paths; and
  - − the mechanical requirements and performance of the backfill itself.

The uncertainties will be considered in further work, which will include:

- ▲ a review of retardation parameters;

- more detailed consideration of potential driving forces and flow paths, including hydrogeological scoping calculations, which will inform additional assessment calculations; and
- backfill formulation development, geotechnical testing and analysis work, the outcomes of which will be integrated into the assessment.

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Appendix A Audit of FEPs

The PSCT FEP list described in Section 7.3 was audited against the FEP list in Watson et al. (2008). This latter FEP list was used since, among public-domain FEP lists, it is the most relevant to stabilisation of caverns developed in rock salt; no published FEP lists have been targeted specifically at this application.

The FEP list in Watson et al. (2008) was developed for auditing safety assessments of underground natural gas storage. Consequently many of the contained FEPs do not correspond precisely to FEPs that describe cavern stabilization. Nevertheless, by interpreting these FEPs appropriately the FEP list can be used to build confidence that no issues relevant to the safety and effectiveness of cavern stabilisation have been omitted from the present assessment.

The audit involved identifying those FEPs in the PSCT FEP list that correspond to each FEP in the previously published FEP list of Watson et al. (2008). This process demonstrated that for each FEP in Watson et al. (2008) that is relevant to cavern stabilisation, there are one or more corresponding FEPs in the PSCT list. The results of the audit are shown in Table A-12-1.

In Table A-12-1, if *all* the sub-FEPs (FEPs at a lower level of the hierarchy) of a FEP in the PSCT FEP list correspond to some aspect of a FEP in the previously published list, then only the higher-level FEP in the PSCT FEP list is recorded.

Table A-12-1: Audit of the PSCT FEP list against the FEP list in Watson et al. (2008).

FEP No.	**FEP list from Watson et al. (2008)**		**FEP No.**	**FEP list developed by Quintessa from a review of information concerning the PSCT** **(The "PSCT FEP list")**	**Comments**
1	**External Factors**		E1	Future human actions (e.g. accidental human intrusion)	EFEPs in the PSCT FEP list
			E2	Exploitation of resources (e.g. mining, water management)	
			E3	Neotectonics (inc. seismicity)	
			E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	
			E5	Accidents and unplanned events	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
1.1	Geological factors		E3 E4	Neotectonics (inc. seismicity) Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	EFEPs in the PSCT FEP list
1.1.1	Neotectonics		E3	Neotectonics (inc. seismicity)	An EFEP in the PSCT FEP list
1.1.2	Hydrological and hydrogeological response to geological changes		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
1.2	Climatic factors		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
1.2.1	Regional and local climate change		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
1.2.2	*Sea level change*			*Screened out*	*The area of the caverns is predicted to remain terrestrial throughout the assessment period.*
1.2.3	Hydrological and hydrogeological response to climate change		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
1.2.4	Responses to climate change		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
1.3	Future human actions		E1	Future human actions (e.g. accidental human intrusion)	An EFEP in the PSCT FEP list The only future human action within the scope is human intrusion; the focus is on sub-surface environmental risks.
1.3.1	*Motivation and knowledge issues*			*Screened out*	*The focus is on sub-surface environmental risks and the only issue of concern are the effects of human intrusion*

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					should it occur. The approach considers "worst case" implications of such intrusion and hence motivation and knowledge issues that might lead to intrusion are irrelevant.
1.3.2	*Social and institutional developments*			*Screened out*	*The focus is on sub-surface environmental risks and the only issue of concern are the effects of human intrusion should it occur. The approach considers "worst case" implications of such intrusion and hence societal and institutional developments that might lead to intrusion are irrelevant.*
1.3.3	*Technological developments*			*Screened out*	*The focus is on sub-surface environmental risks and the only issue of concern are the effects of human intrusion should it occur. The approach considers "worst case" implications of such intrusion and hence technological developments that might lead to intrusion are irrelevant.*
1.3.4	Drilling activities		E1	Future human actions (e.g. accidental human intrusion)	An EFEP in the PSCT FEP list The only future human action within the scope is human intrusion; the focus is on sub-surface environmental risks.
1.3.5	Mining and other underground activities		E1	Future human actions (e.g. accidental human intrusion)	An EFEP in the PSCT FEP list The only future human action within the scope is human intrusion; the focus is on sub-surface environmental risks.
1.3.6	Human activities in the surface environment		E1	Future human actions (e.g. accidental human intrusion)	An EFEP in the PSCT FEP list The only future human action within the scope is human intrusion; the focus is on sub-surface environmental risks, although human intrusion will depend on human activities in the surface environment.
1.3.7	Water management		E2	Exploitation of resources (e.g. mining, water management)	An EFEP in the PSCT FEP list
1.3.8	*Gas presence influencing future operations*			*Not applicable*	*Gas not injected*
1.3.9	Explosions and crashes		E5	Accidents and unplanned events	An EFEP in the PSCT FEP list
2	***Gas Storage***			*Not applicable*	*A cavern stabilisation concept is being evaluated, not gas storage. Strictly, therefore, this FEP and its sub-FEPs are inapplicable to the PSCT project. However, some of the sub-FEPs of FEP 2 in the list of Watson et al. (2008)*

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					correspond to FEPs that need to be considered in the PSCT assessment. These correspondences are noted below.
2.1	*Storage concept*			*Not applicable*	*A cavern stabilisation concept is being evaluated, not storage of any material.*
2.1.1	*Reservoir*			*Not applicable*	*There is no reservoir in the stabilisation concept.*
2.1.2	*Cavern storage*			*Not applicable*	*A cavern stabilisation concept is being evaluated, not storage of any material.*
2.1.2.1	Cavern floor		1.2.2 2.	Sump material Cavern rocks including pillars	
2.1.2.2	Cavern walls		1.2.1 1.5 2.	Cavern roof/wall material Head space Cavern rocks including pillars	In the FEP list of Watson et al. (2008) no FEP corresponds exactly to FEP 1.5 "Head space" in the PSCT FEP list.
2.1.2.3	Lack of roof salt			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 4.1.15 (Stress and mechanical properties), FEP 7.1.1 (Loss of containment) and FEP 7.2 (Impacts on the physical environment) in the FEP list of Watson et al. (2008). Evaluation of roof failure, implying loss of roof salt, is a target of the assessment.
2.1.2.4	Leach zones in salt		1.1.3	Change in geometry due to any salt dissolution/precipitation (inc. pressure solution and direct fluid dissolution)	
2.1.2.5	Bench development		1.1	Cavern internal geometry	
2.1.3	Old brine caverns		1	Cavern zone	All caverns to be considered by the assessment are strictly "old" in the sense defined in the FEP list of Watson et al. (2008).
2.2	*Gas quantities, injection rate*			*Not applicable*	*Gas not injected*
2.3	*Gas composition*			*Not applicable*	*Gas not injected*
2.4	Microbiological contamination			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 7.2.1 (Contamination of groundwater), in the FEP list of Watson et al. (2008).
2.5	Schedule and planning		30	Schedule and planning	Alternative schedules and plans will need to be assessed in the alternative scenarios.
2.6	Administrative control			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 2.5 (Schedule and planning) and FEP 2.8 (Quality control),

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					in the FEP list of Watson et al. (2008).
2.7	Monitoring of storage		31	Monitoring	In the FEP database of Watson et al. (2008) FEP 2.7 covers monitoring of gas, in the PSCT list monitoring covers all activities connected with monitoring site behaviour, before, during and after backfilling.
2.8	Quality control			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 7.1.1 (Loss of Containment), FEP 7.2 (Impacts on the physical environment) and FEP 7.2.1 (Contamination of groundwater) in the FEP list of Watson et al. (2008).
2.9	Accidents and unplanned events		E5	Accidents and unplanned events	An EFEP in the PSCT FEP list
2.10	Overpressuring			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 3.2.1 (Effects of pressurisation on surrounding rocks) in the FEP list of Watson et al. (2008).
3	***Gas Properties, Interactions & Transport***			*Not applicable*	*A cavern stabilisation concept is being evaluated, not gas storage. Strictly, therefore, this FEP and its sub-FEPs are inapplicable to the PSCT project. However, some of the sub-FEPs of FEP 3 in the list of Watson et al. (2008) correspond to FEPs that need to be considered in the PSCT assessment. These correspondences are noted below.*
3.1	*Gas properties*			*Not applicable*	*Gas not injected*
3.1.1	*Physical properties of gas*			*Not applicable*	*Gas not injected*
3.1.2	*Gas phase behaviour*			*Not applicable*	*Gas not injected*
3.1.3	*Gas solubility and aqueous speciation*			*Not applicable*	*Gas not injected*
3.2	*Gas interactions*			*Not applicable*	*In Watson et al. (2008) this FEP covers interactions between stored gas and other fluids (including groundwater) and between stored gas and rock. Hence this FEP and its sub-FEPs are not strictly applicable to cavern backfilling. However, many of the interactions covered by sub-FEPs of FEP 3.2 in Watson et al. (2008) correspond to FEPs that need to be considered in the PSCT project. These correspondences are therefore noted below where*

FEP No.	**FEP list from Watson et al. (2008)**		**FEP No.**	**FEP list developed by Quintessa from a review of information concerning the PSCT** **(The “PSCT FEP list”)**	**Comments**
					applicable.
3.2.1	Effects of pressurisation on surrounding rocks		2.6 2.8 2.10 2.12 3.3 6. 11.	Mechanical properties Change geometry due to creep Fracturing Self-healing Mechanical properties Mechanical properties Change geometry due to creep	In the FEP database of Watson et al. (2008) pressurisation of the surrounding rocks is related to gas injection, whereas pressurisation in the PSCT list is related mainly to loading by backfill.
3.2.2	Effects of depressurisation on surrounding rocks		2.6 2.8 2.10 2.12 3.3 6. 11.	Mechanical properties Change geometry due to creep Fracturing Self-healing Mechanical properties Mechanical properties Change geometry due to creep	In the FEP database of Watson et al. (2008) depressurisation of the surrounding rocks is related to removal of gas from storage, whereas depressurisation in the PSCT list is related mainly to unloading by salt removal during initial cavern development.
3.2.3	Effects of pressurisation on formation fluids		2.13 3.9 16.	Hydraulic gradients and pressures Hydraulic gradients and pressures Hydraulic gradients and pressures	In the FEP database of Watson et al. (2008) pressurisation of formation fluid is related to gas injection, whereas pressurisation in the PSCT list is related mainly to loading by backfill.
3.2.4	Effects of depressurisation on formation fluids		2.13 3.9 16.	Hydraulic gradients and pressures Hydraulic gradients and pressures Hydraulic gradients and pressures	In the FEP database of Watson et al. (2008) depressurisation of formation fluid is related to removal of gas from storage, whereas depressurisation in the PSCT list is related mainly to unloading by salt removal during initial cavern development.
3.2.5	*Interaction with hydrocarbons*			*Not applicable*	*Covers interaction of stored gas with hydrocarbons, whereas cavern stabilisation with cementitious backfill is being evaluated.*
3.2.6	Displacement of saline formation fluids		1.6 2.14 3.6 17.	Advective flow/transport in backfill (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Advective flow/transport in backfill (inc. contaminant transport)	In the FEP database of Watson et al. (2008) displacement of saline formation fluid is related to movement of gas, whereas in the PSCT list displacement of formation fluid is related to migration of backfill porefluid, which is coupled to cavern roof collapse.
3.2.7	Mechanical processes and		2.6	Mechanical properties	In the FEP database of

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
	conditions		3.3 6.	Mechanical properties Mechanical properties	Watson et al. (2008) mechanical processes and conditions covered by FEP 3.2.7 are related mainly to pressurisation / depressurisation during gas injection / extraction, whereas in the PSCT list mechanical processes and conditions relate mainly to loading by backfill.
3.2.8	Induced seismicity		2.11 3.4 14. 29.	Induced seismicity Induced seismicity Induced seismicity Induced seismicity	In the FEP database of Watson et al. (2008) induced seismicity is related to cyclical storage and extraction of gas. In the caverns to be stabilised, cavern collapse could lead to seismicity and loading of the cavern by backfill could also induce seismicity.
3.2.9	Subsidence or uplift			Subsumed	Covered by FEPs in the PSCT FEP list corresponding to FEP 3.2.7 (Mechanical processes and conditions) and FEP 7.2 (7.2 Impacts on the physical environment) in the FEP list of Watson et al. (2008).
3.2.10	Thermal effects on the injection point		1.3.7.3	Temperature evolution	In the FEP database of Watson et al. (2008) thermal effects are related to gas volume changes, whereas temperature evolution in the PSCT list are related mainly to curing of the backfill.
3.2.11	Water chemistry		1.4 2.7.2 3.5.2 5.7.2 9.1 9.2	Existing cavern fluids Brine Brine Fresh water (near-surface) aquifers Saline (deeper) aquifers Fresh water (near-surface) aquifers	In the FEP database of Watson et al. (2008) FEP 3.2.11 relates to the effect of stored gas on water chemistry, whereas in the PSCT list water chemistry is affected by leachate / porewater and possibly gas originating in the backfill, and by any diesel oil blanket.
3.2.12	*Interaction of gas with chemical barriers*			*Not applicable*	*Covers interaction of stored gas with chemical barriers whereas cavern stabilisation with cementitious backfill is being evaluated.*
3.2.13	*Sorption and desorption of gas*			*Not applicable*	*Covers interaction of stored gas with solid phase, whereas cavern stabilisation with cementitious backfill is being evaluated.*
3.2.14	Heavy metal release		1.3.2.2.1 1.3.7.2.3 1.3.8.2.3	Heavy metals Contaminant release due to chemical or physical evolution during curing Contaminant release due to chemical or physical evolution during	In the FEP database of Watson et al. (2008) heavy metal release refers to an interaction between stored gas and surrounding rocks, whereas heavy metal release in the PSCT list occurs from backfill material.

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			20.	consolidation Contaminant release from rocks due to leaching / chemical changes	
3.2.15	Mineral phase		1.3.7.2.1 1.3.8.2.1 2.5 2.6 3.2 3.3 5. 6. 23.3 24.	Solids Solids Chemical properties Mechanical properties Chemical properties Mechanical properties Chemical properties Mechanical properties Cement bonding Borehole seals	In the FEP database of Watson et al. (2008) FEP 3.2.15 is related to interactions between stored gas and mineral phases, whereas in the PSCT list all mineral phases within the backfill and surrounding rocks, and their interactions with leachate and / or formation water are considered.
3.2.15.1	Mineral dissolution and precipitation		1.3.7.2.1 1.3.7.2.2 1.3.7.2.3 1.3.8.2.1 1.3.8.2.3	Solids Pore fluids Contaminant release due to chemical or physical evolution during curing Solids Contaminant release due to chemical or physical evolution during consolidation	In the FEP database of Watson et al. (2008) FEP 3.2.15.1 is related to interactions between stored gas and mineral phases, whereas in the PSCT list all mineral phases within the backfill and surrounding rocks, and their interactions with leachate and / or formation water are considered.
3.2.15.2	Ion exchange		1.8.1 2.16.1 19.1	Sorption/de-sorption Sorption/de-sorption Sorption/de-sorption	Sorption / desorption is considered to cover ion exchange.
3.2.15.3	*Desiccation of clay*			*Not applicable*	*Covers desiccation of clay by interactions with anhydrous gas. Cavern stabilisation does not involve gas and will use hydrous / hydrated materials.*
3.2.16	Gas chemistry		1.4.1 2.7.1 3.5.1 10.1	Gas Gas Gas Gas	While the entry in the FEP database of Watson et al. (2008) concerns stored gas, which is not relevant to cavern stabilisation, the possibility that gas may occur in the geosphere or be generated within the backfill mix, is taken into account in the PSCT FEP list.
3.2.17	*Gas stripping*			*Not applicable*	*Covers interaction of stored gas with hydrocarbons, whereas cavern stabilisation with cementitious backfill is being evaluated.*
3.2.18	*Gas hydrates*			*Not applicable*	*Covers interaction of stored gas with hydrocarbons,*

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					whereas cavern stabilisation with cementitious backfill is being evaluated.
3.2.19	Biogeochemistry		1.3.8.2 1.8 2.5 2.16 3.2 3.8 5. 19. 27.	Chemical (inc. biochemical) and physical properties evolution Contaminant retardation Chemical properties Contaminant retardation Chemical properties Contaminant retardation Chemical properties Contaminant retardation Chemical (inc. biochemical)/physical evolution	Biogeochemistry is taken into account implicitly when assessing chemical properties and their evolution and also when assessing contaminant retardation.
3.2.20	Microbial processes			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 3.2.19 "Biogeochemistry" in the FEP list of Watson et al. (2008).
3.2.21	Biomass uptake of gas			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
3.3	Gas transport		1.6.2 1.7.2 2.14.2 2.15.2 3.6.2 3.7.2 17.2 18.2 27.6	Gas Gas Gas Gas Gas Gas Gas Gas Gas pressurisation within bores (due to corrosion, mechanical effects etc.)	While the entry in the FEP database of Watson et al. (2008) concerns stored gas, which is not relevant to cavern stabilisation, the possibility that gas may occur in the geosphere or be generated within the backfill mix, is taken into account in the PSCT FEP list.
3.3.1	Advection of free gas		1.6.2 2.14.2 3.6.2 17.2	Gas Gas Gas Gas	While the entry in the FEP database of Watson et al. (2008) concerns stored gas, which is not relevant to cavern stabilisation, the possibility that gas may occur in the

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			27.6	Gas pressurisation within bores (due to corrosion, mechanical effects etc.)	geosphere or be generated within the backfill mix, is taken into account in the PSCT FEP list.
3.3.1.1	Fault valving			*Not applicable*	*Applies to fault movement owing to pressurisation by fluid, which will not occur*
3.3.2	Buoyancy-driven flow		1.6 2.14 3.6 17.	Advective flow/transport in backfill (inc. contaminant transport) Advective flow/transport in backfill (inc. contaminant transport) Advective flow/transport in backfill (inc. contaminant transport) Advective flow/transport in backfill (inc. contaminant transport)	The PSCT FEP list considers buoyancy driven flow to be simply a form of advective flow.
3.3.3	Displacement of formation fluids		1.6 2.14 3.6 17.	Advective flow/transport in backfill (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Advective flow/transport in backfill (inc. contaminant transport)	In the FEP database of Watson et al. (2008) FEP 3.3.3 refers to displacement of formation fluids by stored gas, whereas the PSCT list contains FEPs that cover displacement of formation fluids by porewater displaced from the backfill and / or as a result of rock deformation.
3.3.4	Dissolution in formation fluids		1.7.3 2.15.3 3.7.3 18.3	Other fluids (e.g. hydrocarbons) Other fluids (e.g. hydrocarbons) Other fluids (e.g. hydrocarbons) Other fluids (e.g. hydrocarbons)	In the FEP database of Watson et al. (2008) dissolution in formation fluids refers to dissolution of stored gas in the formation water within the surrounding rocks, whereas dissolution in formation fluids in the PSCT list is covered by diffusion of a non-aqueous fluid.
3.3.5	Water mediated transport		1.6 1.7 2.14 2.15 3.6	Advective flow/transport in backfill (inc. contaminant transport) Diffusive transport in backfill (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Advective flow/transport in	In the FEP database of Watson et al. (2008) FEP 3.3.5 refers to migration of stored gas a result of water being present (i.e. as a result of water advection or by diffusion through water). The PSCT list contains FEPs that cover the migration of contaminants due to advection of water or diffusion through water.

FEP No.	**FEP list from Watson et al. (2008)**		**FEP No.**	**FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")**	**Comments**
			3.7 17. 18. 26.	backfill (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Contaminant/waste transport within the disturbed zone	
3.3.6	*Gas release processes*			*Not applicable*	*Gas not injected, gas not expected to occur within the backfill.*
3.3.6.1	*Limnic eruption*			*Not applicable*	*Refers to eruption of gas-charged water from a lake into which gas has leaked.*
3.3.7	*Co-migration of other gases*			*Not applicable*	*Gas not injected, gas not expected to occur within the backfill.*
4	Geosphere		2. 3. 4.	Cavern rocks including pillars Underlying geological formation Overlying geological formations	
4.1	Geology		2. 2.5 2.6	Cavern rocks including pillars Chemical properties Mechanical properties	
4.1.1	Natural resources		E2	Exploitation of resources (e.g. mining, water management)	An EFEP in the PSCT FEP list
4.1.2	*Reservoir type*			*Not applicable*	*Concerns reservoir storage of natural gas and is irrelevant for cavern backfilling.*
4.1.3	*Reservoir geometry*			*Not applicable*	*Concerns reservoir storage of natural gas and is irrelevant for cavern backfilling.*
4.1.4	Reservoir exploitation		E2	Exploitation of resources (e.g. mining, water management)	An EFEP in the PSCT FEP list
4.1.5	Cap rock or sealing formation		2. 3. 4.2 4.3 4.4 5.2 5.3	Cavern rocks including pillars Solling Formation Anhydrite Claystone Muschelkalk Anhydrite	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The “PSCT FEP list”)	Comments
			5.4 6.2 6.3 6.4	Claystone Muschelkalk Anhydrite Claystone Muschelkalk	
4.1.6	Additional seals			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 4.1.5 “Caprock or sealing formation” in the FEP list of Watson et al. (2008).
4.1.7	Lithology		2.1 2.2 2.3 2.5 2.6 3. 3.1 3.2 3.3 4. 4.1 4.2 4.3 4.4 4.5 4.6 4.7 5. 6.	Halite Other Evaporites Shale interbeds and shelving Chemical properties Mechanical properties Solling formation Hydrogeological properties Chemical properties Mechanical properties Hydrogeological properties Salt Anhydrite Claystone Muschelkalk Nedersaken and Altena North Sea Supergroup Near-surface formations Chemical properties Mechanical properties	
4.1.7.1	Lithification/diagenesis		2.5 2.6 3.2 3.3 5. 6.	Chemical properties Mechanical properties Chemical properties Mechanical properties Chemical properties Mechanical properties	
4.1.7.2	Pore architecture		2.4 3.1 4.	Hydrogeological properties Hydrogeological properties Hydrogeological properties	
4.1.8	Natural cavern geometry		1.1 2.8 2.9	Cavern internal geometry Change geometry due to creep Change in geometry due to	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The “PSCT FEP list”)	Comments
			2.10	dissolution / precipitation Fracturing	
4.1.9	Unconformities		7.	Formation boundaries	
4.1.10	Heterogeneities			Subsumed	Covered by the definitions for FEP 7 “Formation boundaries” and FEP 8 “Structures (faults and fractures)” in the PSCT FEP list.
4.1.11	Fractures and faults		8.	Structures (faults and fractures)	
4.1.12	Undetected features			Subsumed	Covered by the definitions for FEP 7 “Formation boundaries” and FEP 8 “Structures (faults and fractures)” in the PSCT FEP list.
4.1.13	Vertical geothermal gradient		1.3.7.3 2.17 3.10 21.	Temperature evolution Temperature gradients Temperature gradients Temperature gradients	
4.1.14	Formation pressure		2.13 3.9 16. 27.7	Hydraulic gradients and pressures Hydraulic gradients and pressures Hydraulic gradients and pressures Pressure gradients across seals	
4.1.15	Stress and mechanical properties		2.6 2.8 2.10 2.11 2.12 2.13 3.3 3.4 3.9 6. 11. 12. 13.	Mechanical properties Change geometry due to creep Fracturing Induced seismicity Self-healing Hydraulic gradients and pressures Mechanical properties Induced seismicity Hydraulic gradients and pressures Mechanical properties Change geometry due to creep Change in geometry due to dissolution/precipitation Fracturing Induced seismicity Self-healing	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			14. 15. 16. 29.	Hydraulic gradients and pressures Induced seismicity	
4.1.16	Petrophysical properties		2.4 3.1 4.	Hydrogeological properties Hydrogeological properties Hydrogeological properties	
4.2	Fluids		2.7 3.5 9. 10.	Cavern rock fluids Solling formation fluids Aquifers Other formation fluids	
4.2.1	Fluid properties		2.7 3.5 9. 10.	Cavern rock fluids Solling formation fluids Aquifers Other formation fluids	
4.2.2	Hydrogeology		2.4 2.13 3.1 3.9 4. 16. 27.7	Hydrogeological properties Hydraulic gradients and Pressures Hydrogeological properties Hydraulic gradients and pressures Hydrogeological properties Hydraulic gradients and pressures Pressure gradients across seals	
4.2.3	Hydrocarbons		3.5.3 10.3	Hydrocarbon liquids Hydrocarbon liquids	
5	Boreholes		22. 23. 24. 25. 26. 27.	Borehole bores Borehole casings Borehole seals Physically/chemically disturbed zone around borehole (inc. breakouts, remedial cement jobs etc.) Contaminant/waste transport within the disturbed zone Chemical (inc. biochemical)/physical evolution Residual contamination from drilling and other operational activities (e.g. drilling fluids)	

FEP No.	**FEP list from Watson et al. (2008)**		**FEP No.**	**FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")**	**Comments**
			28. 29.	Induced Seismicity	
5.1	Drilling and completion		22. 23. 24.	Borehole bores Borehole casings Borehole seals	
5.1.1	Formation damage		27.	Physically/chemically disturbed zone around borehole (inc. breakouts, remedial cement jobs etc.)	
5.1.2	Well lining and completion		23. 23.1 23.2 23.3	Borehole casings Steel casings Steel casing perforations (design or through corrosion) Cement bonding	
5.1.3	Workover			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 5 "Boreholes" in the FEP list of Watson et al. (2008)
5.1.4	Monitoring wells			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 5 "Boreholes" in the FEP list of Watson et al. (2008)
5.1.5	Well records			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 5 "Boreholes" in the FEP list of Watson et al. (2008)
5.2	Borehole seals and abandonment		23. 24.	Borehole casings Borehole seals	
5.2.1	Closure and sealing of boreholes		22. 23. 24.	Borehole bores Borehole casings Borehole seals	
5.2.2	Seal failure		27.	Chemical (inc. biochemical)/physical evolution	
5.2.3	*Blowouts*			*Screened out*	*Blow-outs are only relevant if high-pressure fluids occur naturally within the rock formations, or high-pressure fluid is to be injected. The caverns to be stabilised are not pressurised, nor will pressurised fluids be injected during backfilling.*
5.2.4	Orphan wells			Subsumed	Covered by FEPs in the PSCT FEP list that correspond to FEP 5 "Boreholes" in the FEP list of Watson et al. (2008)

FEP No.	**FEP list from Watson et al. (2008)**		**FEP No.**	**FEP list developed by Quintessa from a review of information concerning the PSCT** **(The "PSCT FEP list")**	**Comments**
5.2.5	Soil creep around boreholes		27.4	Physical deformation due to external stresses (e.g. rock creep)	
6	Near-Surface Environment		4.7.2 5.7.2 4.7 9.2	Shallow aquifers Shallow aquifers Near-surface formations Fresh water (near-surface) aquifers	
6.1	Terrestrial environment			Subsumed	The area of cavern storage is predicted to be terrestrial throughout the assessment period. All other FEPs describe processes operating in the terrestrial environment.
6.1.1	Topography and morphology		E4	Climate and landscape change (e.g. influence water table ; weathering of well head; sea-level change; river meandering; increase/decrease in rainfall)	An EFEP in the PSCT FEP list
6.1.2	Soils and sediments		4.7.3 5.7.3 6.7.3	Soils Soils Soils	
6.1.3	*Atmosphere and meteorology*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.1.4	Hydrological regime and water balance		2.14 3.6 4. 17.	Advective flow/transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Hydrogeological properties Advective flow/transport (inc. contaminant transport)	FEP 4. in the PSCT FEP list covers the hydrogeology of all rock formations above the cavern.
6.1.5	Near-surface aquifers and surface water bodies		4.7 9.2	Near-surface formations Fresh water (near-surface) aquifers	Surface water bodies are not considered separately in the assessment because their contamination would also imply contamination of shallow aquifers.
6.1.6	*Terrestrial flora and fauna*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.1.7	*Terrestrial ecological systems*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.2	*Marine environment*			*Screened out*	*The area of the caverns is predicted to remain terrestrial throughout the assessment period*
6.2.1	*Coastal features*			*Screened out*	*The area of the caverns is*

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					predicted to remain terrestrial throughout the assessment period
6.2.2	*Marine sediments*			*Screened out*	*The area of the caverns is predicted to remain terrestrial throughout the assessment period*
6.2.3	*Marine flora and fauna*			*Screened out*	*The area of the caverns is predicted to remain terrestrial throughout the assessment period*
6.2.4	*Marine ecological systems*			*Screened out*	*The area of the caverns is predicted to remain terrestrial throughout the assessment period*
6.3	Human behaviour		E1	Future human actions (e.g. accidental human intrusion)	The only human behaviour within the scope is human intrusion and exploitation of underground natural resources; the focus is on sub-surface environmental risks.
6.3.1	*Human characteristics*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.3.2	*Diet and food processing*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.3.3	*Lifestyles*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.3.4	Land and water use		E2	Exploitation of resources (e.g. mining, water management)	An EFEP in the PSCT FEP list
6.3.5	*Community characteristics*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
6.3.6	*Buildings*			*Screened out*	*Outside the scope, which is to focus on sub-surface environmental risks*
7	Impacts			See entries below	
7.1	System performance			See entry for 7.1.1	
7.1.1	Loss of containment		2.4 2.13 2.14 2.15 3.1 3.6 3.7	Hydrogeological properties Hydraulic gradients and pressures Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Hydrogeological properties Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Hydraulic gradients and	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			3.9 4. 17. 18. 22.3 23.4 26.	pressures Hydrogeological properties Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Contaminant/waste transport within bores Contaminant/waste transport within an annulus associated with the casing/ outside the casing Contaminant/waste transport within the disturbed zone	
7.2	Impacts on the physical environment		1.1 2.8 2.9 2.10 2.12 3.9 3.10 13. 15. 25.	Cavern internal geometry Change geometry due to creep Change in geometry due to dissolution / precipitation Fracturing Self-healing Change geometry due to creep Change in geometry due to dissolution/precipitation Fracturing Self-healing Physically/chemically disturbed zone around borehole (inc. breakouts, remedial cement jobs etc.)	
7.2.1	Contamination of groundwater		1.3 1.3.2.1 1.3.2.2 1.3.5 1.3.6 1.3.7.2.3 1.3.8.2.3	Stabilisation Backfill Physical properties Contaminants Gas associated with wastes/backfill Waters associated with waste/backfill Contaminant release due to chemical or physical evolution during curing Contaminant release due to chemical or physical evolution during consolidation Advective flow/transport in	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			1.6 1.7 1.8 2.14 2.15 2.16 3.6 3.7 3.8 17. 18. 19. 20. 28.	backfill (inc. contaminant transport) Diffusive transport in backfill (inc. contaminant transport) Contaminant retardation Advective flow/transport (inc. contaminant transport)Diffusive transport (inc. contaminant transport) Contaminant retardation Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Diffusive transport (inc. contaminant transport) Contaminant retardation Contaminant release from rocks due to leaching / chemical changes Residual contamination from drilling and other operational activities (e.g. drilling fluids)	
7.2.2	Impacts on soils and sediments			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.2.3	Release to the atmosphere			*Screened out*	*Outside the scope which focusses on sub-surface environmental risks. In any case, atmospheric contamination is very unlikely since contaminants will be transported by a water pathway*

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
7.2.4	Impacts on exploitation of natural resources			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.2.5	Modified hydrology and hydrogeology		1.6 2.13 2.14 3.6 3.9	Advective flow/transport in backfill (inc. contaminant transport) Hydraulic gradients and pressures Advective flow/transport (inc. contaminant transport) Advective flow/transport (inc. contaminant transport) Hydraulic gradients and pressures	
7.2.6	Modified geochemistry		1.3.7.2 1.3.8.2 2.5 3.2 5. 27.	Chemical and physical properties evolution Chemical (inc. biochemical) and physical properties evolution Chemical properties Chemical properties Chemical properties Chemical (inc. biochemical)/physical evolution	
7.2.7	Modified seismicity		2.11 3.4 14. 29.	Induced seismicity Induced seismicity Induced seismicity Induced seismicity	
7.2.8	Modified surface topography		6. 11. 12. 13.	Mechanical properties Change in geometry due to creep Change in geometry due to dissolution/precipitation Fracturing	
7.2.8.1	Sinkhole formation		6.	Mechanical properties	

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
			11. 12. 13.	Change in geometry due to creep Change in geometry due to dissolution/precipitation Fracturing	
7.3	Impacts on flora and fauna			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.3.1	Asphyxiation effects			*Screened out*	*Contaminants will be transported by a water pathway*
7.3.2	Effect of gas on plants and algae			*Screened out*	*Contaminants will be transported by a water pathway*
7.3.3	Ecotoxicology of contaminants			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25)
7.3.4	Ecological effects			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.3.5	Modification of microbiological systems			Subsumed	Not considered directly, since the assessment compares

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.4	Impacts on humans			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.4.1	Health effects of gas			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.4.2	Toxicity of contaminants			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.4.3	Impacts from physical disruption			Subsumed	Not considered directly, since the assessment compares levels of contamination in

FEP No.	FEP list from Watson et al. (2008)		FEP No.	FEP list developed by Quintessa from a review of information concerning the PSCT (The "PSCT FEP list")	Comments
					water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).
7.4.4	Impacts from ecological modification			Subsumed	Not considered directly, since the assessment compares levels of contamination in water with guideline levels, rather than their impacts (while noting that guideline levels are set by regulators bearing in mind possible impacts). Covered by FEPs in the PSCT FEP list corresponding to contaminant release and retardation (1.3.2.2, 1.3.7.2.3, 1.3.8.2.3, 1.6, 1.7, 1.8, 2.1.4, 2.15, 2.16, 3.8, 17, 18, 19, 20, 21.3, 22.4, 25).

References

Watson S, Metcalfe R, Bond A (2008). Scoping calculations for releases from potential UK underground gas storage facilities. Health and Safety Executive Report RR606.

Appendix B: Bounding Estimates of Hydraulic Conditions at Depth

Historical artesian flow rate data are available from a scan of a KNZ report. Not all the pages are readable. Readable data have been reproduced in Table B-12-2.

Table B-12-2: Measured artesian discharges from the Muschelkalk Formation.

Source Depth (m)	Flow (m^3/h)	Thickness (m)
135	40	13.8
135	30	26.7
146	18	22.1
153	14.5	43.55
136	27	23.5
131	30	38.75
131.7	40	39.8
133	25	39
146	16.5	39.2
146	9	39.2
139.5	2.3	4.3
130.5	4.5	3.2
129.5	5	22.6
136	2.4	12.5
133	2.25	16.4
133	8.5	13.5
121	15	35.3

Since the Muschelkalk Formation primarily comprises low permeability deposits, the artesian flows must reflect horizontal flows in more permeable layers. These flow rates can be used to estimate the overpressure in the Muschelkalk Formation for plausible combinations of hydraulic parameters. Consistent with the scoping/bounding nature of this calculation, the steady state Theim equation for a confined aquifer has been used (Driscoll, 1989):

$$Q = \frac{2.73Kb(H-h)}{\log(R/r)}$$

Where,

Q is the flow rate ($m^3\ s^{-1}$)

K is the hydraulic conductivity (m s^{-1})

b is the aquifer thickness (m)

H is the head in the aquifer beyond the radius of influence of the well, R (m)

h is the elevation of the water in the well (m)

R is the radius of influence of the well (m)

r is the radius of the borehole (m)

The above equation can be re-arranged to calculate H – h, i.e. the overpressure. This relationship is only approximate since it is not a steady state situation; R will increase with time, and Q will decrease with time.

R can be estimated from the hydraulic diffusivity as follows:

$R = \sqrt{(2*K*t/Ss)}$

Where,

t is the time period(s) over which the flow rate was measured following opening of the well (it is assumed the flow rates were measured immediately following opening of the well)

Ss is the specific storage (m^{-1})

K/Ss is the hydraulic diffusivity ($m^2\ s^{-1}$)

The mean value of R over the measurement period is therefore equal to:

$R_m = \sqrt{(K*t/Ss)}$

The overpressure can be used to calculate the vertical hydraulic gradient between the Muschelkalk Formation and the ground surface, i.e. H-h/h, where h is taken to be the depth of the source zone below the ground surface: therefore it is assumed that the flow rate was measured for discharge at the elevation of the ground surface.

Table B-12-3 shows the calculated overpressures and vertical hydraulic gradients for different combinations of aquifer properties and assumed flow measurement times.

Table B-12-3. Estimated Hydraulic Overpressures in the Muschelkalk Formation and Associated Vertical Hydraulic Gradients

K (m s^{-1})	Ss (m^{-1})	t (s)	Arithmetic Mean H-h (m)	Geometric Mean H-h (m)	Arithmetic Mean i_z (-)	Geometric Mean i_z (-)
1E-6	1E-6	600	1.95E+02	1.44E+02	1.44	1.06
1E-5	5E-6	600	2.06E+01	1.53E+01	0.153	0.112
1E-5	5E-6	1800	2.25E+01	1.66E+01	0.166	0.122
1E-4	1E-5	600	2.33E+00	1.73E+00	0.0173	0.0127

Excess heads of the order 100+ m do not seem reasonable for the Twente region, when compared with the data presented by de Jager (2007). Values of the order 10 to 20 m are plausible. Therefore, for scoping calculations, the vertical hydraulic gradient is cautiously assumed to be 0.153. Table B-12-4 gives vertical Darcy velocities for different values of (harmonic) mean vertical hydraulic conductivity.

Table B-12-4. Estimated Vertical Darcy Velocities

K (m s^{-1})	K (m y^{-1})	i_z (-)	V (m y^{-1})
1E-10	3.2E-3	0.153	4.83E-4
1E-11	3.2E-4	0.153	4.83E-5
1E-12	3.2E-5	0.153	4.83E-6

A vertical Darcy velocity of 4.83E^{-4} m y^{-1} can be considered as a cautious upper bound value for scoping calculations. Depending on the cause of the overpressures, this velocity might not be sustainable over the assessment timeframe.

Some further insight is available from the records of a hydraulic test undertaken on the Solling Formation in borehole 313, by Halliburton in 1982. The initial pressure recorded by a gauge at the base of the borehole was 56.3 bar. This equates to 5.63 MPa. The depth of the borehole was 504.9 m. This implies an average water column density of 1137 kg m^{-3}. Assuming that the top 100 m is freshwater and therefore has a density of ~1000 kg m^{-3} then the average density of the brine would be 1171 kg m^{-3}. This density range is similar to the density of brines observed at NWMO's Bruce site in Canada (Intera, 2011), but does not preclude the possibility of a small overpressure in the Solling Formation.

References

de Jager. J. 2007. Geological development, in: Geology of the Netherlands. Ed Th.E.Wong., Batjes, D.A.J. and de Jager, J. Royal Netherlands Academy of Arts and Sciences, 2007: 5-26.

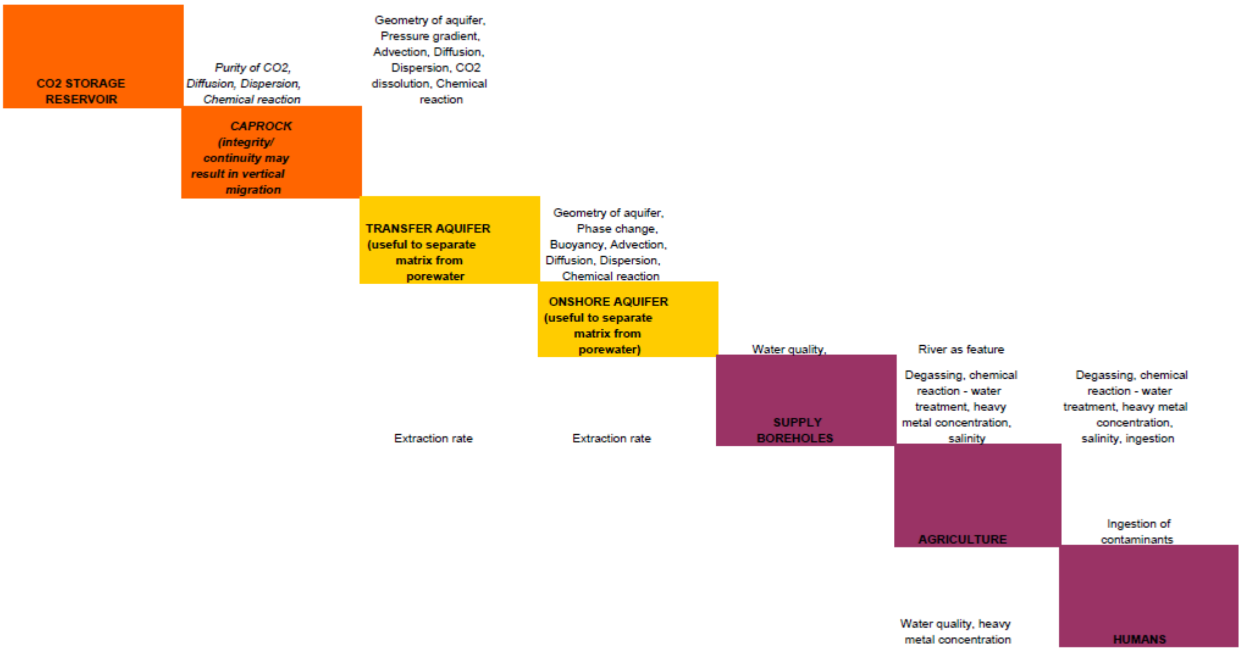
Driscoll, F.G. 1989. Groundwater and Wells. Second Edition. Johnson Filtration Systems Inc.

Intera Engineering Ltd. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Descriptive Geosphere Site Model. NWMO DGR-TR-2011-24.

Appendix C: Interaction Matrices

Interaction matrices represent visually the interactions between Features Events and Processes (FEPs) in a particular scenario. Development of the matrices can be undertaken as part of a structured FEP analysis.

System components are represented by leading diagonal elements (LDE) in a rectangular matrix, and the processes by which pairs of components interact are then listed in off-diagonal elements (ODE). An example is given in Figure C-12-1. In the example, the FEPs "Geometry of aquifer", "Pressure Gradient", "Advection", "Diffusion", "Dispersion", "CO_2 Dissolution" and "Chemical Reaction" describe interactions between the "CO_2 storage reservoir" (represented by the LDE at the upper left of Figure C-12-1) and the "Transfer aquifer" (an aquifer within the overburden).



CO2 STORAGE RESERVOIR	*Purity of CO2, Diffusion, Dispersion, Chemical reaction*	Geometry of aquifer, Pressure gradient, Advection, Diffusion, Dispersion, CO2 dissolution, Chemical reaction				
	CAPROCK (integrity/ continuity may result in vertical migration					
		TRANSFER AQUIFER (useful to separate matrix from porewater	Geometry of aquifer, Phase change, Buoyancy, Advection, Diffusion, Dispersion, Chemical reaction			
			ONSHORE AQUIFER (useful to separate matrix from porewater)	Water quality,	River as feature	
		Extraction rate	Extraction rate	**SUPPLY BOREHOLES**	Degassing, chemical reaction - water treatment, heavy metal concentration, salinity	Degassing, chemical reaction - water treatment, heavy metal concentration, salinity, ingestion
					AGRICULTURE	Ingestion of contaminants
					Water quality, heavy metal concentration	**HUMANS**

Figure C-12-1: Example of an interaction matrix for a scenario describing overpressuring of a CO_2 storage reservoir (after Savage et al., 2004).

References

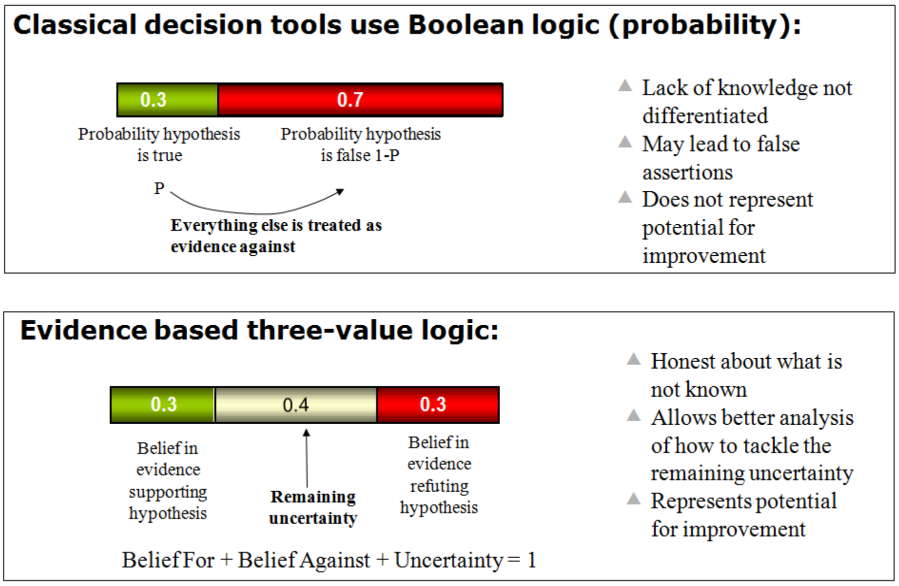
Savage D, Maul PR, Benbow S and Walke RC (2004) A Generic FEP Database for the Assessment of Long-term Performance and Safety of the Geological Storage of CO2. Quintessa Report QRS-1060A-1. (can be downloaded from the following web site: www.ieaghg.org/docs/QuintessaReportIEA.pdf)

Appendix D: ESL and TESLA

Evidence Support Logic involves systematically breaking down a hypothesis under consideration into a logical hypothesis model, the elements of which expose basic judgments and opinions about the quality of evidence associated with a particular interpretation or proposition. A tree structure is constructed that connects some key hypothesis of interest (e.g. *"The salt caverns at Twente can be stabilised safely and effectively using a backfill based on materials from the energy from waste plant"*) to supporting hypotheses that can be tested as easily as possible using direct observations of relevant phenomena or model outputs (e.g. *"Numerical models support solidification of the backfill within the required time interval"*). In practice, intermediate hypotheses will usually occur within the tree, between these readily testable hypotheses and the top-level hypothesis of interest.

Numerical representations of confidence for and against the truth of each hypothesis at the lowest level of the tree are input by users. These representations of confidence are then combined and propagated through the tree to the top-level hypothesis using interval probability theory. The propagation is controlled by numerical sufficiencies (effectively weights) and logical operators that are specified when the tree is constructed. Once a tree is constructed, it may be used to identify what hypotheses are most significant for decision-making at any particular stage of a project. This identification can then be used to prioritise subsequent information gathering and analysis activities. Furthermore, the tree provides a record of the developing decision-making process throughout a project.

A key feature of ESL is its basis on "three value" logic, in contrast to classical probability theory, which follows two-value logic (Figure D-12-2). In this latter case evidence must either be in favour of a hypothesis, or against it. This approach is sometimes described as a "closed world" perspective, in which evidence "for" and evidence "against" are treated as complementary concepts. However, ESL additionally allows for a measure of uncertainty as well, recognising that belief in a proposition may be only partial and that some level of belief concerning the meaning of the evidence may be assigned to an uncommitted state. Uncertainties are handled as "intervals" that enable the admission of a general level of uncertainty providing a recognition that information may be incomplete and possibly inconsistent (i.e. evidence for + evidence against + uncertainty = 1).



Classical decision tools use Boolean logic (probability):

- Lack of knowledge not differentiated
- May lead to false assertions
- Does not represent potential for improvement

Evidence based three-value logic:

- Honest about what is not known
- Allows better analysis of how to tackle the remaining uncertainty
- Represents potential for improvement

Belief For + Belief Against + Uncertainty = 1

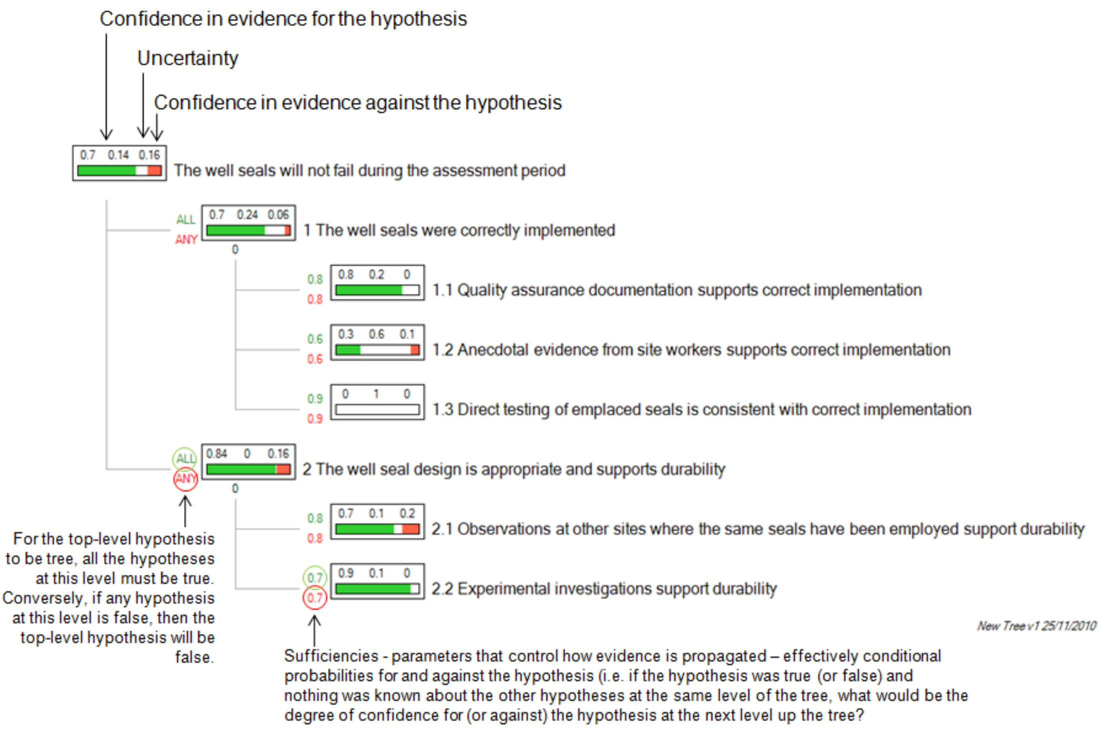
Figure D-12-2: Classical two-value probability analysis compared with three-value logic.

The ESL approach has been implemented within Quintessa's TESLA software (Quintessa, 2011), which provides:

- an interface for constructing and displaying a tree;
- functionality to embed supporting explanations, documents; and web page links within the tree; and
- tools to analyse a tree.

The implementation of ESL within TESLA is illustrated in Figure D-12-3 to Figure D-12-7.

An example hypothesis model to illustrate the approach is given in Figure D-12-3.

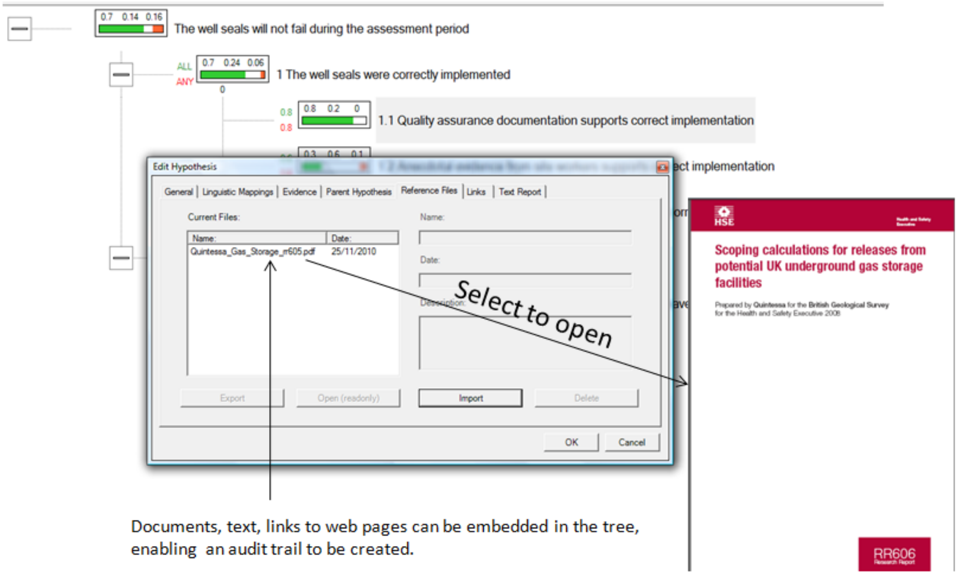


For the top-level hypothesis to be tree, all the hypotheses at this level must be true. Conversely, if any hypothesis at this level is false, then the top-level hypothesis will be false.

Sufficiencies - parameters that control how evidence is propagated – effectively conditional probabilities for and against the hypothesis (i.e. if the hypothesis was true (or false) and nothing was known about the other hypotheses at the same level of the tree, what would be the degree of confidence for (or against) the hypothesis at the next level up the tree?

Figure D-12-3: Example hypothesis model illustrating how degrees of confidence in hypotheses that closely relate to information or data (at the extreme right) are propagated to determine the degree of confidence in some hypothesis of interest (at top left. An actual tree would typically be considerably larger than this example.

TESLA enables users to embed supporting information within a hypothesis model, thereby producing an audit trail for the overall decision. This information can include, *inter alia*, text, reports (e.g. pdf files), spreadsheets and links to web pages (Figure D-12-4).



Name:	Date:
Quintessa_Gas_Storage_rr605.pdf	25/11/2010

Documents, text, links to web pages can be embedded in the tree, enabling an audit trail to be created.

Figure D-12-4: Example of an embedded report in a hypothesis model developed in TESLA.

The TESLA software includes several tools to analyse hypothesis models. The “portfolio tool” allows a user to compare, in one diagram, multiple hypothesis models that have the same structure, but different evidence values (Figure D-12-5).

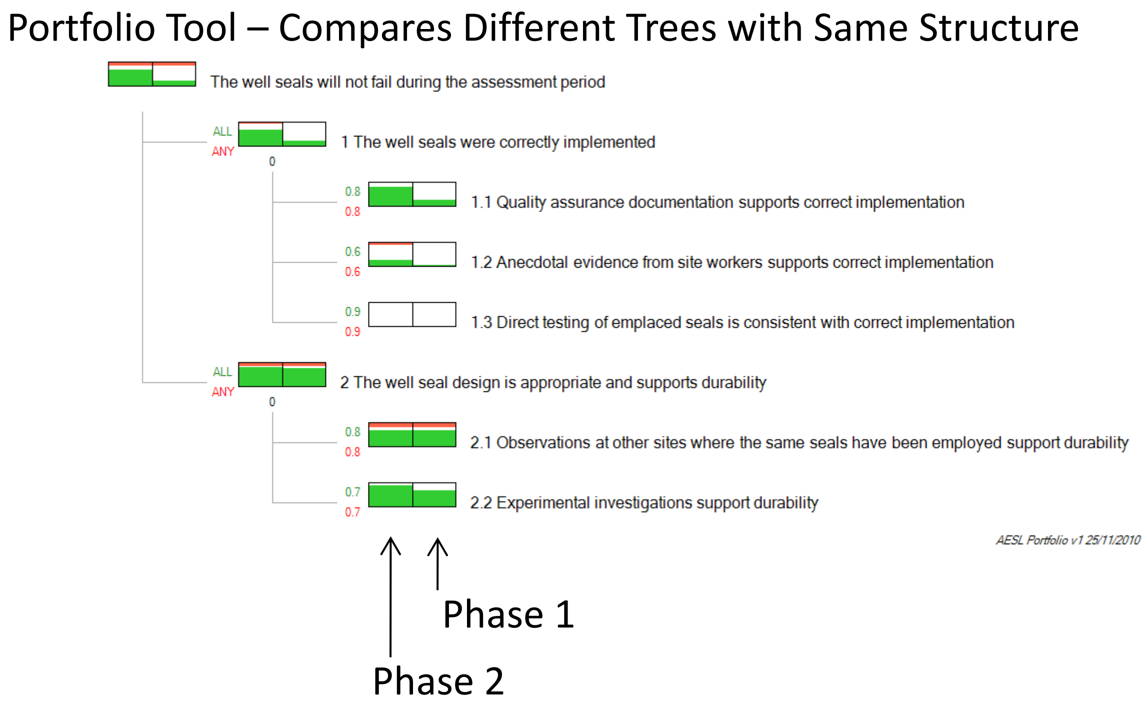


Figure D-12-5: Example application of the portfolio tool to compare two instances of the hypothetical tree in Figure D-12-3, each of which has different evidence values.

In the present project, this tool could be valuable for comparing degrees of confidence in relevant hypotheses at each stage of the project. To make such a comparison, a hypothesis model would be constructed. An instance of the tree would then be developed by inputting confidence values based on the information in Hendriks et al. (2012) and its supporting documents. Subsequent instances of the tree would be constructed by inputting confidence values based on:

- additional literature reviews;
- scoping calculations; and
- numerical analysis.

At each stage, the portfolio tool could be used to compare the trees, thereby highlighting the added value of activities in the previous phase of work.

TESLA also has a “tornado plot” tool, which plots the impact on the highest level hypothesis of varying by a tiny increment confidence values for and against each hypothesis at the lowest level in turn (Figure D-12-6). This tool is particularly valuable for identifying information to which the highest level hypothesis is most sensitive. In this way, the tool can help to identify priorities for further investigations, or conversely highlight where uncertainties or conflicts in information are in fact unimportant.

A "ratio plot" tool allows the user to plot the ratio of confidence for / against each hypothesis versus the residual uncertainty in the hypothesis (Figure D-12-7). A particularly useful application of this tool is to compare the confidence in the top-level hypothesis to confidence in each of the lowest-level hypotheses. The user can define fields of confidence on the plot (e.g. the green field in Figure D-12-7 indicates where the balance of evidence is in favour of a hypothesis ***and*** the residual uncertainty is low).

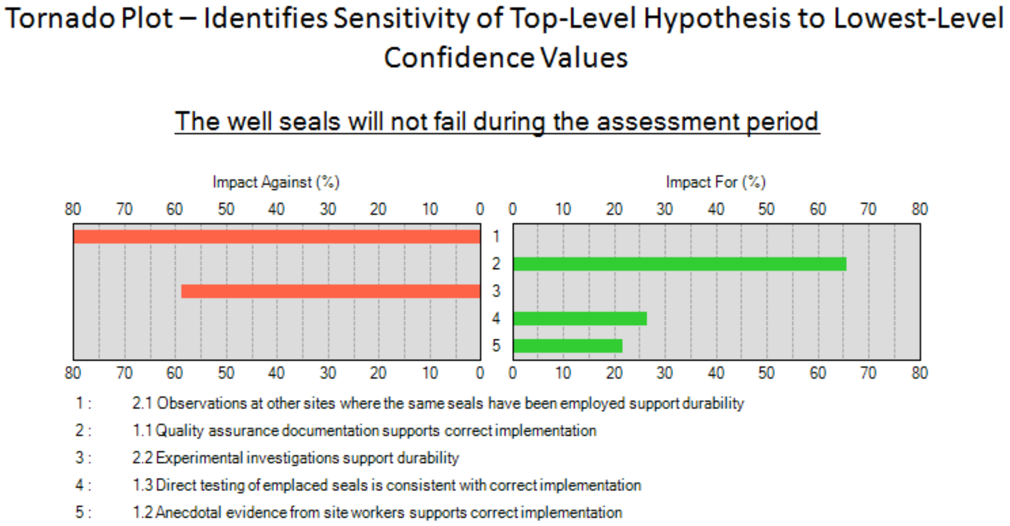


Figure D-12-6: Example tornado plot, constructed for the hypothesis model in Figure D-12-3. Observations at other sites have the greatest negative impact on the highest-level hypothesis, whereas quality assurance documentation has the highest impact in favour of the top-level hypothesis.

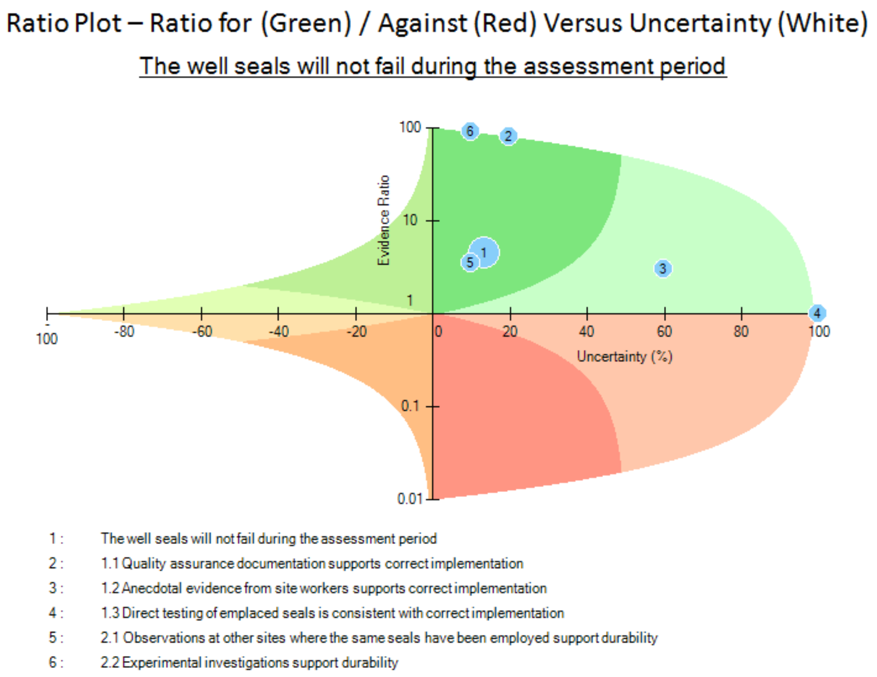


Figure D-12-7: Example ratio plot, constructed for the hypothesis model in Figure D-12-3. The top-level hypothesis (1) is likely to be correct and hence plots in the green field.

Appendix E: Detailed Tree Report

Full details of the model tree, its parameterisation, and judgements on logic and confidence/evidence, is provided below. The information is provided in raw 'TESLA Model Report' output form.

Tree Structure

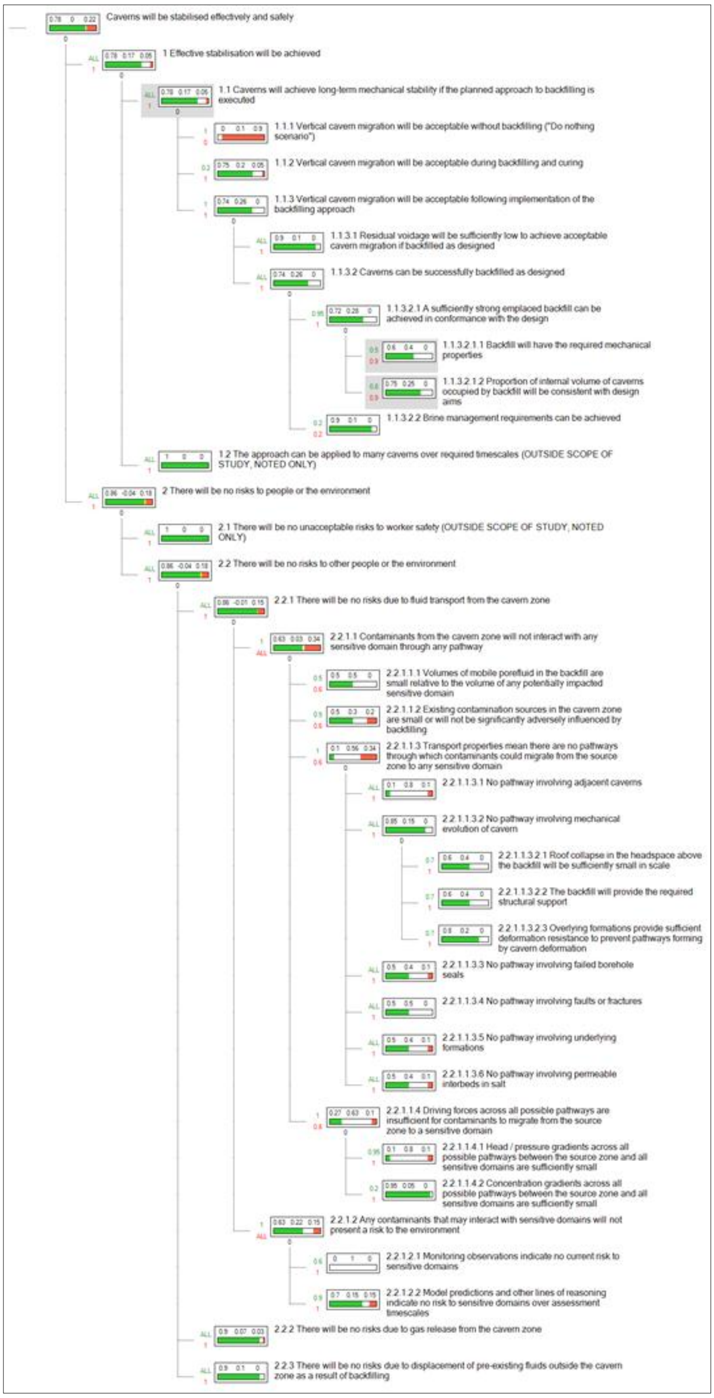


Figure E-1: The tree structure, showing confidence values and tree parameters.

Hypotheses

Details of each hypothesis in the tree are given in Table 1. The indentation of the hypothesis name indicates its level in the tree. The rationale behind the tree structure is given in Table 2, and any general notes entered against hypotheses are given in Table 3.

Table E1: Hypothesis details.

Hypothesis Name and Summary	Detailed Explanation
0 Caverns will be stabilised effectively and safely The salt caverns at Twente can be stabilised effectively and safely using a backfill based on materials from the energy from waste plant.	'Effective stabilisation' means: •· There is no risk (i.e. extremely small likelihood) of sink-hole formation, or of an unacceptable general surface deflection. • The primary requirement is to avoid sink holes, but rates of general surface deflection of > 5-25cm/yr that do not lead to sink holes would also be unacceptable. 'Safely' means: •· There will be no risk (i.e. extremely small likelihood/consequence of impact) to humans or the environment as a result of backfilling. That is, there will be no unacceptable impact by sensitive receptors. Other than workers carrying out backfilling operations (noted, but beyond the scope of this study) sensitive receptors of interest are: •· aquifers that may be used as water sources (for irrigation, drinking etc.); • environments at the land surface that are used by humans; • humans; •animals and plants. Impacts of concern include: •·any impacts associated with gas release to surface; and •contamination released during and after backfilling. Any other impacts are considered to be bracketed by the above. Success criteria for impacts to aquifers are defined as: •·Concentrations of any contaminants that might enter the

	receptor as a result of cavern backfilling and/or evolution will be below drinking water standards. • Chemical effects (e.g. due to brine displacement) within the aquifer associated with cavern backfilling and/or evolution will not lead to leaching of contaminants from the rock matrix to above drinking water standards. Timeframes of interest: • ·the period of backfilling and curing; • the period to the end of monitoring (and thus also to the end of the period after which no mitigation actions can be undertaken); • longer term (up to around 1000, years); and • very long-term (up to 10,000 years).
1 Effective stabilisation will be achieved The overall objective of backfilling, which is to achieve cavern stabilisation and thereby prevent unacceptable surface deformation, will be achieved.	'Effective stabilisation' and 'achieved' - see definition and success criteria in parent.
1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed Cavern behaviour will be consistent with 'effective stabilisation', as defined in the root hypothesis.	'Effective stabilisation' means: •· There is no risk (i.e. extremely small likelihood) of sink-hole formation, or of an unacceptable general surface deflection. • The primary requirement is to avoid sink holes, but rates of general surface deflection of > 5-25cm/yr that do not lead to sink holes would also be unacceptable.
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario") Effective stabilisation will be achieved even if there is no backfill.	This hypothesis concerns the "do nothing" scenario. 'Effective stabilisation' means: •· There is no risk (i.e. extremely small likelihood) of sink-hole formation, or of an unacceptable general surface deflection. The criteria for success are that any migration of the cavern roof is sufficiently small that the backfilling is unnecessary, namely ensuring that:

	- sink holes will not form at the surface; - rates of general surface deflection that do not lead to sink holes are < 5-25cm/yr . - Hcav < Hmax / [1 - (BF - 1], where Hcav is the height of the cavern, Hmax is the distance between the top of the cavern and a point 40 m below the base of the Tertiary and BF is the Bulking Factor, which is the volume of rock after excavation / volume of rock before excavation. The effectiveness of backfilling, if it takes place, is judged in Hypothesis 1.1.3 "Vertical cavern migration will be acceptable following implementation of the backfilling approach".
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing Effective stabilisation will not be compromised before the backfill is able to provide its required design function	Effective stabilisation' means: - There is no risk (i.e. extremely small likelihood) of sink-hole formation, or of an unacceptable general surface deflection. The criteria for success are that any migration of the cavern roof is sufficiently small that the objectives of the backfilling will not be called into question, namely ensuring that: - sink holes will not form at the surface; - rates of general surface deflection that do not lead to sink holes are < 5-25cm/yr .
1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach Effective stabilisation will be achieved following backfilling	Effective stabilisation' means: - There is no risk (i.e. extremely small likelihood) of sink-hole formation, or of an unacceptable general surface deflection. The criteria for success are that any migration of the cavern roof is sufficiently small that the objectives of the backfilling will not be called into question, namely ensuring that: - sink holes will not form at the surface; - rates of general surface deflection that do not lead to sink holes are < 5-25cm/yr .
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	Effective stabilisation' means: There is no risk (i.e. extremely small likelihood) of sink-

If the backfill is implemented as designed and provides the required mechanical strength, effective stabilisation will be achieved.	hole formation, or of an unacceptable general surface deflection. “As designed” means that the backfill is mixed and emplaced in accordance with the design. The design must be appropriate to ensure stabilisation. This hypothesis concerns a judgement of the suitability of the design of the backfill. That is, if the design is implemented properly then it is adequate to meet the aims of the stabilization project. Criteria for success are that: •· The design is commensurate with insufficient collapse of residual voidage to form sink holes at the surface. • The design is commensurate with insufficient collapse of residual voidage to cause rates of general surface deflection that do not lead to sink holes > 5-25cm/yr .
1.1.3.2 Caverns can be successfully backfilled as designed ••·Concerns confidence in the ability to implement backfilling to design requirements (i.e. effective stabilisation). Does not consider whether those requirements are sufficient to achieve performance; that is the topic of hypothesis 1.1.3.1.	Three lines of reasoning are relevant to establishing if cavern backfilling will be successful: • The proportion of the internal volume of the caverns occupied by the backfill must be consistent with design aims. • The backfill, once cured, must have the designed mechanical strength. • Brine management arrangements must be successfully achieved. The relative 'sufficiency' values indicate how important each element is to proving/dis-proving this hypothesis, always bearing in mind the key design aim is to ensure successful stabilisation, and thus brine management may not be as critical as other matters.
1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design The emplaced volume of backfill will be sufficiently strong and sufficiently large in relation to the size of the cavern that the design aims are met.	This hypothesis concerns the overall mechanical characteristics of the final emplaced volume of backfill within a cavern.
1.1.3.2.1.1 Backfill will have the required mechanical properties	

Considers the level of confidence that the backfill will have the as-designed level of ability to resist deformation (strength and stiffness).	
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims Here, 'design aims' reflect the filling proportion embedded in the design aims (linked in turn to 'effective stabilisation').	
1.1.3.2.2 Brine management requirements can be achieved Considers the level of confidence that brine will be managed successfully according to the required management strategy during backfilling.	
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY) The required number of caverns can be backfilled to the 'as design' timescale (reflecting requirements for confidence in performance). OUT OF SCOPE of the current study but noted for completeness. Default confidence values applied.	The overall success of the backfilling project will depend upon the feasibility of backfilling all the unstable caverns that have yet to collapse before any of them start to collapse. This feasibility will depend in large part on the timely availability of sufficient quantities of suitable backfill. Therefore, the issue is noted here, although it is outside the scope of the risk assessment. A confidence value of 1 is input on the assumption that the required number of caverns can be backfilled in a timely manner, so as to allow proper analysis of the other aspects of safety that are within the scope of the risk assessment.
2 There will be no risks to people or the environment The probability of people or the environment being impacted is acceptably small and /or the magnitudes of the impacts are acceptably small.	As defined in the parent, the root hypothesis: • There will be no risk (i.e. extremely small likelihood/consequence of impact) to humans or the environment as a result of backfilling. That is, there will be no unacceptable impact by sensitive receptors. Other than workers carrying out backfilling operations (noted, but beyond the scope of this study) sensitive receptors of interest are: • aquifers that may be used as water sources (for irrigation, drinking etc.);

	• environments at the land surface that are used by humans; • humans; • animals and plants. Impacts of concern include: •· any impacts associated with gas release to surface; and • contamination released during and after backfilling. Any other impacts are considered to be bracketed by the above.
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY) The safety of workers who are carrying out the backfilling will be ensured.	An important part of proving overall safety is proving worker safety; however, that is OUT OF SCOPE of the current study. Therefore, the issue is noted here, but a confidence value of 1 is input on the assumption that worker safety can be ensured, so as to allow proper analysis of the other aspects of safety that are within the scope of the risk assessment.
2.2 There will be no risks to other people or the environment As defined in the root node, reflects the level of confidence that there will be no risks to non-workers or the environment. Note that as most plausible risks to non-worker people will most likely occur via an environmental pathway e.g. aquifer exploitation, risks associated with leachate transport are primarily treated as being related to risks to aquifers. Risks due to gas release also require appropriate assessment.	Sub-hypotheses consider: •· the level of confidence concerning whether there are plausible pathways by which contaminants associated with cavern zone (e.g. backfill) could be transported and interact with a receptor, and whether any contaminants that might interact with receptors could present a risk to that receptor; • whether gas release could lead to safety risks; • whether pre-existing contaminants associated with fluids outside the cavern zone could be displaced as a result of backfilling activities leading to environmental impacts.
2.2.1 There will be no risks due to fluid transport from the cavern zone As noted in the parent, concerns: ••·whether there are plausible pathways by which contaminants associated with backfilling could be transported and interact with a receptor; and ••whether any such contaminants that might interact with receptors could present a risk	

to that receptor.	
2.2.1.1 Contaminants from the cavern zone will not interact with any sensitive domain through any pathway Concerns the level of confidence that exists in the absence of a source, a plausible pathway and driving force that could lead to contaminant transport from the source zone to an aquifer, or other receptor/sensitive domain. Contaminants could either arise from leachate associated with the backfilling and/or displacement of pre-existing contaminants (e.g. diesel) as a result of backfilling. NB risks that would occur without backfilling are not within the scope of the current study.	Sub-hypotheses reflect the above lines of reasoning. If there is no plausible source, pathway, and/or driving force, logically this will prove no impact.
2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain Concerns establishing whether the source term associated with the backfill will always be so small that there can be no risk.	Confidence 'for' this hypothesis means that the volume of mobile porefluid is sufficiently small that it is not plausible that contaminants within it could cause any significant impact to an environmental receptor even if a fast transport pathway exists. Confidence 'against' means the converse.
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling Concerns the potential for existing contaminant sources in the cavern zone, to be influenced by backfilling (e.g. by displacement of diesel) such that they become a plausible source term.	Situations whereby there is pre-existing contamination, but backfilling does not significantly enhance its status as a potential source term of concern, are out of scope of the current analysis.
2.2.1.1.3 Transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain	Confidence 'for' this hypothesis means that, for physically realistic ranges of driving forces, it is not plausible that any transport pathway, or combination of transport pathways, could lead to transport of contaminants that would result in an impact of significance to an

	environmental receptor. The various sub-hypotheses test whether each class of pathway could be part of such a plausible pathway either ON ITS OWN or IN COMBINATION WITH OTHER PATHWAYS e.g. roof collapse zone intersecting with faults. If there is confidence that there could be a plausible pathway in establishing confidence AGAINST this hypothesis, then appropriate dependency values will need to be selected to avoid double-counting of plausible pathways, if the pathway(s) identified combines more than one class of pathway (e.g. in the above example, a dependency will need to be set recognising that if there is evidence for both roof collapse and faults being part of a plausible pathway because they are part of the same combined pathway, those judgements share the same evidence base and this double-counting needs to be accounted for through selecting a dependency value approaching 1).
2.2.1.1.3.1 No pathway involving adjacent caverns This hypothesis concerns whether adjacent caverns provide all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	'Plausible pathway' - see definition in parent.
2.2.1.1.3.2 No pathway involving mechanical evolution of cavern This hypothesis concerns whether mechanical evolution of the cavern will lead to all or part of a plausible pathway for contaminant transport from the cavern to a receptor. In turn, sub-hypotheses consider whether different elements, in a similar way to the treatment of pathways at the hypothesis sibling level. The following processes could ON THEIR OWN or (arguably more likely) IN COMBINATION lead to a pathway, or part of a pathway, being created due to cavern migration. •·Roof collapse in the headspace •Backfill not providing structural support •Overlying formations providing less deformation resistance than expected	'Plausible pathway' - see definition in parent. Due to definition, there may be dependencies between child hypotheses if one or more contribute to confidence in existence of the same pathway.

(evolution of caverns)	
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale This hypothesis concerns whether roof collapse contributions to the mechanical evolution of the cavern will be sufficiently small to prevent all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	
2.2.1.1.3.2.2 The backfill will provide the required structural support This hypothesis concerns whether the backfill contributes sufficient support to prevent the mechanical evolution of the cavern leading to all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	The hypothesis recognizes that cavern deformation may lead to pathways forming even if there is no roof collapse. For example, cavern deformation accompanied by creep of the salt may conceivably cause pathways to develop within the walls of the cavern.
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation This hypothesis concerns whether overlying formations providing sufficient deformation resistance to prevent mechanical evolution of the cavern leading to all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	The hypothesis recognizes that overlying formations could be affected by cavern deformation even if there is no roof collapse. Additionally, the hypothesis also covers the possibility that pathways may not be only vertically above the cavern. For example, cavern deformation accompanied by creep of the salt may conceivably cause flexure of the overburden at some lateral distance from the cavern.
2.2.1.1.3.3 No pathway involving failed borehole seals This hypothesis concerns whether boreholes (following seal failure) provide all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	'Plausible pathway' - see definition in parent.

2.2.1.1.3.4 No pathway involving faults or fractures This hypothesis concerns whether faults (or fractures) provide all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	'Plausible pathway' - see definition in parent.
2.2.1.1.3.5 No pathway involving underlying formations This hypothesis concerns whether formations underlying the cavern system provide all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	'Plausible pathway' - see definition in parent.
2.2.1.1.3.6 No pathway involving permeable interbeds in salt This hypothesis concerns whether permeable interbeds within salt provide all or part of a plausible pathway for contaminant transport from the cavern to a receptor.	'Plausible pathway' - see definition in parent.
2.2.1.1.4 Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain This hypothesis concerns all the potential pathways noted under 2.2.1.1.3, and thus there is a clear logical link with judgements made under the hypothesis. If no plausible pathways are identified under 2.2.1.1.3, then this hypothesis, and sub-hypotheses, may have blank entries.	In many cases there may be dependence between the judgements on pathways under 2.2.1.1.2 and the judgements on driving forces operating across pathways in sub-hypotheses here. These will need to be recognised to avoid double counting of confidence, in particular in terms of confidence 'against'. Sub-hypotheses consider different properties that could provide driving forces. As it is considered much more likely that pressure/head gradients would drive flow and thus transport rather than concentration gradients, then confidence associated with the former is considered more sufficient to prove no driving force. However, confidence in both children is required for full confidence in this hypothesis. Confidence 'against' either, however, could be sufficient to disprove this hypothesis. 'Sufficient for contaminants to migrate' - indicates that a non-insignificant fraction of the backfill inventory could migrate through the pathways identified and interact with a sensitive domain / receptor (impacts associated with that interaction assessed separately under 2.2.1.2).

2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small See parent for details.	'Sufficient for contaminants to migrate' - indicates that a non-insignificant fraction of the backfill inventory could migrate through the pathways identified and interact with a sensitive domain / receptor (impacts associated with that interaction assessed separately under 2.2.1.2). The confidence evaluation here needs to take into account the potential for head/pressure gradients to lead to migration through any of pathways identified under 2.2.1.1.2. There may be dependence between these judgements, in particular if it is uncertain that the pathways exist because their properties are uncertain.
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small See parent for details.	'Sufficient for contaminants to migrate' - indicates that a non-insignificant fraction of the backfill inventory could migrate through the pathways identified and interact with a sensitive domain / receptor (impacts associated with that interaction assessed separately under 2.2.1.2). The confidence evaluation here needs to take into account the potential for head/pressure gradients to lead to migration through any of pathways identified under 2.2.1.1.2. There may be dependence between these judgements, in particular if it is uncertain that the pathways exist because their properties are uncertain.
2.2.1.2 Any contaminants that may interact with sensitive domains will not present a risk to the environment Sensitive domains are environmental receptors of interest, e.g. aquifers. The test of success used here concerns whether concentrations of contaminants within such receptors will be below guideline levels. In particular, WHO drinking water standards have been identified as a set of guidance levels with appropriate provenance.	Confidence 'for' this hypothesis means that concentrations of contaminants in environmental receptors will not exceed WHO standards or any other appropriate assessment targets either directly as a result of contaminant transport following backfilling, or indirectly as a result of (for example) heavy metal leaching from rock following chemistry change within the receptor water body.
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains This hypothesis concerns monitoring observations, and the extent to which they	Confidence 'for' this hypothesis reflects confidence that monitoring observations indicate concentrations of contaminants associated with backfilling operations will be below target (e.g. WHO) standards in receptors of

indicate that there is no present risk to sensitive domains / receptors.	interest. There may be a dependency with hypothesis 2.2.1.2.2 assuming monitoring information is also central to predictions of performance.
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales This hypothesis is not just limited to calculations/model outputs as a range of sources of evidence (for example logical argument, opportunities for mitigation) may also be relevant in building confidence in predictions of safety over assessment timeframes.	Confidence 'for' this hypothesis will indicate that the relevant lines of reasoning provide confidence that concentrations of contaminants in sensitive domains / receptors will remain below targets (e.g. WHO standards) for the assessment timeframe. There may be some dependency identified with evidence sources utilised for this hypothesis and that for hypothesis 2.2.1.2.1.
2.2.2 There will be no risks due to gas release from the cavern zone This tests the hypothesis that: ••·There will not be a source term of gas of any significance produced as a result of backfilling operations; and/or ••There are no plausible pathways by which a sufficient proportion of any released gas could reach environmental domains of interest (aquifers, surface features); and/or ••Impacts to those sensitive environmental domains/receptors will be low.	
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling This hypothesis considers whether displacement of pre-existing fluids (such as brine) outside the cavern zone could occur as a direct result of backfilling operations, and if so, whether an environmental risk (as defined in other hypotheses) might occur. Note that these risks would need to be additional to 'do nothing' (no backfilling) baseline risks to be of relevance - risks associated with the baseline are otherwise	Confidence 'for' this hypothesis indicates confidence that: •· there are no fluids outside the cavern zone that could be affected by backfilling; and/or • those fluids are not associated with contaminants; and/or • there are no pathways whereby those fluids could interact with sensitive domains/receptors; and/or • any such interactions would not lead to an impact. Confidence 'against' this hypothesis would indicate that on the contrary, contaminant-bearing fluids outside the cavern zone will be displaced as a result of backfilling

out of scope of the current study.	and will have an impact on the receptor.

Table E-2: Rationale behind the tree structure.

Hypothesis Name	Rationale Behind Tree Structure
0 Caverns will be stabilised effectively and safely	
1 Effective stabilisation will be achieved	The structure of sub-hypotheses is based upon identifying whether cavern backfilling approaches will be sufficient to prevent unacceptable vertical migration. An additional 'out of scope' hypothesis is also included considering whether backfilling of all unstable caverns that have not yet collapsed could be achieved within required timeframes. The feasibility of backfilling all these caverns needs to be considered when judging whether the overall project goals can be met, but is outside the scope of the present project, which concerns specifically the risks associated with a single cavern. The parent hypothesis (the root hypothesis of the tree) by definition can be true only if Hypothesis 1 that "Effective stabilisation will be achieved" and its sibling, Hypothesis 2 that "There will be no risks to people or the environment", are both true. Hence the propagation parameter for Hypothesis 1 is ALL. If this hypothesis is untrue the parent hypothesis (the root hypothesis of the tree) will also be untrue by definition. Hence a sufficiency of 1 against Hypothesis 1 is specified.
1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed	Hypothesis 1.1 "Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed" concerns the goal of backfilling and therefore is defined as a "necessary hypothesis". The hypothesis has one sibling, Hypothesis 1.2 "The approach can be applied to many caverns over required timescales", which is outside the scope of the risk assessment. Hypothesis 1.2 is included for completeness, to indicate that the feasibility of backfilling all unstable caverns that have not yet collapsed needs to be considered when judging whether the overall project goals can be met. To be consistent with the logical structure, the parent Hypothesis 1 "Effective stabilisation will be achieved" will

	be true only if Hypothesis 1.1 and Hypothesis 1.2 are true. Hence the propagation parameter for Hypothesis 1.1 is set to ALL. If Hypothesis 1.1 is untrue, then by definition its parent Hypothesis 1 "Effective stabilisation will be achieved" will also be untrue. Hence, Hypothesis 1.1 is assigned a sufficiency against of 1. The following logic applies to the sub-hypothesis structure. •·Hypothesis 1.1.1 considers the level of confidence in vertical cavern migration being acceptable even if there is no backfilling. 'against' Hypothesis 1.1.1 on its own does not imply that the parent hypothesis is untrue. •·Hypothesis 1.1.2 considers whether unacceptable migration could occur prior to the backfill achieving its design performance. •·Hypothesis 1.1.3 the main sub-hypothesis evaluating performance upon backfill strategy implementation (reverts to Hypothesis 1.1.1 if backfill is not to be utilised, in contrast to the current baseline).
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")	Hypothesis 1.1.1 considers the level of confidence in vertical cavern migration being acceptable even if there is no backfilling. That is, Hypothesis 1.1.1 corresponds to a "do nothing" scenario. If this hypothesis is true then by definition the parent, Hypothesis 1.1 "Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed" is true. Consequently the sufficiency for Hypothesis 1.1.1 is set to 1. In contrast confidence 'against' Hypothesis 1.1.1 on its own does not imply that the parent hypothesis is untrue. The parent could still be true if backfilling does take place. For this reason sufficiency for Hypothesis 1.1.1 is set to be 0.
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing	This hypothesis recognizes the possibility that there could be some migration of the cavern roof during the period of backfilling and thereafter during the period of backfill curing. The hypothesis also covers the possibility that the act of backfilling itself may cause some collapse of the roof. This hypothesis is similar to Hypothesis 2.2.1.1.3.2.1 "Roof collapse in the headspace above the backfill will be sufficiently small in scale". However, here the overall

	mechanical effectiveness is being judged, whereas Hypothesis 2.2.1.1.3.2.1 concerns the possibility that roof collapse might lead to the development of pathways for contaminant transport, irrespective of whether or not the objective of backfilling (preventing unacceptable deformation at the surface) is not met. It should be noted that if vertical cavern migration is judged to be unacceptable from a mechanical stability perspective then the overall judgement will be that safe and effective backfilling does not occur (i.e. the root hypothesis will fail). Under these circumstances an evaluation of contaminant migration is irrelevant.
1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach	If Hypothesis 1.1.3 "Vertical cavern migration will be acceptable following implementation of the backfilling approach" is true, then the parent hypothesis 1.1 "Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed" must be true. Consequently Hypothesis 1.1.3 is assigned sufficiency for of 1. Conversely, if Hypothesis 1.1.3 is untrue, by definition the parent Hypothesis 1.1 must also be untrue. Hence, Hypothesis 1.1.3 is assigned a sufficiency against of 1. Both (ALL) of the following lines of reasoning are required for success: •·The cavern residual voidage must be sufficiently low to ensure cavern stabilisation, assuming that the backfilling achieves the design criteria •The cavern must be successfully backfilled to the design criteria These elements are reflected in sub-hypotheses.
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	Hypothesis 1.1.3.1 "Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed" has one sibling, Hypothesis 1.1.3.2 "Caverns can be successfully backfilled as designed". Whereas Hypothesis 1.1.3.1 concerns a judgement of the suitability of the design, Hypothesis 1.1.3.2 concerns a judgement of the design's implementation. The parent, Hypothesis 1.1.3 "Vertical cavern migration will be acceptable following implementation of the backfilling approach" will be true only if both its children, Hypotheses 1.1.3.1 and 1.1.3.2 are true. That is, only if the backfill design is suitable and properly implemented will cavern stabilisation be achieved. For this reason,

	confidence for Hypothesis 1.1.3.1 is propagated using the ALL parameter. Conversely, if the design is unsuitable, that is Hypothesis 1.1.3.1 is untrue, the parent, Hypothesis 1.1.3 that "Vertical cavern migration will be acceptable following implementation of the backfilling approach" will also be untrue. For this reason, confidence against Hypothesis 1.1.3.1 is propagated by specifying a sufficiency against of 1.
1.1.3.2 Caverns can be successfully backfilled as designed	Hypothesis 1.1.3.2 "Caverns can be successfully backfilled as designed" has one sibling, Hypothesis 1.1.3.1 "Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed" has one sibling. Whereas Hypothesis 1.1.3.1 concerns a judgement of the suitability of the design, Hypothesis 1.1.3.2 concerns a judgement of the design's implementation. The parent, Hypothesis 1.1.3 "Vertical cavern migration will be acceptable following implementation of the backfilling approach" will be true only if both its children, Hypotheses 1.1.3.1 and 1.1.3.2 are true. That is, only if the backfill design is suitable and properly implemented will cavern stabilisation be achieved. For this reason, confidence for Hypothesis 1.1.3.2 is propagated using the ALL parameter. Conversely, if the design is improperly implemented, that is Hypothesis 1.1.3.2 is untrue, the parent, Hypothesis 1.1.3 that "Vertical cavern migration will be acceptable following implementation of the backfilling approach" will also be untrue. For this reason, confidence against Hypothesis 1.1.3.2 is propagated by specifying a sufficiency against of 1.
1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design	
1.1.3.2.1.1 Backfill will have the required mechanical properties	
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims	This hypothesis differs from 1.1.3.1 because 1.1.3.2.1.2 judges whether or not backfill can be emplaced, whereas 1.1.3.1 concerns the performance of the backfill assuming that it has been emplaced correctly.
1.1.3.2.2 Brine management	

requirements can be achieved	
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	The hypothesis has one sibling, Hypothesis 1.1 "Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed". To be consistent with the logical structure, the parent Hypothesis 1 "Effective stabilisation will be achieved" will be true only if Hypothesis 1.1 and Hypothesis 1.2 are true. Hence the propagation parameter for Hypothesis 1.2 is set to ALL. If Hypothesis 1.2 is untrue, then by definition its parent Hypothesis 1 "Effective stabilisation will be achieved" will also be untrue. Hence, Hypothesis 1.2 is assigned a sufficiency against of 1. Hypothesis 1.2 has no sub-hypotheses because it is included in the tree simply as a marker, to indicate that an overall judgement of cavern stability being attained must cover all caverns and the feasibility of them being backfilled. As noted previously, it is outside the scope of the risk assessment to evaluate this hypothesis.
2 There will be no risks to people or the environment	Within the scope of the risk assessment, the sub-hypothesis of primary concern is Hypothesis 2.2 that "There will be no risks to other people of the environment". An additional 'out of scope' hypothesis, Hypothesis 2.1 "There will be no unacceptable risks to worker safety" is also included to recognize that risks to workers involved in backfilling operations need to be considered. Hypothesis 2.2 is not expanded into sub-hypothesis because it is outside the scope of the present assessment. The parent hypothesis (the root hypothesis of the tree) by definition can be true only if Hypothesis 2 that "There will be no risks to people or the environment", and its sibling, Hypothesis 1 that "Effective stabilisation will be achieved", are both true. Hence the propagation parameter for Hypothesis 2 is ALL. If Hypothesis 2 is untrue the parent hypothesis (the root hypothesis of the tree) will also be untrue by definition. Hence a sufficiency of 1 against is specified.
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	Hypothesis 2.1 has no sub-hypotheses because it is included in the tree simply as a marker, to indicate that an overall assessment of risks must include a judgement about the safety of workers. As noted previously, it is outside the scope of the risk assessment to evaluate this

	hypothesis.
2.2 There will be no risks to other people or the environment	
2.2.1 There will be no risks due to fluid transport from the cavern zone	
2.2.1.1 Contaminants from the cavern zone will not interact with any sensitive domain through any pathway	
2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	
2.2.1.1.3 Transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain	
2.2.1.1.3.1 No pathway involving adjacent caverns	
2.2.1.1.3.2 No pathway involving mechanical evolution of cavern	
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale	
2.2.1.1.3.2.2 The backfill will provide the required structural support	
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	
2.2.1.1.3.3 No pathway involving failed borehole seals	

2.2.1.1.3.4 No pathway involving faults or fractures	
2.2.1.1.3.5 No pathway involving underlying formations	
2.2.1.1.3.6 No pathway involving permeable interbeds in salt	
2.2.1.1.4 Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain	
2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	
2.2.1.2 Any contaminants that may interact with sensitive domains will not present a risk to the environment	
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains	The sufficiency for is lower than the sufficiency for sibling hypothesis 2.2.1.2.2 "Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales" because monitoring cannot cover the whole assessment time period, whereas model predictions can cover this time period.
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales	The sufficiency for is higher than the sufficiency for sibling hypothesis 2.2.1.2.1 "Monitoring observations indicate no current risk to sensitive domains" because monitoring cannot cover the whole assessment time period, whereas model predictions can cover this time period.
2.2.2 There will be no risks due to gas release from the cavern zone	
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	

Confidence Values

Only confidence values for leaf hypotheses (those with no children) are entered by the user. All other confidence values are calculated using the Evidence Support Logic algorithm. Values of confidence for and confidence against are listed in Table 4 for each hypothesis.

Table E-4: Confidence for (supporting) and confidence against (refuting) for each hypothesis.

Hypothesis Name	Confidence For	Confidence Against
0 Caverns will be stabilised effectively and safely	0.78	0.22
1 Effective stabilisation will be achieved	0.78	0.05
1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed	0.78	0.05
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")	0.00	0.90
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing	0.75	0.05
1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach	0.74	0.00
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	0.90	0.00
1.1.3.2 Caverns can be successfully backfilled as designed	0.74	0.00
1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design	0.72	0.00

1.1.3.2.1.1 Backfill will have the required mechanical properties	0.60	0.00
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims	0.75	0.00
1.1.3.2.2 Brine management requirements can be achieved	0.90	0.00
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	1.00	0.00
2 There will be no risks to people or the environment	0.86	0.18
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	1.00	0.00
2.2 There will be no risks to other people or the environment	0.86	0.18
2.2.1 There will be no risks due to fluid transport from the cavern zone	0.86	0.15
2.2.1.1 Contaminants from the cavern zone will not interact with any sensitive domain through any pathway	0.63	0.34
2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	0.50	0.00
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	0.50	0.20
2.2.1.1.3 Transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain	0.10	0.34
2.2.1.1.3.1 No pathway involving adjacent caverns	0.10	0.10
2.2.1.1.3.2 No pathway involving mechanical	0.85	0.00

evolution of cavern		
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale	0.60	0.00
2.2.1.1.3.2.2 The backfill will provide the required structural support	0.60	0.00
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	0.80	0.00
2.2.1.1.3.3 No pathway involving failed borehole seals	0.50	0.10
2.2.1.1.3.4 No pathway involving faults or fractures	0.50	0.00
2.2.1.1.3.5 No pathway involving underlying formations	0.50	0.10
2.2.1.1.3.6 No pathway involving permeable interbeds in salt	0.50	0.10
2.2.1.1.4 Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain	0.27	0.10
2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.10	0.10
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.95	0.00
2.2.1.2 Any contaminants that may interact with sensitive domains will not present a risk to the environment	0.63	0.15
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains	0.00	0.00
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales	0.70	0.15

2.2.2 There will be no risks due to gas release from the cavern zone	0.90	0.03
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	0.90	0.00

Tables 5 and 6 show how the confidence values for each leaf hypothesis were entered; the Evidence Quality reflects the confidence in the validity of the evidence, whilst the Evidence Coverage indicates if an exhaustive search of all possible sources has been carried out.

Table E-5: Breakdown of confidence for values entered for leaf hypotheses.

Leaf Hypothesis Name	Face Value of Evidence For	Quality	Evidence Coverage	Total Confidence For
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")				0.00
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing				0.75
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed				0.90
1.1.3.2.1.1 Backfill will have the required mechanical properties				0.60
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims				0.75
1.1.3.2.2 Brine management requirements can be achieved				0.90
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)				1.00
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)				1.00

2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain				0.50
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling				0.50
2.2.1.1.3.1 No pathway involving adjacent caverns				0.10
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale				0.60
2.2.1.1.3.2.2 The backfill will provide the required structural support				0.60
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation				0.80
2.2.1.1.3.3 No pathway involving failed borehole seals				0.50
2.2.1.1.3.4 No pathway involving faults or fractures				0.50
2.2.1.1.3.5 No pathway involving underlying formations				0.50
2.2.1.1.3.6 No pathway involving permeable interbeds in salt				0.50
2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small				0.10
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small				0.95
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains				0.00

2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales				0.70
2.2.2 There will be no risks due to gas release from the cavern zone				0.90
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling				0.90

Table E-6: Breakdown of confidence against values entered for leaf hypotheses.

Leaf Hypothesis Name	Face Value of Evidence Against	Quality	Evidence Coverage	Total Confidence Against
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")				0.90
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing				0.05
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed				0.00
1.1.3.2.1.1 Backfill will have the required mechanical properties				0.00
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims				0.00
1.1.3.2.2 Brine management requirements can be achieved				0.00
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)				0.00
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)				0.00
2.2.1.1.1 Volumes of mobile porefluid in the				0.00

backfill are small relative to the volume of any potentially impacted sensitive domain				
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling				0.20
2.2.1.1.3.1 No pathway involving adjacent caverns				0.10
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale				0.00
2.2.1.1.3.2.2 The backfill will provide the required structural support				0.00
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation				0.00
2.2.1.1.3.3 No pathway involving failed borehole seals				0.10
2.2.1.1.3.4 No pathway involving faults or fractures				0.00
2.2.1.1.3.5 No pathway involving underlying formations				0.10
2.2.1.1.3.6 No pathway involving permeable interbeds in salt				0.10
2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small				0.10
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small				0.00
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains				0.00
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive				0.15

domains over assessment timescales				
2.2.2 There will be no risks due to gas release from the cavern zone				0.03
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling				0.00

Sufficiency Values

The sufficiency acts like a weighting term when propagating confidence through the tree from child to parent hypothesis. Different sufficiency values can be applied to confidence for and against; Table 7 lists the values of this parameter for each hypothesis in the tree.

A sufficiency recorded as "ANY" indicates that the success or failure of any member of the set comprising the hypothesis and its siblings is sufficient for the success or failure of the parent; thus the *largest* confidence value is propagated directly to the parent.

A sufficiency recorded as "ALL" indicates that the success or failure of all members of the set comprising the hypothesis and its siblings is required for the success or failure of the parent; thus the *smallest* confidence value from the set is propagated directly to the parent.

Table E-7: Sufficiency values entered for each hypothesis, for confidence for and confidence against.

Hypothesis Name	Sufficiency For	Sufficiency Against
0 Caverns will be stabilised effectively and safely	N/A	N/A
1 Effective stabilisation will be achieved	ALL	1.00
1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed	1.00	1.00
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")	1.00	0.00

1.1.2 Vertical cavern migration will be acceptable during backfilling and curing	0.20	1.00
1.1.3 Vertical cavern migration will be acceptable following implementation of the backfilling approach	ALL	1.00
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	0.80	1.00
1.1.3.2 Caverns can be successfully backfilled as designed	0.50	1.00
1.1.3.2.1 A sufficiently strong emplaced backfill can be achieved in conformance with the design	0.95	1.00
1.1.3.2.1.1 Backfill will have the required mechanical properties	0.50	0.90
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims	0.80	0.90
1.1.3.2.2 Brine management requirements can be achieved	0.20	0.20
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	0.50	1.00
2 There will be no risks to people or the environment	ALL	1.00
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	0.50	1.00
2.2 There will be no risks to other people or the environment	ALL	1.00
2.2.1 There will be no risks due to fluid transport from the cavern zone	0.50	ALL
2.2.1.1 Contaminants from the cavern zone will not interact with any sensitive domain through any pathway	1.00	0.50

2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	0.50	0.60
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	0.50	0.60
2.2.1.1.3 Transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain	ALL	0.60
2.2.1.1.3.1 No pathway involving adjacent caverns	0.40	1.00
2.2.1.1.3.2 No pathway involving mechanical evolution of cavern	0.40	1.00
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale	0.70	1.00
2.2.1.1.3.2.2 The backfill will provide the required structural support	0.70	1.00
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	0.70	1.00
2.2.1.1.3.3 No pathway involving failed borehole seals	0.40	1.00
2.2.1.1.3.4 No pathway involving faults or fractures	0.40	1.00
2.2.1.1.3.5 No pathway involving underlying formations	0.40	1.00
2.2.1.1.3.6 No pathway involving permeable interbeds in salt	0.40	1.00
2.2.1.1.4 Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain	1.00	0.60

2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.95	1.00
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.20	1.00
2.2.1.2 Any contaminants that may interact with sensitive domains will not present a risk to the environment	1.00	0.50
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains	0.60	1.00
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales	0.90	1.00
2.2.2 There will be no risks due to gas release from the cavern zone	0.50	1.00
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	0.50	1.00

Dependency Values

The dependency parameter encapsulates the overlap in scope between sibling hypotheses in the tree and compensates for double-counting of evidence sources. Dependency values can be allocated to an entire set of siblings or to individual pairs. A list of dependency values for the tree is given in Table 8.

Table E-8: Dependency values for groups of sibling hypotheses

Hypotheses	Dependency
Effective stabilisation will be achieved	0.00
There will be no risks to people or the environment	
Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed	0.00

The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	
Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")	0.00
Vertical cavern migration will be acceptable during backfilling and curing	
Vertical cavern migration will be acceptable following implementation of the backfilling approach	
Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	0.00
Caverns can be successfully backfilled as designed	
A sufficiently strong emplaced backfill can be achieved in conformance with the design	0.00
Brine management requirements can be achieved	
Backfill will have the required mechanical properties	0.00
Proportion of internal volume of caverns occupied by backfill will be consistent with design aims	
There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	0.00
There will be no risks to other people or the environment	
There will be no risks due to fluid transport from the cavern zone	0.00
There will be no risks due to gas release from the cavern zone	
There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	
Contaminants from the cavern zone will not interact with any sensitive domain through any pathway	0.00
Any contaminants that may interact with sensitive domains will not present a risk to the environment	
Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	0.00

Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	
Transport properties mean there are no pathways through which contaminants could migrate from the source zone to any sensitive domain	
Driving forces across all possible pathways are insufficient for contaminants to migrate from the source zone to a sensitive domain	
No pathway involving adjacent caverns	0.00
No pathway involving mechanical evolution of cavern	
No pathway involving failed borehole seals	
No pathway involving faults or fractures	
No pathway involving underlying formations	
No pathway involving permeable interbeds in salt	
Roof collapse in the headspace above the backfill will be sufficiently small in scale	0.00
The backfill will provide the required structural support	
Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	
Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	0.00
Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	
Monitoring observations indicate no current risk to sensitive domains	0.00
Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales	

Necessary Hypotheses

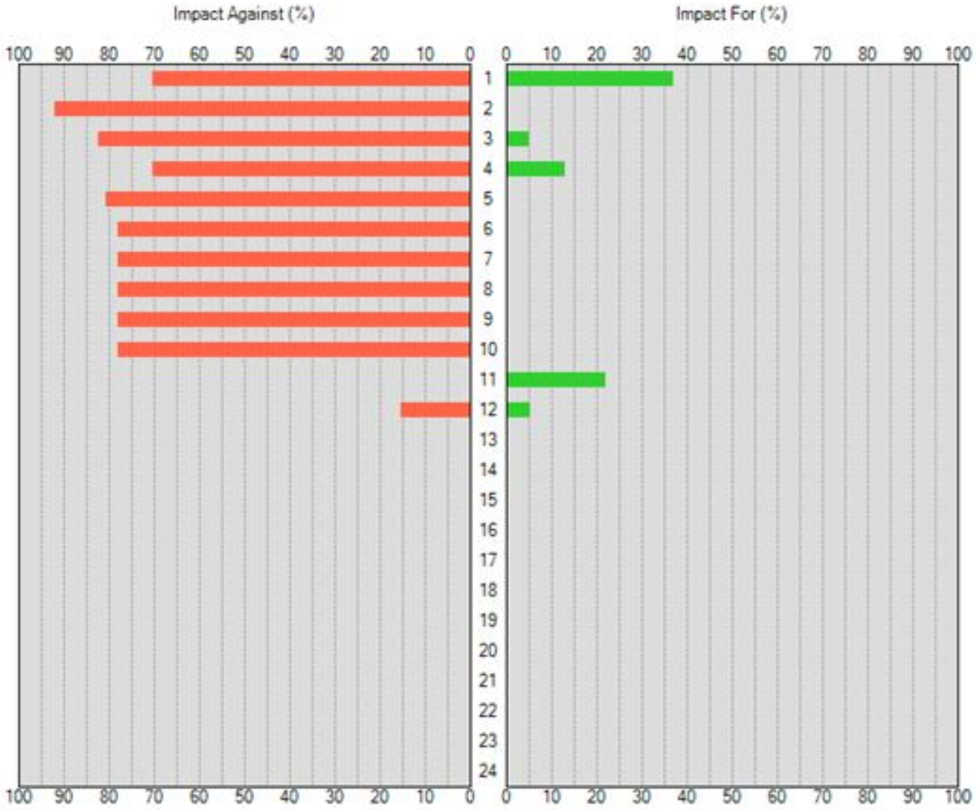
A hypothesis is deemed “necessary” if its failure causes the immediate failure its parent hypothesis, regardless of the values of the rest of its siblings.

Failure Criteria: Confidence Against > 0.5

Necessary Hypotheses:	1.1 Caverns will achieve long-term mechanical stability if the planned approach to backfilling is executed
	1.1.3.2.1.1 Backfill will have the required mechanical properties
	1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims

Tornado Plot

The tornado plot (Figure E-2) shows which hypotheses would have the biggest impact on the top-level hypothesis if their confidence values were changed by a small amount. This helps to identify areas where it would be beneficial to do more research in order to reduce uncommitted belief (or improve the balance of confidence) in the tree.

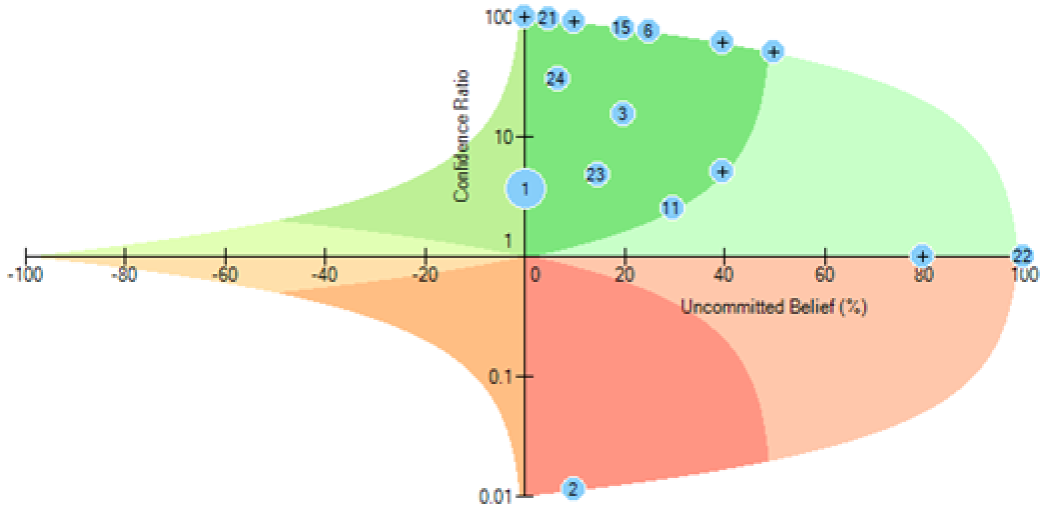


1 : 1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims
2 : 2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales
3 : 1.1.2 Vertical cavern migration will be acceptable during backfilling and curing
4 : 1.1.3.2.1.1 Backfill will have the required mechanical properties
5 : 2.2.2 There will be no risks due to gas release from the cavern zone
6 : 2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)
7 : 1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed
8 : 1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)
9 : 2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains
10 : 2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling
11 : 1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")
12 : 1.1.3.2.2 Brine management requirements can be achieved
13 : 2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain
14 : 2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling
15 : 2.2.1.1.3.1 No pathway involving adjacent caverns
16 : 2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale
17 : 2.2.1.1.3.2.2 The backfill will provide the required structural support
18 : 2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation
19 : 2.2.1.1.3.3 No pathway involving failed borehole seals
20 : 2.2.1.1.3.4 No pathway involving faults or fractures
21 : 2.2.1.1.3.5 No pathway involving underlying formations
22 : 2.2.1.1.3.6 No pathway involving permeable interbeds in salt
23 : 2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small
24 : 2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small

Figure E-2: Tornado plot for the top-level hypothesis, showing the leaf hypotheses that have most impact on the confidence values at the top-level hypothesis.

Ratio Plot

The ratio plot (Figure E-3) shows the ratio of 'confidence for' to 'confidence against' versus the uncommitted belief for each hypothesis in the tree. The coloured regions depict areas of confidence in each hypothesis; those falling in the dark green or dark red areas have good levels of confidence (in the balance of probabilities, the evidence supports or refutes the hypothesis), whereas confidence in those falling in the light green or red areas is small (it is undecided whether the evidence supports or refutes the hypothesis). The top-level node is labelled number 1 in the plot.



1 : Caverns will be stabilised effectively and safely

2 : 1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")

3 : 1.1.2 Vertical cavern migration will be acceptable during backfilling and curing

4 : 1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed

5 : 1.1.3.2.1.1 Backfill will have the required mechanical properties

6 : 1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims

7 : 1.1.3.2.2 Brine management requirements can be achieved

8 : 1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)

9 : 2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)

10 : 2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain

11 : 2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling

12 : 2.2.1.1.3.1 No pathway involving adjacent caverns

13 : 2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in scale

14 : 2.2.1.1.3.2.2 The backfill will provide the required structural support

15 : 2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation

16 : 2.2.1.1.3.3 No pathway involving failed borehole seals

17 : 2.2.1.1.3.4 No pathway involving faults or fractures

18 : 2.2.1.1.3.5 No pathway involving underlying formations

19 : 2.2.1.1.3.6 No pathway involving permeable interbeds in salt

20 : 2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small

21 : 2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small

22 : 2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains

23 : 2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales

24 : 2.2.2 There will be no risks due to gas release from the cavern zone

25 : 2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling

Figure E-3: Ratio plot for the tree, showing confidence in the outcome of each hypothesis.

Reasons for Selecting Confidence Values

Reasons for selecting confidence values are listed in Table 10 for each leaf hypothesis. Longer descriptions of each reason are shown in Table 11.

Table E-10: Reasons for selecting confidence values.

Hypothesis Name	Reasons for Selecting Confidence For	Reasons for Selecting Confidence Against
1.1.1 Vertical cavern migration will be acceptable without backfilling ("Do nothing scenario")		Backfilling only done if hypothesis fails
		Reason for white space
1.1.2 Vertical cavern migration will be acceptable during backfilling and curing	Observations on existing caverns	Acknowledgment of possibility of early failure
	Experience of other backfilled caverns elsewhere	
	Geomechanical modelling	
1.1.3.1 Residual voidage will be sufficiently low to achieve acceptable cavern migration if backfilled as designed	Calculations support adequate support following backfilling	
1.1.3.2.1.1 Backfill will have the required mechanical properties	Laboratory measurements	
	Past experience of backfill preparation	
	Uncertainty in required properties	
	Variability in materials used to make backfill	
1.1.3.2.1.2 Proportion of internal volume of caverns occupied by backfill will be consistent with design aims	Past experience of backfill preparation	

	Laboratory measurement	
	Uncertain cavern properties	
1.1.3.2.2 Brine management requirements can be achieved	Experience of brine management	
1.2 The approach can be applied to many caverns over required timescales (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	Assumption in order to evaluate risk factors associated with backfilling itself	
2.1 There will be no unacceptable risks to worker safety (OUTSIDE SCOPE OF STUDY, NOTED ONLY)	Assumption in order to evaluate risk factors associated with backfilling itself (2)	
2.2.1.1.1 Volumes of mobile porefluid in the backfill are small relative to the volume of any potentially impacted sensitive domain	Containment of porefluid	
	Uncertain definition of sensitive domains	
	Uncertain backfill properties	
	Uncertain hydrogeological properties (rock permeabilities and head gradients)	
2.2.1.1.2 Existing contamination sources in the cavern zone are small or will not be significantly adversely influenced by backfilling	Experience with oil recovery	Hazardous nature of the oil blanket
	Impact will be less than "do nothing scenario"	
	Low-permeability rocks favour containment	
2.2.1.1.3.1 No pathway involving adjacent caverns	Low-permeability material between caverns	Pressure responses
2.2.1.1.3.2.1 Roof collapse in the headspace above the backfill will be sufficiently small in	Calculations support limited extent of collapse	

scale	column	
2.2.1.1.3.2.2 The backfill will provide the required structural support	Calculations (2) support limited extent of collapse column	
2.2.1.1.3.2.3 Overlying formations provide sufficient deformation resistance to prevent pathways forming by cavern deformation	Properties of formations	
2.2.1.1.3.3 No pathway involving failed borehole seals	Borehole properties	Borehole seals will degrade over the long term
2.2.1.1.3.4 No pathway involving faults or fractures	Rock properties	
2.2.1.1.3.5 No pathway involving underlying formations	Formation properties	Hydraulic response of adjacent caverns
		Integrity of cavern floors
2.2.1.1.3.6 No pathway involving permeable interbeds in salt	Properties of interbeds / formations	Hydraulic response of adjacent caverns
2.2.1.1.4.1 Head / pressure gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	Peak head may be in the Muschelkalk	Potential for upwards flow from depth
2.2.1.1.4.2 Concentration gradients across all possible pathways between the source zone and all sensitive domains are sufficiently small	Length of diffusive pathway	
2.2.1.2.1 Monitoring observations indicate no current risk to sensitive domains	No data	
2.2.1.2.2 Model predictions and other lines of reasoning indicate no risk to sensitive domains over assessment timescales	Expected evolution and other scenarios unlikely to lead to risk to sensitive domains	Lower probability scenarios
2.2.2 There will be no risks due to gas release from the cavern zone	Backfill development means limited gas generation post-injection	Evidence of gas generation for PFA containing concretes
2.2.3 There will be no risks due to displacement of pre-existing fluids outside the cavern zone as a result of backfilling	Not generating sufficient pressure	

Table E-11: Descriptions of each reason for selecting confidence values

Reason	Description
Backfilling only done if hypothesis fails	Specify to fail since we are evaluating the rest of the tree which concerns backfilling.
Reason for white space	We can never be 100% sure that the cavern will migrate. The size of this uncertainty cannot be estimated confidently, especially without site-specific information.
Observations on existing caverns	Observations on existing caverns shows that it is reasonable to expect that even and unstable cavern will not collapse significantly during the timescale of a few years over which backfilling will occur.
Experience of other backfilled caverns elsewhere	Caverns in salt in broadly similar geological settings elsewhere have been successfully backfilled without collapse during backfilling.
Geomechanical modelling	Geomechanical modelling shows that it is reasonable to expect that caverns will remain stable for a number of years - sufficient to undertake backfilling.
Acknowledgment of possibility of early failure	The fact that any cavern that is backfilled will be judged unstable raises at least some possibility that failure may occur during backfilling. It is assumed that the probability will be low and will have been demonstrated as such by geomechanical investigations / modelling. The backfilling process causes temperature and pressure changes which , though small, contribute to instability.
Calculations support adequate support following backfilling	The calculations show that for all reasonable bulking factors, once backfilling has been undertaken and the designed residual voidage attained, then sinkhole formation or unacceptable surface subsidence rates will not occur. There is some uncertainty about bulking factors, which explains largely the white space.
Laboratory measurements	There have been laboratory measurements of backfill mechanical properties. These are supportive of the backfill having the required stiffness. However, at the time of the present assessment, strength data are not available, contributing to a relatively high degree of uncertainty (white

	space).
Past experience of backfill preparation	The company formulating the backfill (K-UTEC) has long experience of developing backfill mixes. This builds some confidence that the proposed mix is likely to be suitable.
Uncertainty in required properties	There is some uncertainty about the required properties in order to prevent collapse becoming unacceptable.
Variability in materials used to make backfill	There will be variability in the nature of the materials available to formulate the backfill. This variability contributes to uncertainties in the backfill performance - and hence the white space associated with this hypothesis.
Laboratory measurement	There have been laboratory measurements of backfill mechanical properties. These are supportive of the backfill having the required flow properties. However, at the time of the present assessment, not all data are available contributing to some degree of uncertainty (white space).
Uncertain cavern properties	Cavern walls and roof will be irregular, leading to uncertainty as to whether or not the backfill can fully fill the cavern.
Experience of brine management	Brine management procedures are well established. The uncertainty arises because this particular application of brine management has new aspects (e.g. producing slurry for use in the backfill).
Assumption in order to evaluate risk factors associated with backfilling itself	The purpose of the staged risk assessment is primarily to evaluate whether the pilot backfilling will work successfully. This hypothesis is outside the scope of the work and is included in the tree as a marker, to demonstrate that it is recognized to be important in an overall judgment of backfilling feasibility. In order to focus attention, for the purposes of the risk assessment, on risk factors associated with actual backfilling, this hypothesis has been assigned confidence for of 1.
Assumption in order to evaluate risk factors associated with backfilling itself (2)	The purpose of the staged risk assessment is primarily to evaluate whether the pilot backfilling will work successfully. This hypothesis is outside the scope of the work and is included in the tree as a marker, to demonstrate that it is recognized to be important in an overall judgment of backfilling feasibility. In order to focus attention, for the purposes of the risk assessment, on risk factors associated with actual backfilling, this hypothesis has been assigned confidence for of 1.

Containment of porefluid	The porefluid will be contained by the low-permeability overburden. Calculations for the expected evolution scenario support this view.
Uncertain definition of sensitive domains	Uncertainty (white space) is relatively large because the nature of the sensitive domains of concern to regulators and other stakeholders is uncertain (requires discussion).
Uncertain backfill properties	Uncertainty (white space) is large because there is uncertainty about the volume of porefluid in the backfill owing to uncertainty about the backfill formulations, which is as yet unconfirmed.
Uncertain hydrogeological properties (rock permeabilities and head gradients)	Perhaps the largest contributor to uncertainty (white space) is a lack of information about hydrogeological properties (rock permeabilities and head gradients) at depth.
Experience with oil recovery	Attempts to remove diesel used as a blanket showed that it was very difficult to remove all the diesel in most cases. This observation gives some confidence in favour of the hypothesis.
Impact will be less than "do nothing scenario"	There will be less likelihood that migration of pre-existing contaminants will occur if the cavern is backfilled than if a cavern is not backfilled. In this latter case, buoyancy of oil used in the blanket will tend to cause it to migrate towards sensitive domains through the collapse column.
Hazardous nature of the oil blanket	There is some confidence against this hypothesis owing to the fact that residual diesel used in the oil blanket is buoyant and therefore relatively mobile and at the same time is potentially hazardous in small concentrations.
Low-permeability rocks favour containment	The cavern is within and surrounded by low-permeability rocks that will tend to contain diesel used in the oil blanket. The most likely pathway for any diesel migration out of the containment system would be via the brine extraction borehole. Mitigation procedures could appropriately manage the risks arising from this.
Low-permeability material between caverns	Caverns are separated by low-permeability salt. This tends to support a lack of connection (green space).
Pressure responses	Some pressure responses have been measured in some caverns during activities in adjacent caverns. This provides some confidence against this hypothesis. However the nature of

	the response is unclear - it could be a mechanical response of the rock, or a response of the groundwater.
Calculations support limited extent of collapse column	Calculations show that a cavern that is backfilled as designed will not undergo sufficient collapse to connect the cavern to a shallow sensitive domain. However, there is some uncertainty about where the base of these sensitive domains actually lie.
Calculations (2) support limited extent of collapse column	Calculations show that a cavern that is backfilled as designed will not undergo sufficient collapse to connect the cavern to a shallow sensitive domain. There is some uncertainty concerning the design requirements for the backfill to ensure this, and whether the backfill will meet those requirements. Arguably this is a stiffer test, however, than that concerning avoiding unacceptable surface deflection, as cavern migration could occur that does not lead to unacceptable impacts on the surface but does lead to an interaction with a sensitive domain, or another pathway that interacts with that domain. In addition, there is some uncertainty about where the base of these sensitive domains actually lie. Overall, it is considered that the confidence 'for' this hypothesis is similar to its sibling that concerns migration of headspace,
Properties of formations	There is heterogeneity and variability, but in general the mechanical properties of the surrounding rocks tend to act against pathway formation. On analysing mechanical behaviour of formations and collapses that may have already occurred, we have an understanding of the rock properties that provides confidence 'for' this hypothesis, as they indicate the system will stabilise upon backfilling. This is reflected in the current understanding of the 'bulking' factor. However, there must be remaining uncertainty, as we do not have a full understanding concerning why cavern migration has or has not occurred to date in specific cases.
Borehole properties	There is reasonable confidence that boreholes can be effectively sealed, however there is uncertainty concerning the evolution of the seal over the timescales of interest. In addition, there are older wells that intersect the source zone that have already been sealed / blocked. Overall while these features are relatively narrow and, in particular while seal performance lasts, it seems unlikely they will provide a pathway of significance, there is a substantial level of remaining uncertainty.
Borehole seals will degrade over the long term	The boreholes do connect the source zone with sensitive domains (e.g. the surface) and experience of borehole seals across various industries has shown that borehole seals have a

	finite lifetime. Therefore, there is evidence that, at some point in the future, a pathway could exist as a result of seal degradation.
Rock properties	The is no current evidence suggesting that there are fractures or faults that could provide such a pathway at present. Even if faults or fractures do exist, it is plausible, given rock properties, that they might be sealed structures. That is, the evidence that is available supports this hypothesis, but like the sibling hypothesis concerning wells, there is substantial remaining uncertainty.
Formation properties	The formations are of pretty low permeability and unlikely to provide a pathway (n.b. faults and fractures in these formations are covered in a sibling hypothesis). However, there is uncertainty. For example, there is limited data on the Solling Formation.
Hydraulic reöponse of adjacent caverns	One plausible explanation for the observed response of water levels etc. in one cavern following activities in another is that there is a hydraulic connection, indicating the possibility of an interaction that could provide part of a larger pathway. However, the confidence 'against' provided by this argument is not substantial, as there are other plausible causes (e.g. mechanical interactions).
Integrity of cavern floors	The integrity of some of the cavern floors is known to be suspect, and so there is a reasonable expectation of a small risk of connection with other features/pathways through the floors.
Properties of interbeds / formations	The permeability of the interbeds is thought to be low, but there is remaining uncertainty.
Peak head may be in the Muschelkalk	There is substantial uncertainty in this hypothesis in general. However, there is evidence of a high pressure in the Muschelkalk, which indicates a possibility that the pressure gradient might be away from the sensitive domains.
Potential for upwards flow from depth	There is the potential that the high heads in the Muschelkalk are reflective of upwards flows from depth, and thus there is a small amount of evidence that a driving force could exist.
Length of diffusive pathway	There is no evidence that concentration gradients will be substantial, in particular considering the length of the diffusive pathway between the source and the receptor. Therefore, it appears very unlikely that concentration gradients could provide a driving force of any significance across plausible pathways

	given the length of them.
No data	No monitoring data is available to support judgements either for or against this hypothesis.
Expected evolution and other scenarios unlikely to lead to risk to sensitive domains	Calculations have been performed for a range of scenarios. Of these, calculated impacts for the Expected Evolution scenario and a number of other plausible evolutions of the system are below targets over timeframes of interest. These scenarios together represent a reasonably high probability of occurrence. In addition, the calculations are cautiously parameterised, further building confidence 'for' the results.
Lower probability scenarios	A smaller number of the scenarios explored, that together have a lower probability of occurrence than the 'expected' evolution and other scenarios, are associated with calculated impacts above targets during timeframes of interest. The probability of occurrence is low but not negligible, and so this outcome constitutes evidence 'against'. However, it is also noted that the calculations for these scenarios are cautiously parameterised.
Backfill development means limited gas generation post-injection	The main risks of gas generation (H2 evolution) is during backfill mixing. That is, it is considered highly unlikely that significant volumes of gas will be evolved during or following injection. If any gas does evolve, it is unlikely that there will be significant build-up of gas in the cavern, as the boreholes will not be sealed during the operational/monitoring period, and in the longer term gas evolution is increasingly unlikely.
Evidence of gas generation for PFA containing concretes	There is evidence, from other industries in particular, that concrete mixes can lead to gas generation and explosions. There is not very much confidence 'against' on the basis that (as explained in the reasons 'for') any gas evolution for the cavern backfill is expected prior to injection. Nevertheless there remains a very small possibility of some gas evolution post-injection.
Not generating sufficient pressure	It is considered very unlikely that the action of backfilling will lead to generation of a pressure/head gradient of sufficient significance to cause displacement of fluid bodies outside the cavern zone, and thus it is very unlikely that such an interaction will occur and lead to an impact to a sensitive domain.
Geomechanical modelling	Geomechanical modelling shows that it is reasonable to expect that caverns will remain stable for a number of years - sufficient to undertake backfilling.

Acknowledgment of possibility of early failure	The fact that any cavern that is backfilled will be judged unstable raises at least some possibility that failure may occur during backfilling. It is assumed that the probability will be low and will have been demonstrated as such by geomechanical investigations / modelling. The backfilling process causes temperature and pressure changes which , though small, contribute to instability.
Calculations support adequate support following backfilling	The calculations show that for all reasonable bulking factors, once backfilling has been undertaken and the designed residual voidage attained, then sinkhole formation or unacceptable surface subsidence rates will not occur. There is some uncertainty about bulking factors, which explains largely the white space.
Variability in materials used to make backfill	There will be variability in the nature of the materials available to formulate the backfill. This variability contributes to uncertainties in the backfill performance - and hence the white space associated with this hypothesis.
Uncertain hydrogeological properties (rock permeabilities and head gradients)	Perhaps the largest contributor to uncertainty (white space) is a lack of information about hydrogeological properties (rock permeabilities and head gradients) at depth.
Low-permeability rocks favour containment	The cavern is within and surrounded by low-permeability rocks that will tend to contain diesel used in the oil blanket. The most likely pathway for any diesel migration out of the containment system would be via the brine extraction borehole. Mitigation procedures could appropriately manage the risks arising from this.
Pressure responses	Some pressure responses have been measured in some caverns during activities in adjacent caverns. This provides some confidence against this hypothesis. However the nature of the response is unclear - is it a mechanical response of the rock or a response of groundwater.