Preesall Gas Storage Project:
Independent Geological Assessment

Conducted for

DECC

By

Senergy Technical Team

Final Report
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Executive Summary

Planning applications submitted by Halite Energy Group (HEG) for a development consent order for an underground gas storage facility at Preesall, Lancashire have been rejected on separate occasions in 2004 and 2009. The Panel Authority responsible for the application evaluation have on both occasions stated that a 'significant contributory factor was the lack of a single, fully illustrated geological summary and the failure to demonstrate that the development would not present an unacceptable risk of gas migration'. Senergy (GB) Limited (Senergy) was appointed to provide an independent geological evaluation of the most up-to-date model carried by the Applicant and to generate a revised volumetric calculation.

The proposed gas storage project consists of 19 caverns within the Preesall Halite. The caverns are distributed between two separate 'planning polygons' which define the geographic boundaries of the project. The Working gas capacity, as supplied by the Applicant in the Geostock report “Revision of Working Gas Volume”, report no. GKF.0.J.0003, 9th May 2014), is presented as 324 million sm³. (Reports, Section 2.2.1)

A dataset comprising newly-acquired 2D seismic, plus re-processed legacy lines, was supplied by the Applicant, along with an updated geological model built by Geostock, the company responsible for generating the updated Cavern Development Plan and associated volumetric capacity. Borehole geophysical logs were included in the geological model. Previous test data (e.g. pressure test data) and modelling work was re-presented in an updated geological summary report. However, the data that Senergy received was sometimes incomplete or late and delivered in obscure formats. It is not known why this was so. Examples of this are missing or very late arriving log data, no check shot or Vertical Seismic Profile (VSP) data received, improperly formatted seismic data, seismic interpretations at Base Salt with mis-ties, an absence of fault interpretations, and an absence of the intra-salt mudstone interpretation within the geological model; the report is necessarily limited to the data received.

Data coverage within the planning polygons has been much improved by the additional seismic data. A geological model for the basin which shows the key basin-bounding faults and salt boundaries has been generated and provides a framework on which to hang the subsurface data.

In general, the interpretation presented is geologically-reasonable and can be validated by the available geological data down to the top of the salt. However, the Applicant presents only one subsurface model for the project. The Base Salt is not adequately imaged by the new seismic in parts of the proposed polygon areas, and there is no borehole data to confirm seismic picks within the development polygons. For these reasons the interpretation within the development polygons is speculative and unconstrained in the deeper parts of the basin, and this leaves considerable uncertainty in the volumetric calculations. Alternative interpretations, which are equally geologically-valid given the dataset, are presented which illustrate the uncertainty in the subsurface interpretation of Base Salt, and fault presence and distribution in some parts of the basin.

The key risk to the current development plan is that if Base Salt is any shallower than currently mapped, the cavern placement, size, and therefore capacity will be affected; up to 9 caverns lie within 10 m of the current Base Salt interpretation – variation of 10s to 100s metres depth along this horizon may be possible. The alternative scenarios presented by
both this review and the Applicant need to form the foundation of a range of working models that better capture the uncertainty remaining in the subsurface description. This uncertainty in the geological data has been carried forward to the methodology applied within the Volumetric Capacity review. To reduce uncertainty around the Base Salt depth within the cavern development areas, it is necessary to have more Base Salt penetrations or seismic which better images the relevant horizons.

The cavern development plan was reviewed by experts in gas storage developments. While the basic methodology applied to the updated plan is acceptable, several of the criteria used were considered to be somewhat optimistic in the values used. Alternative ranges of values are suggested to again represent the uncertainty in the subsurface.

Senergy has produced a revised volumetric calculation based on its evaluation of the various input parameters and their associated uncertainty. In a base case calculation Senergy estimates Total, Cushion and Working gas volumes of 350, 147 and 203 million m$^3$ respectively. The Working gas volume of 203 million m$^3$ is equivalent to 7.2 bscf so the base case project could deliver 0.6 to 0.7 bscf/d over a 10 to 12 day production period. The sensitivity of these capacities to the uncertainty in eight key parameters was investigated using a Monte Carlo simulation. This analysis indicates a 50% probability of achieving a Working gas volume of 190 million m$^3$, a 90% probability of 124 million m$^3$ and a 10% probability of 258 million m$^3$. There is less than a 2% probability of achieving a Working gas volume of 300 million m$^3$. 

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1 Introduction

1.1 Background

Planning applications submitted by Halite Energy Group (HEG) for a development consent order for an underground gas storage facility at Preesall, Lancashire have been rejected on separate occasions in 2004 and 2009. The Panel Authority responsible for the application evaluation have on both occasions stated that a ‘significant contributory factor was the lack of a single, fully illustrated geological summary and the failure to demonstrate that the development would not present an unacceptable risk of gas migration’ (Updated Geological Summary Report; Mott MacDonald, 2014).

In the most recent Preesall Report Panel Findings to the Secretary of State, paragraph 5.62 summarises the crux of the problem in the 2009 application:

‘Where detailed geological information is available, the Applicant has decided that the halite is too faulted or too close to existing workings to be suitable for safe construction and operation of UGS. However, by the very nature of defining the two proposed cavern development areas by avoiding known geological hazards, the polygons have been located in areas in which there is little geological data. The assumption that the polygon areas are therefore suitable for the cavern construction is based on extrapolation of data in the 3D model, and that the faulting does not extend into these areas. This may be entirely plausible, but in our view will only be confirmed beyond reasonable doubt as further detailed geological surveys are carried out’.

Following the refusal to grant development consent on the most recent (2009) application, the decision was quashed by the High Court in February 2014. The Secretary of State withdrew an appeal and proceeded to re-determine the application. As part of this process, the Secretary of State appointed Senergy (GB) Limited (Senergy) as an Independent Geological Assessor with the role of advising on geological matters pertinent to the application, and to produce this Geological Report.

1.2 Project Scope

The main objectives of this technical study were:

1. To assess content and load the key digital geological information already provided during the Examination and available on the National Infrastructure Planning Portal;
2. To assess and integrate any further geological information submitted to the Secretary of State by interested parties during the re-determination of the application;
3. To produce a Geological Report for the Secretary of State’s consideration;
4. Provide further geological advice as necessary on any further representations received in response to consultation on the Geological Report.

Specific tasks identified at project start-up included:

1. Review current geological information related to storage volumes and site integrity;
2. Evaluate current storage volume assessments by the site developer based on the information provided by them in the National Infrastructure Planning Portal;

3. Load current geological models and seismic data to assess basis for assessment of storage volumes;

4. Load and assess further geological/geophysical information loaded to the National Infrastructure Planning Portal; and

5. Assess and report on the Developer proposed storage volumes (Total, Working, Cushion), taking into account high level geomechanical considerations and major hazards.

1.3 Technical Approach

The current geological model represents the most comprehensive interpretation of the available subsurface data to date. Previous planning applications (submitted in 2004 and 2009) were rejected due in large part to the 'lack of a single, fully illustrated geological summary and the failure to demonstrate that the development would not present an unacceptable risk of gas migration' (Report H30; Mott MacDonald, 2014). The updated database and model are considered to contain the results of over 4 years (January 2010 – May 2014) technical data acquisition and interpretation (see Section 2 for further details). The available data and geological model were transferred to Senergy where an evaluation of the current dataset and interpretation was carried out by a technical team comprising geologists, specialist structural geologists, geophysicists, geomechanics specialists and reservoir engineers. The updated cavern development plan and volumetric capacity calculation were re-assessed in the light of the technical review. The main focus of this review was to ensure the appropriate range of values, given the data available, was used in the capacity calculation; i.e. ensuring any uncertainty in the subsurface knowledge or model is represented.

1.4 National Policy Statement Guidelines

The Preesall Gas Storage project under assessment here falls under the National Policy Statement (NPS) for Gas Supply Infrastructure and Gas and Oil Pipelines (EN-4). The 'Assessment and Technology-Specific Information' (Part 2) of EN-4 provided the basis for the evaluation of the geological model of the subsurface in the area of interest to the project. This was reviewed to ensure that all NPS requirements for an application for development consent are met by the Preesall gas storage project.

The key statements in EN-4 with regard to this evaluation are:

Para. 2.8.1: Underground natural gas storage can take place in porous rock and in salt caverns, both on and offshore.

Para. 2.8.5: There are limitations as to where natural gas can be stored underground due to natural geological constraints. The surface geology influences the extent of the potential gas reservoir and the feasibility of using it for an underground storage facility.

Para. 2.8.7: Natural gas can also be stored in man-made salt caverns. In some areas, Britain has salt present in strata which are, or could be, suitable for gas storage. The most extensive areas, where suitably thick natural layers of salt are found, are in northern England and in smaller areas further south.
Para. 2.8.9: Applicants should undertake and supply [to the Infrastructure Planning Commission (IPC)], a detailed geological assessment to demonstrate the suitability of the geology at the site for the type of underground gas storage proposed. When considering storage in a salt cavity, the geological assessment should include depth below surface, salt thickness, salt purity and presence of shale bands which could affect cavern design. In addition, a study of the geological integrity of the overlying strata and potential for collapse, taking account of the proposed minimum and maximum working pressures, will need to be undertaken. The assessments should include the construction, operational and decommissioning phases and should cover the long term integrity of the affected strata after decommissioning or closure of the facility. The [IPC] will consider the geological assessment alongside the environmental assessment if the former does not form part of the EIS'.
2 Database

2.1 Provision of Data

Data was provided via the HEG technical and legal representatives. Senergy made a data request to Department of Energy and Climate Change (DECC) at project start-up for a data package to include the current geological model and seismic data. The original reports and supporting documentation from the 2009 application were immediately available. Further, updated documentation and technical data were made available as the project progressed (see summary tables below).

2.2 Database

2.2.1 Reports Made Available and Referenced in Text

Several technical reports from both the 2009 application and updated subsurface work programme were made available to this review. Table 2.1 summarises all the written reports provided.

<table>
<thead>
<tr>
<th>Report Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original Documents (2009)</strong></td>
<td><strong>Available at Project start-up (May 2014)</strong></td>
</tr>
<tr>
<td>3.1.1</td>
<td>Appendices part 2: project Overview</td>
</tr>
<tr>
<td>9.2.2</td>
<td>Geological Summary Report</td>
</tr>
<tr>
<td>9.1.6</td>
<td>Construction Report</td>
</tr>
<tr>
<td>9.2.4</td>
<td>Assessment of Brine Well 45 Incident</td>
</tr>
<tr>
<td>9.2.5</td>
<td>Review of Drilling &amp; Completions Programmes</td>
</tr>
<tr>
<td>9.2.7</td>
<td>Seismic Desk Study</td>
</tr>
<tr>
<td></td>
<td>Preesall Report Panel Findings</td>
</tr>
<tr>
<td></td>
<td>Preesall Decision</td>
</tr>
<tr>
<td></td>
<td>Approved Halite Judgement: 17th January 2014</td>
</tr>
<tr>
<td><strong>Updated Documents</strong></td>
<td><strong>Available 14th May 2014</strong></td>
</tr>
<tr>
<td>CR.13.122</td>
<td>Results of an Interpretation of Newly Acquired Seismic Lines over the Preesall Saltfield (BGS): Volume 1 Report</td>
</tr>
<tr>
<td>CR.13.122</td>
<td>Results of an Interpretation of Newly Acquired Seismic Lines over the Preesall Saltfield (BGS): Volume 2 Report Figures</td>
</tr>
<tr>
<td>GKF.0.J.0002</td>
<td>Revision of Field Layout (Geostock)</td>
</tr>
<tr>
<td>GKF.0.J.0003</td>
<td>Revision of Working Gas Volume (Geostock)</td>
</tr>
<tr>
<td>H30</td>
<td>Updated Geological Summary Report (Mott MacDonald)</td>
</tr>
<tr>
<td>GKF_R_J_0001-rev A</td>
<td>Geomechanical Study (Geostock)</td>
</tr>
<tr>
<td></td>
<td>Hay Nook 2 Gas Fracs Test 3 &amp; 4-final</td>
</tr>
</tbody>
</table>
The technical data provided consisted of three key items (Table 2.2) which were made available between 15th May 2014 (Geological Model and spreadsheets) and 29th May (seismic and interpretation).

<table>
<thead>
<tr>
<th>Data Type</th>
<th>File Name/Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological Model in Petrel</td>
<td>Preesall_geological_model_may2014</td>
</tr>
<tr>
<td>Numerical Maps (xyz files)</td>
<td>Base_Salt_v4; Isopach_v4; Top_Salt_v4</td>
</tr>
<tr>
<td>Spreadsheets</td>
<td>GSR Volume Calcs- Three Cases &amp; Volume estimate for Halite</td>
</tr>
<tr>
<td>Seismic Data (migrated stack) &amp; Interpretation</td>
<td>Raw SEGY seismic data files for 13 lines (HEG-13 lines 01 to 08; CAN-97-lines D, E &amp; F; IELP-99-25 and GCE86-DV371)</td>
</tr>
<tr>
<td></td>
<td>Horizon interpretation: TopPH &amp; BasePH; Deeper base_PH</td>
</tr>
<tr>
<td></td>
<td>Fault Interpretation: 50 fault files</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of Report Database

Table 2.2: Summary of the Technical Database

2.2.2 Seismic Data

The seismic data coverage consists of eight recently acquired 2D seismic lines (2013; the ‘HEG’ lines) and five legacy 2D seismic lines. All those seismic lines were processed in 2013 to standardise the seismic imaging across the different 2D seismic vintages. Neither the seismic acquisition nor the seismic processing reports were made available for this evaluation. According to the ascii headers of the SEGY files, the processing sequence used was a very simple post-stack migration sequence.

The newly acquired seismic data added 19.64 line kilometres (km) to the original seismic database, giving a total of 35.34 km of new and re-processed seismic data in the project area (note that only 5.5 km of these new data actually fall within the planning polygons). Seven new dip (E-W) lines plus a single N-S strike line were acquired to supplement the legacy seismic dip lines (Figure 2.1).

2.2.2.1 Seismic Interpretation

Interpretation of the seismic data was limited to picking Top and Base Salt horizons across the basin using checkshot and pseudo-checkshot data to calibrate synthetic seismograms; no further stratigraphic interpretation was carried out. Fault mapping was also carried out on the migrated stack data. The completed horizon interpretations were then contoured and depth-converted in Gocad.

It should be noted that as the Arm Hill #1 borehole did not penetrate Base Salt (see Section 2.2.3 below), a pseudo synthetic seismogram was generated from logs from the Hay Nook #1 borehole. While only 1.1 km along strike from Hay Nook, the variable nature of the base salt...
boundary as seen at Hay Nook and Burrows Marsh, and the presence of a significant syn-depositional fault zone (the Burrows Marsh Fault Zone) which was active during early halite deposition suggests that this tie should be used with care. There are no other constraints on salt thickness in this location to corroborate the Base Salt 'pick' used (ICI exploratory borehole B6 is located within 200 m but no well logs other than a synthetic 'zone' to represent the halite were provided).

Figure 2.1: 2D Seismic Dataset and Key Boreholes with Planning Polygons Overlaid

2.2.3 Well/Borehole Data

Subsurface well data across the area are available from a large database of historical brine-wells, exploratory boreholes and four more recent (2003 – 2009) deep exploratory boreholes in which a broad suite of downhole geophysical logs were run and cores collected for logging and geomechanical analysis. In addition, an older (1974) borehole (the Coat Walls) was re-logged. Several boreholes and wells penetrate the Top Salt horizon, however, of the more recent boreholes, only the deviated Burrows Marsh borehole (located between the two planning polygons) and the Hay Nook #1 borehole (to the south of the southern planning polygon) actually went deep enough to reach the base of the Preeall Halite. This lack of well control is considered to contribute to uncertainty on the accuracy of the Base Salt interpretation in the deepest parts of the basin (i.e. where the salt is thickest).

2.2.3.1 In-situ and Core Test Data

A range of in-situ and core-based measurements have been carried out in the Arm Hill #1 (2004 dataset) and Hay Nook #1 (2009 and 2011 datasets) boreholes to test the
geomechanical properties and permeability of both the Preesall Halite and the overlying mudstones. In addition, a range of downhole permeability and pressure tests were carried out on the Hay Nook #1 borehole. The objective was to test the permeability characteristics of a small fault identified within an intra-salt mudstone. The results and a summary interpretation of these tests are provided in the Updated Geological Summary Report.

2.2.4 Geological Model

The current geological model (as provided; Figure 2.2) is reportedly based on an updated version of that submitted in the previous 2009 planning application. Discussion with the British Geological Survey (BGS) and Mott MacDonald indicated that the geological model version provided for this Senergy review was generated by Geostock as part of their work to develop the updated (2014) cavern development plan. This updated model was built in the industry-standard software package Petrel using the depth-converted Top and Base Salt horizons generated from the BGS interpretation of the newly acquired and the re-processed heritage seismic data. The fault interpretation developed by the BGS during their seismic interpretation was not brought into this version of the geological model. Instead, the faults were built using a ‘fault omission’ approach, using the depth-converted Top and Base Salt horizons. No information as to the methodology used to map the faults between the seismic lines (e.g. fault length) was made available for this current assessment.

![Figure 2.2: Geological Model: Base and Top Salt, Geostock 2014 Fault Model](image-url)

Although originally requested at project start-up, the version of the geological model provided did not contain the 2D seismic data. This was provided at a later stage after a further specific
request for these data was made via DECC. Although data loading proved problematic, the seismic data (in time format) was loaded by Senergy.

In addition to the Top and Base Salt surfaces, the geological model also contains the available borehole data as well sticks and any associated downhole geophysical log data. The log data for the deviated Burrows Marsh borehole were not present in the geological model (a synthetic ‘zone’ to represent the Preesall Halite thickness was present) but the log file and deviation survey was provided towards the end of the project and loaded by Senergy.

### 2.2.4.1 Extent of the Geological Model

The extent of the geological model is restricted to the area of the two planning polygons, north and south (Figure 2.2). The seismically-mapped horizons have been ‘clipped’ to the model boundaries. In order to review the complete seismic database and interpretation, Senergy imported the time data and horizon/fault interpretation into an industry-standard seismic interpretation environment (‘Kingdom’) prior to importing the data into the Petrel-based geological model.

### 2.2.5 Issues with Database

Although the original data request was for the complete geological model (including the seismic data and interpretation used to generate and update the model), the dataset which was ultimately delivered was effectively a subset of separate data items. Seismic and interpretation loading issues took a significant period of time to overcome (the HEG technical team did finally send some useful information to help as they too had had similar issues).

One of the biggest issues with the subsurface data provided was that it did not represent a direct copy of the dataset used by the HEG technical team to interpret the newly acquired and reprocessed seismic data; once all data were loaded to Petrel and Kingdom, it was necessary to carry out QC of the data project to ensure that it appeared equivalent to that presented in the written reports.

#### 2.2.5.1 Missing Data

There are some data items which were not provided or were supplied late in the evaluation:

- Checkshots and/or VSPs were not provided and only few details on the depth conversion method were made available. Consequently, no time-depth tables were provided to allow borehole data to be tied to the seismic;

- The geophysical log data for the Burrows Marsh borehole was provided at a late stage in the project;

- A complete set of formation tops was not provided. Only the interpreted formation tops for Top and Base Salt were provided; no stratigraphic tops for the overburden or deeper (below salt) section were included in the geological model. As such, it was not possible to review or correlate the regional stratigraphy both within the basin and across the major basin-bounding faults (i.e. the Preesall and Burn Naze faults);

- Intra-salt mudstone correlation: The BGS carried out a relatively detailed correlation of the intra-salt mudstones (as shown by Figure 5.6 in the Updated Geological Summary Report H30). These formation tops were not present in the geological
model and no information provided as to how the location and thickness of the mudstones impacted the cavern placement.

- As mentioned in Section 5 of this report, the volumetrics calculation spreadsheets provided by Geostock did not contain the formulae used to generate the reported capacity numbers. In order to assess the methodology and data presented, it was necessary to back-calculate these formulae and validate against the data.

2.3 Data Coverage

As stated in Section 1, the key issue with previous applications was the lack of a comprehensive and integrated subsurface dataset for the planning area. The current planning polygons have reportedly been sited to cover geographic areas that avoid known hazard zones of faults, boreholes and wet rock head and the mining hazards of solution brine wells and dry mining. However, until the new seismic dataset was acquired, the data to support this subsurface model was considered inadequate. The technical assessor for the 2007 Public Inquiry recommended that at least two more seismic lines be acquired and drilling and geophysical logging of boreholes on these lines carried out, ‘to ground’ truth the model (REP170, paragraphs 5.13 and 5.14, REP166, paragraph 3.1.5).

The current subsurface dataset is shown in Figure 2.1 (Fig. 1 in BGS Report CR/13/122). The seismic database provides good regional coverage of both the planning polygons and the surrounding area. Several lines (seven in total) are interpreted to show the location of the western margin of the basin, providing increased confidence in the location of the bounding Burn Naze Fault, although loss of data quality in this area is observed.

Only a single strike line has been acquired to tie all the existing and new dip lines. This line (HEG-13-08) only clips the margins of both the planning polygons. Given the depth range of the salt across the basin, a second strike line could have potentially enhanced the Base Salt interpretation. In some places, this strike line gave some cause for concern as minor mis-ties on the Base Salt horizon were observed (i.e., the ‘pick’ for the Base Salt was placed at a different depth to that on the dip line at the position where the dip and strike lines cross). This was observed in both the Kingdom and Petrel projects generated by Senergy; after following loading advice from the HEG technical team. This serves to emphasise the issue of not being provided with a complete data project: it is unclear as to how this horizon was edited to generate the depth-converted Base Salt surfaces used in the geological model.

Overall however, there is good data coverage across the region; most of the planned cavern locations sit within approximately 200 m of a seismic dip line, however there is a more significant data gap in the southern planning polygon. A 550 m ‘gap’ exists between seismic lines HEG-13-01 and HEG-13-02 (Figure 2.1). This is apparently due to access issues during seismic acquisition as the presence of a tidal channel prevented practicable, safe access, even at low tide. While this is entirely understandable it should be noted that two caverns (Caverns 17 and 18) have been sited in this gap and, while they are still less than 200 m from their nearest line, it is not clear if the access problems will also apply to the required site-specific data collection (i.e. sonar data acquisition prior to cavern development).

Subsurface well data coverage is good in the east of the basin where the halite thins towards the basin margin, but the majority of the wells/boreholes are old and not all wells in the geological model had geophysical data associated with them. Data to the north and west of
the planning area is sparse (or at least, absent in the geological model) and this reduces the ability to 'ground truth' the seismic interpretation.

The more recent (2004 and 2008/9) boreholes do provide good quality geophysical data. This has been used to build an understanding of the salt body geometry and intra-salt character. However, Base Salt has only been penetrated in two of the recent boreholes adjacent to the planning polygons (the deviated Burrows Marsh #1 and Hay Nook #1 boreholes). This is a cause for concern in mapping the Base Salt horizon, particularly in the deeper parts of the basin where loss of seismic resolution is greatest.
3 Geological Model

3.1 Geological Setting

3.1.1 Structure

The data and interpretation presented support the current model of a faulted, asymmetrical basin which trends North-South and is bounded to the east and west by the Preesall and Burn Naze fault zones respectively. The eastern margin of the basin is, however, only picked up on two legacy seismic lines (IELP-99-25 and GASGCE-86-DV371; Figure 2.1). The geological units, which sit below glacial drift deposits, dip in a westerly direction with depth to the top of the Preesall Halite also increasing westwards. The axis of the basin deepens to both north and south from the uplifted Burrows Marsh Fault Zone which forms the north-eastern boundary of the southern planning polygon and the south-western boundary of the northern planning polygon (Figure 3.1).
**Figure 3.1** shows the Base Salt map (in depth) with the interpreted topography at Base Salt level. The planning polygons sit on either side of the uplifted Burrows Marsh area which creates two distinct depositional lows. The more recently-drilled and re-logged boreholes (Hay Nook #1, Burrows Marsh #1, Coats Wall, Arm Hill #1) are also shown.

### 3.1.2 Stratigraphy

#### 3.1.2.1 Overburden

According to the BGS Updated Geological Summary Report (UGSR), the Preesall Halite sits between the younger Breckells and Coat (also spelt ‘Cote’ in some descriptions) Walls Mudstones and the deeper, older Thornton Mudstones, and forms part of the Mercia Mudstone Group. As discussed earlier in Section 2, no regional stratigraphic formation tops were provided to allow evaluation of the enclosing mudstones. The overlying mudstones (Breckells and Coat Walls) are described as forming thick structureless muds and laminated siltstones. This description is borne out by the generally high gamma response seen on the geophysical logs. The package immediately above the Top Salt horizon is seen as a 40 to 50 m thick, overall fining-upwards package of muds and silts. Above this level, the logs appear to become more variable with smaller coarsening-upwards packages interbedded with thinner beds of higher gamma response sediment (**Figure 3.2**).
While no well ties to the seismic were provided (the synthetic seismograms presented in the report only show Top and Base Salt), the seismic data in the area of the planning polygons does appear relatively undisturbed, comprising laterally relatively continuous reflectors across the planning polygons. In the immediate vicinity of the polygons, no significant faulting of the shallow (post-salt) section is observed. However, to the south, it is clear that both Top Salt and the younger mudstones in the overburden are cut by syn-depositional faults (see Figures 11 and 12 in BGS Report CR/13/122).

3.1.2.2 Juxtaposed Strata

The syncline is bounded by two post-depositional faults which have significant displacement along them. The Preesall Fault forms the boundary of the syncline to the east of the planning polygons. This ‘down to the west’ fault juxtaposes the Preesall Halite against the older Sherwood Sandstone. Exchange and migration of fresh (or at least low salinity) ground water between the Sherwood Sandstone and the Preesall Halite is reported and has resulted in some local leaching/dissolution of the salt.

On the western edge of the planning area, the Burn Naze Fault has been mapped on both the legacy and newly acquired seismic. No interpretation of the stratigraphy to the west of the fault was provided, however the fault is thought to sit between two ICI Exploratory boreholes: B1 and E27. No geophysical logs data are available for these boreholes, but the BGS were able to use core descriptions to interpret the stratigraphy either side of the fault (D. Evans, pers comm.). Borehole B1 sits to the west of the mapped fault and penetrates rocks which are older than the Preesall Halite with recent superficial cover (glacial) sitting on top of a sequence of successively older Thornton, Singleton and Hambleton Mudstones and reaching total depth (TD) in the Sherwood Sandstone Group at 473.58 m below ground. To the east of the Burn Naze Fault, the E27 borehole cut through the Coat Walls Mudstone and at least 30 m of the underlying (i.e. older) Preesall Halite. The risk here is that it is possible that the fault juxtaposes Sherwood Sandstone against the Preesall Halite near the base of the salt. While this is not likely to represent a hazard to the gas storage plan in this southerly location, the stratigraphy on either side of the Burn Naze Fault may need to be better characterised in the north of the planning area where the fault is in closer proximity to the planning polygons. Any risk for exchange of fresh or saline fluids across the fault, and the possible impact of this, should be assessed. In the absence of additional data acquisition, further analysis is, however, likely to be difficult as the stratigraphy beneath the Preesall Halite is reportedly difficult to interpret.

3.2 Seismic Interpretation

3.2.1 Data Quality

The quality of the seismic data is considered good down to the Top Salt. Below the Top Salt, the seismic signal becomes less coherent. This has resulted in a degree of uncertainty in the interpretation of the Base Salt pick, the intra-salt character and the deeper, pre-salt stratigraphy. This has the potential to have a major impact on the calculated volumetric capacity of the gas storage project (see Section 5 for detail).

3.2.2 Well to Seismic Tie

The BGS report (CR/13/122) mentions that there are VSPs on the Burrows Marsh #1 and Hay Nook #1 boreholes. This data was not made available to this review and therefore, it was not
possible to review the well to seismic tie carried out by the BGS. Figures 5 to 8 of the BGS report (CR/13/122) show the calibration panels used for the well to seismic tie. The match between the well synthetic response and the seismic data is accurate but rather ambiguous: the last observable pick on the seismic data (e.g. Figure 8 of the BGS report) appears to correspond with the top of the salt while the regional intra-salt mudstones also generate a clear response on the synthetic seismograms, as does the base of the salt. However, neither the regional intra-salt mudstones, nor the base of the salt, are readily observed on the seismic.

3.2.3 Top Salt and Base Salt Interpretation

The Top Salt interpretation in the time domain is considered of good quality with little or no uncertainty. However, the picking uncertainty of the base of the salt is considered to be significant in some parts of the basin since it is not clearly observed on the seismic data away from the shallow boreholes, particularly in the northern polygon area. While the Base Salt interpretation is controlled by the Hay Nook #1 and Burrows Marsh #1 boreholes (which do penetrate Base Salt), away from the well penetrations there is high degree of uncertainty on where the Base Salt sits. Base Salt has also been tied to the seismic using the Arm Hill #1 borehole, however, as previously mentioned, there must be some uncertainty associated with this tie as the borehole reached TD within the halite body.

The BGS Base Salt interpretation (as reported in Report CR/13/122) is repeatedly described as being a ‘conservative pick’, however no further information is presented as to how this particular ‘conservative pick’ was selected. The difficulty in carrying a seismic interpretation around the data grid away from the shallow boreholes is illustrated by the alternative ‘deeper Base Salt’ pick which was interpreted in the northern-most seismic lines. It should also be noted that, while the potential for an increase in salt thickness was discussed (i.e. by moving the Base Salt pick deeper in the seismic section), the converse, or a reduction in thickness, was not considered in the BGS report. Figures 3.3 to 3.6 show equally-viable Base Salt interpretations for four of the newly-acquired HEG-13 seismic lines which honour the borehole data but illustrate the potential for alternative models for the salt distribution and thickness. In each of these new interpretations, the salt has been moved further up in the section. This does not imply that the current interpretation is incorrect, merely that the current Base Salt horizon should be considered as one of a range of possible interpretations.

3.2.4 Depth Conversion and Depth Uncertainty

The VSP data acquired on the Burrows March #1 and Hay Nook #1 boreholes were not made available and it is therefore not possible to quality check (QC) the depth-converted grids. The BGS reports (CR/13/122) that a second-order polynomial equation was used to depth convert the two-way-time interpretation for the Top Salt. Neither the data used to derive the equation, nor the equation itself were made available. Therefore, it was not possible to assess the error on the depth conversion to the top of the salt. It is considered the errors on the Top Salt depth conversion should be small and perhaps in the range of ±2 to ±5%.

To generate the Base Salt depth map, the two-way-time salt thickness was multiplied by the salt interval velocity (estimated to be 4,290 m/sec) to convert it to salt thickness. The salt thickness is then added to the top of the salt depth map to generate the base of the salt map. This depth conversion procedure is considered to be appropriate. Unfortunately, little data, such as the VSP, was provided to justify the workflow and to quantify the error on the depth conversion of the base of the salt.
Based on the limited available data it is considered appropriate that a maximum error of ±12% at the base of the salt in the centre of the syncline (deepest part) should be carried into any volumetric calculation. This error should decrease towards areas of lesser salt thickness (i.e. on the basin margins) where the resolution of the seismic data is improved and better constrained by borehole data. A linear variation on the error was calculated assuming zero error at the location of the shallowest Base Salt cavern (Base Salt at 418 m) to 12% error at the location of the deepest Base Salt cavern (Base Salt at 715 m). This linear error distribution translates to a zero to 25% error in salt thickness, with an average value of 15%. This error should account for the uncertainty in the seismic picking (seismic interpretation) of the base of the salt and the depth conversion errors when applied to the volumetric capacity calculations.

3.3 Faults

‘Identification of the location of any faults is a critical element of understanding the suitability of the Preesall Halite for UGS. Faulting impacts on the integrity of the halite and overlying strata to retain the stored gas as faults can provide gas migration pathways. The location of faults needs to be identified, with confidence, so that the design can ensure that the caverns are constructed at a safe distance from them’ (Panel Report on the 2009 Application).

3.3.1 Post-Depositional Bounding Faults

3.3.1.1 Burn Naze Fault

The position of the Burn Naze Fault, which defines the western margin of the basin, has been a source of some concern in previous geological models. In the 2009 application, the thickness of the halite in this area was increased from the 81 m in the E1 borehole to 220 m on the basis that the borehole had penetrated the Burn Naze fault and the salt was tectonically-thinned (it could also be noted that the same application also stated that the Burn Naze Fault could lie further to the west, i.e. away from the E1 borehole, which suggests that some significant uncertainty in the salt thickness in this area should have been carried in the model).

The newly-acquired HEG-13 lines have successfully delineated the position of the Burn Naze Fault Zone showing it to lie further to the west than previously mapped and is currently well to the west of the southern polygon. The fault zone sits closer to the northern polygon, with the most easterly fault showing some displacement sitting within 100 to 150 m of Cavern 1. An alternative interpretation of the Burn Naze main fault is also shown in Figure 3.6, showing the fault as a possible detachment. Salt thickness in the E1 borehole is shown to be correct suggesting the salt thins quite significantly onto the western margin of the basin.

A brief review of the seismic data to the south of the planning polygons also suggests that there may be some post-depositional inversion and reactive salt movement (line CAN-97-F). This interpretation is not currently carried by the geological model but should be considered further if the project should proceed.

3.3.2 Syn-Depositional Faults

The lack of coherent seismic signal below Top Salt makes delineating the syndepositional fault pattern responsible for the change of thickness of the salt very difficult. Given the lack of
image at the base of the salt level, it is not even possible to determine whether or not the current seismic spacing is sufficient to map all key geological features.

As with the ‘conservative’ Base Salt horizon pick, the current interpretation is stated to be a worst case scenario with the potential that ‘an alternative interpretation may not recognise such structures [faults], or further data may prove faulting to be absent or of lower magnitude’ (BGS Report CR/13/122). Again, the potential for additional faults (both sub-seismic or missed due to poor seismic resolution) to be present is not carried into the final geological model.

The seismic data and current interpretation was evaluated by a structural specialist with over 23 years experience and an industry expert in salt basins. The main points are:

- Several alternative, equally viable structural interpretations are possible within the constraints of the relatively low resolution seismic data and locally sparse well ties;

- There are scenarios (illustrated semi-schematically in Figures 3.3 to 3.6) where Base Salt can be interpreted to be considerably more shallow than the BGS ‘conservative’ pick – this will significantly impact cavern placement and volumetrics as differences (cf. The BGS conservative case) in Base Salt depth are locally of the order of >100 milliseconds two way travel time (10s to hundreds of metres depth); and

- Alternative fault linkages and new fault interpretations are also reasonable and may affect cavern placement.

These or equivalent scenarios need to form the foundation of a range of working models that better capture the uncertainty remaining in the subsurface description.
Figure 3.3: Line HEG-13-01 Alternative Base Salt and Fault Interpretation

Alternative Base Salt and fault geometries within Southern Polygon: dashed orange line is alternative Base Salt, red are alternative faults/linkages thereof – other horizons and faults from BGS interpretation.
Figure 3.4: Line HEG-13-02 Alternative Base Salt and Fault Interpretation

Alternative Base Salt and fault geometries within Southern Polygon: dashed orange line is alternative Base Salt, red are alternative faults/linkages thereof – other horizons and faults from BGS interpretation.
Figure 3.5: Line HEG-13-03 Alternative Base Salt and Fault Interpretation

Alternative Base Salt and fault geometries within Southern Polygon: dashed orange line is alternative Base Salt, red are alternative faults/linkages thereof – other horizons and faults from BGS interpretation.
Figure 3.6: Line HEG-13-07 Alternative Base Salt and Fault Interpretation

Alternative Base Salt and fault geometries within Northern Polygon: dashed orange line is alternative Base Salt, red are alternative faults/linkages thereof – other horizons and faults from BGS interpretation.
3.4 Intra-Salt Stratigraphy and Composition

3.4.1 Mudstone Content of the Preesall Halite

Log analysis of the borehole data is considered by the BGS to show that the intra-salt stratigraphy of the Preesall Halite is well-developed and predictable across the planning area. Six ‘hallitic mudstone’ interbeds have been recognised with average thickness varying between 0.5 and 4.2 m. The deepest mudstones are only present within the lowest parts of the basin where earliest deposition took place. These clastic-dominated horizons represent distinct events in the depositional basin, bringing clastic material in and interrupting the precipitation of the salt. Correlation of the six distinct mudstone units by the BGS suggests a level of regional correlation across the planning area, and possibly over a much greater area. No additional data have been presented to prove this correlation (e.g. through time markers which support the geologically syn-depositional nature of the mudstones) but, given the environment of deposition it is not unreasonable to assume continuity of the thickest mudstones across the immediate area away from the borehole control. The approach taken to extend the mudstones across the planning area is appropriate and would generate a geologically-reasonable map of the intra-salt mudstones. However, given the absence of the mudstone correlation in the geological model, it is not clear how this information was used in the placement of the caverns; the cavern placement cross-sections do not show the intra-salt mudstones.

The BGS has carried out a detailed evaluation of these mudstones to better understand their composition and impact on cavern development. This included geophysical logging, core logging, geochemical analysis (XRD and wet chemical) and geomechanical (in-situ and core-based) data collection. Data were collected from both the Arm Hill #1 and Hay Nook #1 boreholes. No data have been seen from any work carried out on the Burrows Marsh borehole. Qualitative comparisons of the Arm Hill #1 borehole gamma ray log with those from the Burrows Marsh and The Heads boreholes suggest that the Arm Hill #1 borehole can be considered representative of the intra-salt character across this southern part of the basin.

Geophysical logs and core logging from the Arm Hill #1 borehole (which is fairly central to the planning areas) suggest that halitic mudstones form between 4 and 12% of the total salt body. Given the depth range of the halite (using the salt isopach (thickness) from the geological model), this equates to 3.6 m mudstone at the 4% level in the thinnest sections, to 40 m at the 12% level in the thickest salt section. This range of values becomes important in the volumetric calculations (Section 5).

3.4.2 Insoluble Content of the Preesall Halite

The insoluble content of the salt body is important to understand to allow for the reduction in cavern volume after construction. The analytical data suggest that between 5 and 21% of the combined salt and mudstone is effectively insoluble. The majority of this is derived from the halitic mudstones. The halite itself has been split into Upper and Lower sections with the lowest sections being significantly more pure (with respect to insoluble content) than the upper section (<1% insoluble material in the Lower compared with 2.5 – 8.5% in the Upper section). As these measurements are based on core data, these values are assumed to represent only the salt section (i.e. minus the mudstones). Again, this range of values needs to be carried into the volumetric calculations as the caverns are sited throughout the Preesall Halite body.
All the data presented for the intra-salt composition are derived from the original 2009 application; no further work appears to have been carried out. In the review of that application, the Panel Authority supported this interpretation of the mudstones stating that 'the purity of the halite and mudstone interbeds do not present an issue with regard to cavern design...'. However, it should be emphasised that the final cavern design will have to take site-specific data into account and this may impact final capacity.

3.5 Gas Tightness

The risk of gas migration out of the storage caverns has been assessed using a combination of the in-situ permeability and pressure testing, core and log analysis and the updated geological model. Both the overburden and the Preesall Halite (including the intra-salt mudstones) have been tested to derive static formation pressure, hydrofracture pressure and, at Hay Nook, the gas threshold pressure and re-fracture pressure. Initial testing at the Arm Hill #1 borehole was carried out in 2004 with two further phases of testing at the Hay Nook #1 borehole in 2009 and 2011. The 2011 test phase was a repeat to check the anomalously low sub-static pore pressures.

The test site selection covers the key risk elements (with regard to gas migration) of the gas storage sites: multiple tests were taken in both boreholes within the overburden mudstones, the clean Preesall Halite, and two of the regionally-mapped mudstones. The results indicate that the permeability and fracture pressures of both the salt, intra-salt mudstones and the overburden mudstones are sufficiently low to reduce the risk of gas migration through capillary migration.

3.6 Impact of Wet Rockhead and Wild Brine Runs

No further technical appraisal of the potential impact of wet rockhead or wild brine runs from historical workings has been undertaken since the 2000 application. The cavern design rules proposed by the Applicant site new caverns at least 4 Radii (R) from mapped wet rockhead areas and 5R from former brine caverns of unknown shape and any brine run that may be connected to it (REP207, paragraph 5.47). This approach was accepted by the Panel Authority for the 2009 application and if applied as stated should not impact the cavern design.

3.7 Summary

A significant volume of subsurface data has been acquired and assembled to generate the most up-to-date subsurface model of the geology in the project area. The newly acquired seismic dataset has provided a basin framework on which to hang the borehole log and test data. Data coverage is reasonable and provides a number of seismic-to-well tie points around the basin.

The geological model is (as provided), however, somewhat simplistic. The lack of any regional stratigraphic interpretation, other than Top and Base Salt, prevents any evaluation of the geology beyond the immediate planning area. The lack of ties to deeper geological formations also hinders the structural interpretation at and below Base Salt.

Overall, the interpretation of the subsurface dataset appears to be valid, given the data coverage. The conclusions derived from this interpretation are also broadly acceptable. However, the model presented – and used by Geostock as the basis for the updated Cavern
Development Plan (see Section 4) can only, and should only, be considered as one single realisation of the subsurface. As discussed in Sections 2 and 3, there is some significant uncertainty with key elements of the geological interpretation, most notably the Base Salt interpretation and fault model. The former has a major impact on cavern placement. If Base Salt is moved upwards by even 10 m, up to nine caverns may be impacted as they sit within this distance of the Base Salt surface in the geological model.

The key risk to the current development plan is that if Base Salt is any shallower than currently mapped, the cavern placement, size and therefore capacity will be adversely affected. The alternative scenarios presented by both this review and the BGS (e.g. the ‘deeper’ Base Salt pick) need to form the foundation of a range of working models that better capture the uncertainty remaining in the subsurface description.

This uncertainty in the geological data has been carried forward into the Volumetric Capacity review in Section 5.
4 Cavern Development Plan

Since the 2009 application, an updated cavern development plan and working capacity calculation has been developed using the updated geological interpretation of the subsurface. Part of the scope of work (Section 1) for this project was a brief review of the geomechanics studies and impact on the cavern development plan. As such, the appropriate documents were reviewed in some detail by KBB Underground Technologies (KBB UT), Germany who are technical experts in this area and who were brought in to complement the Senergy technical team. The following section contains excerpts from their review report which highlights the focus of their work and the key comments resulting from that review. The full report is contained in Appendix 1 of this report.

Information about the conceptual design work of Geostock was provided by Senergy by the following documents:

- Halite Energy Gas Storage, Preesall Gas Storage Project, Revision of Cavern field Layout, Report GKF/0/J/0002

At the request of the Senergy technical team, KBB UT was asked to undertake the following pieces of work:

- Evaluation of the general cavern development methodology (procedure);
- Evaluation of the applied design/assessment criteria and their appropriate limiting values with regard to safety and tightness as well as reliability (risk); and
- Risk assessment on realising the intended storage volume.

It should be noted that KBB UT had only a restricted time window in which to review the available reports and therefore only criteria identified in the report were addressed and the consequences for possible changes in the design or the risk potential can only be stated qualitatively. A quantitative statement affords sufficiently more effort.

4.1 General Methodology

4.1.1 Applied Procedure

The Geostock conceptual design study relies on the updated geological site characterisation that was made on the basis of 2D seismic surveys, as interpreted by the BGS. The resultant maps for top of salt, bottom of salt and salt thickness were used for setting cavern locations in combination with design rules which consider:

- minimum salt roof above the cavern;
• minimum length of the cavern neck (distance between last cemented casing shoe and cavern roof);
• minimum salt bottom below the cavern;
• minimum salt pillar thickness between caverns;
• cavern roof and sump development;
• minimum distance to fault zones identified in the rock layers above and below the salt section; and
• definition of three different generic-type caverns in order to adjust cavern to geological boundary conditions.

In order to estimate the possible volume of the cavern that can be used for gas storage, the following de-rating factors were taken into account:

• leaching factor describing the percentage of volume that can be leached within the designed shape;
• loss of leached volume by the settlement of insolubles (percentage of insolubles and bulking factor); and
• a reduction of the leached net cavern volume due to brine being unavailable due to debrining.

Cavern storage capacity was calculated based on coupled thermodynamic/rock mechanic simulation models in order to recommend minimum and maximum cavern pressure and limiting withdrawal/injection rates. Intercalated non-salt layers within the cavern section as well as non-salt rock layers above and below the salt section were considered by the simulation models. Initial rock mass stresses were calculated due to the assumption of average densities for the non-salt layers (2.5 t/m³) and the salt (2.26 t/m³).

Assessment criteria in order to recommend these layout parameters consider stability and tightness of the caverns. Generally accepted software (SCTS for thermodynamic modelling and ABAQUS for coupled thermo-mechanical modelling) was used. The studied load case considers an operation time period of about 20 years.

Based on the conceptual design and layout it was assessed that the proposed daily withdrawal/injection capacity of 1 bscf/d is feasible with 19 caverns for a period of 12 days.

4.1.2 Evaluation of Methodology

The overall methodology (procedure) for the conceptual design can be considered as ‘state of the art’ and therefore appropriate. However, the following constraints have to be noted:

• It is stated that the geological site characterisation takes into account a conservative approach by the BGS, but the remaining degree of uncertainty in determining the top and bottom layer of the salt is not mentioned. According to Senergy this uncertainty can be up to 10% [due to a shallower Base Salt]. This does not mean that KBB UT
doubts the specialists of BGS, but consider that this uncertainty will reduce available salt thickness and therefore cavern volume.

- The applied design parameters for cavern location and field design do not consider minimum distances to the boundaries of the concession area. This may be possible due to local legislation, but should be proven. In other countries this is not common practice.

- For the determination of the net leachable volume an average leaching factor is adopted, but it is not mentioned how this factor is influenced by the intercalated non-salt layers.

- It remains unclear whether the applied values for insolubles as well as for the rock mass densities rely on site specific data or on general assumptions. The amount of insolubles influences the feasible cavern volume, whereas the density profile has an impact on the limiting cavern pressures.

- The conceptual design study considers the leaching phase, gas first fill and storage operation period. Worst case scenarios during operation (e.g. blow out) as well as cavern abandonment are not addressed in the information provided. In particular, the blow out case may afford additional pillar thickness as well as salt above the roof and below the sump. The blow-out case is considered to ensure cavern stability even if the cavern pressure was reduced to atmospheric by accident.

KBB UT screened the criteria applied to the cavern design and layout, and the volumetric calculations and presented their evaluation of each. These are tabulated in the KBB UT report in Appendix 1. In general, their review suggests the criteria applied range from realistic to overly optimistic. Section 5 discusses this evaluation in more detail and applies their comments to the updated volumetric calculation.

### 4.1.3 Assessment of Geomechanical Simulation Results

The performed thermodynamic/rock mechanic simulations form the basis for the estimate of the withdrawal/injection potential of the designed caverns. An essential parameter for this estimate is the working gas volume that is mainly determined by the minimum and maximum cavern pressure. Due to the assessment of Geostock in the geomechanical study, the minimum cavern pressure should be raised to 0.07 and 0.08 bar/m (Type I and III caverns respectively). However, it seems that this assessment relies on salt dilatancy strength data which were taken from the literature. This has to be checked against site-specific material data in the future in order to prove that these recommended minimum cavern pressures will still be valid.

There is a mismatch in fulfilling the ‘No Tensile Criterion’ during cyclic operations. If this criterion is strictly followed, the pressure rates have to be reduced, which results in a decline in delivery potential. Internationally-accepted rock mechanical experts do not have a unique view upon the issue whether thermally-induced cracks propagate over time.

The tightness of the intercalated mudstone layers within the cavern section is not explicitly assessed. This may lead to a reduction of the maximum cavern pressure. So far, to KBB UT’s knowledge, only cores have been tested in the lab and some specific field test results
from boreholes. It should be checked, if and how these test results can be applied for the Preesall gas storage project, especially to caverns showing maximum diameters of 100 m.

4.2 Additional Risk Factors

KBB UT also identified a number of possible additional risks which may influence the storage potential:

- **Loss of integrity of the last cemented casing:** The cementation of the last cemented casing string has to be carried out extremely carefully, otherwise the cavern well will be not gas tight and not suited for gas storage. While repairing of the un-tight [poor] cementation may be possible, this is a costly procedure.

- **Loss of integrity of the cavern caused by fractures in the salt deposit:** The Preesall salt deposit is influenced by faults that can be identified in the overlying and underlying strata. These faults may have generated fracture systems in the salt and may be “touched” during the cavern construction. They are deemed to be closed by salt crystals and tight to brine, but maybe not to gas at high pressure. This implies a possible risk to lose a cavern.

  o Regarding the total number of 19 caverns, the risk is estimated to represent a loss of 1 to 2 caverns caused by loss of integrity of the cementation or salt fractures.

- **The cavern section is intercalated by non-salt layers (mudstones):** Even though it can be assumed from similar locations in Cheshire that these mudstone layers are gas tight due to salt impregnation, or because of consolidated conditions, a risk to gas tightness remains unless in-situ tests are successfully performed for each specific location. Due to these test results there may be a need to reduce the maximum cavern pressures. It is noted that the tests carried out at Arm Hill #1 and Hay Nook #1 boreholes indicate that gas migration via the intra-salt clastic layers is not identified as a major risk.

- **Frequent gas injection and gas withdrawal:** It is planned to operate the caverns at frequent gas injection/withdrawal cycles, so called “huff and puff” operation. This means frequent pressurisation/depressurisation of the cavern. The contour stability and tightness may be affected. Finally this may reduce the cavern lifetime. Because the “huff and puff” operation is a relatively recent development, no little long term experience is available of this type of cavern operation.

4.3 Summary

It can be stated that, in general, the methodology applied by Geostock in the Conceptual Design Study is appropriate. However, it also implies some uncertainties that will influence the predicted storage potential in terms of daily withdrawal and injection volumes. Main items related to the general cavern design, which were identified by KBB UT in this brief Third Party review, are the following:

- The degree of uncertainty in the geological model is not stated, although it is stated that the conservative BGS approach is applied. The degree of uncertainty in terms of minimum salt thickness could be provided in order to enable a conservative estimate.
• With regard to all safety dimension of the main load bearing elements it should be taken into account that maximum diameters of 100 m for gas storage cavern are state of the art but also at the upper boundary of experience.

• Possible cavern volumes were calculated by Geostock using a relatively optimistic value for the leaching factor and slightly optimistic values for the bulking factor (the average insoluble content could not be checked by KBB UT). Taking into account the assumed leaching factor of 85% alone, it can be assumed that the cavern volume available for gas storage will be reduced by about 15%. If the bulking factor turns out to be slightly higher, then this reduction may increase, possibly up to 20%.

• Minimum dimensions of the main load-bearing elements in the salt should be slightly increased. With regard to the salt roof and bottom this will lead to smaller cavern volumes. How the revised salt pillars will influence the feasible storage volume depends on the field layout.

• The local rules with regard to minimum distances of the caverns from the boundaries of the concession area have to be clarified. This may affect a number of caverns.

Apart from the cavern volumes which are estimated by the proposed design, working gas volumes are restricted by thermodynamics and rock mechanical constraints in order to guarantee long-term stability tightness and deliverability:

• Convergence effects seem to be negligible according to the simulations of Geostock, but will have to be checked with future observations. Convergence reduces the storage volume over time (and creates surface subsidence).

• Required minimum cavern pressures may be slightly higher than proposed by Geostock (as already indicated in the Geomechanical Study) in order to sustain long-term stability of the cavern contour.

• Although the calculated maximum pressure rates of about 5 bars/d are relatively moderate, the coupled thermo-mechanical analysis shows thermally-induced fractures in a small zone of up to 2 m behind the cavern wall. If it cannot be proven that these fractures will not grow during operations, and that the cavern contour stability and tightness is not impaired by this occurrence of thermally-induced fractures, the permissible pressure rate (mainly the gas withdrawal rates) has to be reduced, which will impair the maximum daily rate but not the overall working gas volume.

4.4 Subsidence Modelling

The procedure for subsidence modelling is summarised in the Updated Geological Summary Report as follows:

• Processes involved are described by creep closure and roof failure

• SaltSubsid is applied for modelling
• Poor cavern design must be avoided, thus only wide area subsidence is relevant for newly-built gas storage caverns, but old ‘unstable’ caverns have to considered in subsidence prediction

• Different kinds of subsidence – wide area (normal) and special point subsidence (due to sinkholes) – are addressed

• The need for on-going monitoring and extension of the existing levelling grid is addressed

• Observations of the existing ICI caverns should be incorporated

• Improvement of the subsidence model by history matching and coupling of subsidence modelling and rock mechanical modelling is indicated

The presented procedure can be considered as state of the art. However, if the project proceeds, the ‘ifs’, ‘buts’ and ‘shall’ in the procedure must be considered accurately. Two special items need a detailed review:

• The assumption of input parameters for subsidence modelling; and

• The consideration of safety distances between existing but unstable/collapsed caverns and newly-planned caverns for gas storage.

4.4.1 Evaluation of Input Parameters for Subsidence Modelling

It is stated that a cavern convergence of 0.01% per year is assumed according to a RESPEC Report in 2005. Basically cavern convergence mainly depends on cavern depth, difference between lithostatic and cavern pressure (e.g. operation period at minimum pressure), creep characteristic of the salt, rock mass temperature, and cavern shape. As caverns are located at different depths, this should be considered in subsidence modelling. The characteristic value is, therefore, the representative rock mechanical depth (not casing shoe depth), which can be assumed at ⅔ of the cylindrical height, or at mid depth for spherical caverns.

Cavern closure rate is assumed to be 0.01%/year. Compared to the geomechanical study of Geostock (2014), cavern total convergence is calculated at about 0.5% after 25 years of operation. This would result in an average rate of 0.02%/year, which appears to contradict the assumption made in the subsidence prediction. The assumed convergence rates should be based on assumptions that are specific to the location (material properties, cavern depth, pressure history, etc.).

4.4.1.1 Consideration of Existing Unstable Caverns

It is mentioned that the planned new gas storage caverns are partly in the neighbourhood of existing but partly unstable caverns, where the salt cover in the roof turned out to be too small. The minimum required salt pillar between cavern wall contours of the newly planned gas storage caverns and those old caverns is assumed to be 4 times the maximum radius of the two adjacent caverns. This required that a minimum distance is already mentioned in earlier studies. If pressures in these ‘collapsed’ caverns cannot be maintained at brine-fill level, the pillar stresses will increase and thus (although stability is not impaired) may influence the convergence rate of the adjacent gas storage cavern(s).
4.5 Conclusion

The general procedure for subsidence modelling follows state of the art concepts. A rough check with data from other locations shows that assumed values for convergence rates are within the range of experience. However, assumed model parameters have to be compared to measurements and observations. Compared to the results of the Geomechanical Study, the Geostock-assumed convergence rates in the subsidence prediction are lower.
5 Volumetric Calculation

5.1 Comments on Geostock’s Calculation (Report GKF.0.J.0003)

Senergy was provided with an Excel spreadsheet showing the results of Geostock’s revised volumetric calculation (volume estimate for Halite.xlsx - with internal date stamp SALT CAVERN DESIGN, HEG - PREESALL - BGS SEISMIC, 02.05.2014 - REV4). This was a ‘dead’ spreadsheet only containing numbers, i.e. without any formulae. An alternative ‘live’ version with the embedded formulae was requested but this was not provided quoting IP issues. Consequently, Senergy has produced a ‘live’ version of the Geostock spreadsheet principally by adding the relevant geometric formulae and incorporating a gas properties calculator.

In the course of doing this it was noted that the value of the height of the stack of insolubles in column BX is used to correct the depth of the base of the cavern for the calculation of the mid depth (column DI) and 2/3rds depth (column DJ). However the correct height for the stack of insolubles (by the Geostock evaluation method) is in column DB. But the Geostock method does not take into account the fact that the actual leached volume is smaller than the geometric volume so the height of pile of insolubles should be higher than the Geostock estimate.

Also, it appears that gauge pressures (depth multiplied by pressure gradient) have been used to evaluate gas properties (density to correct pressure with depth in columns DO and DV and z-factor evaluation in columns DP and DX) rather than absolute pressure (add 1.01325 bar to gauge pressure). Z-factor is correctly calculated at surface conditions in column EO.

In a number of columns (for example CC, CE, CF, CG, CH and CI) the numbers have been rounded to the nearest 1,000 m$^3$ which makes a difference of typically ±1% compared to the actual volumes so it wouldn’t be expected that the Senergy regeneration of the Geostock spreadsheet would produce exactly the same answers.

KBB UT in their report (Section 4 and Appendix 1) noted that a single pressure gradient of 0.06 bar/m has been used as the minimum pressure gradient, whereas Geostock’s geomechanics study concluded that this should be varied by cavern type. Strictly the value of 0.06 bar/m applies for Type II caverns; 0.07 bar/m should be used for Type I caverns and 0.08 bar/m for Type III caverns. Type I caverns ar those that have >750,000 m$^3$ usable volume, Type III caverns <380,000 m$^3$ usable volume with Type II caverns being all values in between.

Rows 2 and 3 in Table 5.1 show the original Geostock volumes of Total, Cushion and Working gas and the amount calculated using the Senergy recreation of the ‘live’ spreadsheet. The results are the same to within ~0.5%. Rows 4 to 6 in Table 5.1 show additional results making adjustments in relation to the points mentioned above. The main effect is a reduction of ~10% in the working gas volume when the minimum pressure gradient is varied by cavern type
<table>
<thead>
<tr>
<th>Case</th>
<th>Total (million m³)</th>
<th>Cushion (million m³)</th>
<th>Working (million m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geostock original</td>
<td>537.0</td>
<td>212.6</td>
<td>324.3</td>
</tr>
<tr>
<td>Senergy recreation of Geostock calculation</td>
<td>538.3</td>
<td>212.8</td>
<td>325.5</td>
</tr>
<tr>
<td>Using absolute pressure in property evaluation</td>
<td>546.9</td>
<td>220.9</td>
<td>326.0</td>
</tr>
<tr>
<td>Plus correction to insolubles pile height</td>
<td>546.4</td>
<td>216.1</td>
<td>330.3</td>
</tr>
<tr>
<td>Plus vary minimum pressure gradient by cavern type</td>
<td>546.4</td>
<td>248.9</td>
<td>297.5</td>
</tr>
</tbody>
</table>

Table 5.1: Senergy Recreation of Geostock Calculation of Total, Cushion and Working Gas Volumes

5.2 Senergy Estimate of Total, Cushion and Working Gas Volumes

Further to this, Senergy has produced a more substantial revision of the volumetric calculation and the associated uncertainty. This is based on Senergy’s own evaluation of the interpreted seismic, borehole logs and the geological model, together with consideration of the implication of KBB UT’s comments and recommendations on the Geostock reports.

Table 5.2 lists the parameters involved together with the values used in the Geostock volumetric calculation, KBB UT’s views and recommendations regarding these values (where provided), the values used in Senergy’s revised base case calculation and the ranges of values investigated in Senergy’s sensitivity study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Geostock</th>
<th>KBB UT comment and recommendation</th>
<th>Value used in Senergy base case</th>
<th>Range investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Salt pick</td>
<td>Used BGS picks</td>
<td>No comment</td>
<td>BGS picks</td>
<td>Zero uncertainty at shallowest pick (418 m) up to ±12% at deepest pick (715 m). The effect of this is a variation in sand body thickness at the cavern locations from zero to ±25% with an average variation of ±13%</td>
</tr>
<tr>
<td>Minimum distance between caverns</td>
<td>1.4 x average diameter of adjacent caverns (range of diameters 60 to 100 m)</td>
<td>Optimistic. In discussion with Senergy on 23/6/14, KBB UT recommended 1.5 x average diameter (in line with Prof Rokahr’s recommendations)</td>
<td>1.5 x average diameter. Implemented by reducing diameter of caverns slightly with centre points remaining the same (range of diameters now 57.9 to 100 m - no caverns were increased in diameter)</td>
<td>Not varied</td>
</tr>
</tbody>
</table>

### Minimum height of cavern neck

- **Effectively 5 to 15 m depending on cavern diameter**
- **15 to 25 m or effectively 0.5 x cavern radius**
- **0.5 x cavern radius**
- **Not varied**

### Minimum salt roof above caverns

- **1 x cavern radius**
- **Realistic but check stability of overburden layers.**
- **In discussion with Senergy on 23/6/14, KBB UT recommended up to 1 x cavern radius above top of neck**
- **Used 0.75 x cavern radius above top of neck (gives offset from top salt to top of cavern of 1.25 x cavern radius or 36.2 to 62.5 m)**
- **Not varied**

### Minimum salt below caverns

- **0.2 x cavern radius or 5 to 10 m (except caverns 14, 16, 18 and 19 where special conditions applied and offset is 50 to 180 m)**
- **Optimistic. Increase limiting value**
- **0.5 x cavern radius giving offsets from 14.5 to 25 m (except caverns 14, 16, 18 and 19 where current offset maintained)**
- **Not varied**

### Roof and sump

- **Cone with 20 deg angle at top and 35 deg angle at base**
- **Domal shape leads to better stress conditions**
- **Retained cones as proposed by Geostock (20 deg angle at top and 35 deg angle at base).**
- **It is recognised that a dome shape gives a better load distribution but with cavern H/D relatively low (0.7 to 2.5) only relatively flat domes could be accommodated**
- **Not varied**

### Shape factor (actual irregular leached volume/geometric volume)

- **85%**
- **Too optimistic. Recommend 70%**
- **75%. Senergy has raised this somewhat from the KBB UT recommendation as the intended geometric volumes have already discounted the volume lost by incorporating the cones into the planned geometric shape**
- **60 to 90%**

### Amount of insoluble mudstone

- **27 m average thickness which represents between 8 and 30% of salt column thickness at caverns (typically ~15%)**
- **Check against site specific values**
- **8%**
- **4 to 12%**

### Insoluble material bulking factor

- **1.5**
- **Optimistic. Increase to 1.8 to 2**
- **1.9**
- **1.4 to 2.4**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remaining brine after first gas fill</td>
<td>2%</td>
<td>Realistic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Insoluble content of salt layers</td>
<td>6%</td>
<td>No comment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble content of interbedded mudstone layers</td>
<td>50%</td>
<td>No comment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum pressure gradient at casing shoe</td>
<td>0.185 bar/m</td>
<td>Safety margin not addressed and no consideration of near fault areas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.185 bar/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum pressure gradient at 2/3 cavern depth</td>
<td>0.06 bar/m</td>
<td>Point out that this should strictly be 0.07 bar/m for Type I caverns and 0.08 bar/m for Type III caverns. The value 0.06 bar/m is for Type II caverns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Used these values with Type I caverns taken as &gt;750,000 m3, Type III &lt;380,000 m3 usable volume; cavern Type II all values in between</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not varied</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavern temperature at maximum inventory</td>
<td>30 degC</td>
<td>No comment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavern temperature at minimum inventory</td>
<td>10 degC</td>
<td>No comment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas composition (mol%)</td>
<td>C1 87.22, C2 5.66, C3 1.73, C4 0.61, C5 0.17, C6 0.08, CO2 1.4, N2 3.13</td>
<td>No comment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas migration arising from poorly sealing salt fractures or cementation of final casing string</td>
<td>100% possibility of success</td>
<td>Total loss of 1 or 2 caverns</td>
</tr>
</tbody>
</table>

Table 5.2: Consideration of Parameters Involved in Total, Cushion and Working Volume Calculation

The results of Senergy’s revised base case volumetric calculation using the parameter values specified in Table 5.2 (column 4) are shown in Table 5.3. Note that the coordinates of the centre points of the caverns, and the Top and Base Salt depths are unchanged. Compared to the GeoStock calculation as supplied, the Working gas volume has decreased by 37% to 203 million sm³ or 7.16 bscf. With a withdrawal period of 10 to 12 days, this would imply a maximum daily rate of 0.6 to 0.7 bscf/d rather than the planned 1 bscf/d.
<table>
<thead>
<tr>
<th>Cavern</th>
<th>Diameter (m)</th>
<th>Ratio P/D</th>
<th>Top cavern (m)</th>
<th>Base cavern (m)</th>
<th>Geometric volume (m³)</th>
<th>Probable usable volume (m³)</th>
<th>Total gas (million sm³)</th>
<th>Cushion gas (million sm³)</th>
<th>Working gas (million sm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.9</td>
<td>1.50</td>
<td>363.8</td>
<td>403.7</td>
<td>51,024</td>
<td>27,176</td>
<td>2.0</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>96.5</td>
<td>1.51</td>
<td>408.7</td>
<td>498.3</td>
<td>404,646</td>
<td>215,520</td>
<td>17.7</td>
<td>7.6</td>
<td>10.1</td>
</tr>
<tr>
<td>3</td>
<td>62.4</td>
<td>1.50</td>
<td>359.5</td>
<td>413.2</td>
<td>96,743</td>
<td>51,527</td>
<td>3.7</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>80.0</td>
<td>1.66</td>
<td>383.8</td>
<td>436.0</td>
<td>119,852</td>
<td>63,835</td>
<td>4.9</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>5</td>
<td>95.0</td>
<td>1.51</td>
<td>406.0</td>
<td>486.2</td>
<td>328,936</td>
<td>175,196</td>
<td>14.3</td>
<td>6.1</td>
<td>8.2</td>
</tr>
<tr>
<td>6</td>
<td>100.0</td>
<td>1.68</td>
<td>412.7</td>
<td>516.4</td>
<td>535,701</td>
<td>285,322</td>
<td>23.6</td>
<td>10.3</td>
<td>13.3</td>
</tr>
<tr>
<td>7</td>
<td>67.2</td>
<td>1.51</td>
<td>417.1</td>
<td>576.4</td>
<td>480,502</td>
<td>255,922</td>
<td>22.1</td>
<td>10.0</td>
<td>12.0</td>
</tr>
<tr>
<td>8</td>
<td>76.0</td>
<td>1.51</td>
<td>386.6</td>
<td>550.3</td>
<td>620,319</td>
<td>330,391</td>
<td>25.8</td>
<td>12.1</td>
<td>13.7</td>
</tr>
<tr>
<td>9</td>
<td>100.0</td>
<td>1.94</td>
<td>408.1</td>
<td>531.8</td>
<td>692,990</td>
<td>369,096</td>
<td>30.2</td>
<td>11.5</td>
<td>18.7</td>
</tr>
<tr>
<td>10</td>
<td>60.0</td>
<td>2.60</td>
<td>339.6</td>
<td>403.6</td>
<td>120,778</td>
<td>64,328</td>
<td>4.3</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>11</td>
<td>60.0</td>
<td>2.17</td>
<td>368.1</td>
<td>426.6</td>
<td>105,227</td>
<td>56,045</td>
<td>4.2</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>63.7</td>
<td>1.50</td>
<td>395.0</td>
<td>526.0</td>
<td>345,551</td>
<td>184,046</td>
<td>14.9</td>
<td>6.6</td>
<td>8.2</td>
</tr>
<tr>
<td>13</td>
<td>66.9</td>
<td>1.50</td>
<td>393.7</td>
<td>516.6</td>
<td>348,165</td>
<td>185,438</td>
<td>14.9</td>
<td>6.6</td>
<td>8.3</td>
</tr>
<tr>
<td>14</td>
<td>72.4</td>
<td>1.50</td>
<td>425.6</td>
<td>530.7</td>
<td>326,742</td>
<td>174,027</td>
<td>15.3</td>
<td>6.5</td>
<td>8.8</td>
</tr>
<tr>
<td>15</td>
<td>100.0</td>
<td>1.52</td>
<td>416.2</td>
<td>510.4</td>
<td>460,693</td>
<td>245,371</td>
<td>20.5</td>
<td>8.8</td>
<td>11.7</td>
</tr>
<tr>
<td>16</td>
<td>98.0</td>
<td>1.50</td>
<td>456.2</td>
<td>618.1</td>
<td>959,197</td>
<td>510,882</td>
<td>48.2</td>
<td>18.4</td>
<td>29.8</td>
</tr>
<tr>
<td>17</td>
<td>98.0</td>
<td>1.52</td>
<td>433.3</td>
<td>608.9</td>
<td>1,062,485</td>
<td>565,894</td>
<td>50.1</td>
<td>19.7</td>
<td>30.4</td>
</tr>
<tr>
<td>18</td>
<td>72.0</td>
<td>1.50</td>
<td>422.2</td>
<td>559.7</td>
<td>455,845</td>
<td>242,789</td>
<td>21.2</td>
<td>9.4</td>
<td>11.8</td>
</tr>
<tr>
<td>19</td>
<td>72.0</td>
<td>1.50</td>
<td>391.8</td>
<td>486.2</td>
<td>280,037</td>
<td>149,152</td>
<td>11.8</td>
<td>5.1</td>
<td>6.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>7,795,431</strong></td>
<td></td>
<td><strong>4,151,956</strong></td>
<td><strong>349,5</strong></td>
<td><strong>146,7</strong></td>
<td><strong>202,8</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.3: Results of Senergy’s Revised Base Case Volumetric Calculation**
However, it is important to remember that although best judgement has been used to determine the base values for the various parameters that go into the volumetric calculation, there is a significant uncertainty around many of them. Eight key parameters have been identified and the sensitivity of the volume estimates to changing the values of these parameters within the ranges specified in Table 5.2 (column 5) was determined using a Monte Carlo simulation. For each parameter varied it was assumed that all values within the ranges specified were equally probable and overall 5,000 calculations were performed and analysed for each case.

The overall result in terms of the probability distribution for Total, Cushion and Working gas volumes is shown in Table 5.4 with the Senergy base case shown for comparison. The result of the analysis indicates that there is a 50% probability (P50) that a Working volume of up to 190 million \(\text{sm}^3\) can be achieved, a 90% probability (P90) that a Working volume of up to 124 million \(\text{sm}^3\) can be achieved and a 10% probability (P10) that a Working volume of up to 258 million \(\text{sm}^3\) can be achieved. The distribution of Working gas volume is shown pictorially in Figure 5.1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Total (million (\text{sm}^3))</th>
<th>Cushion (million (\text{sm}^3))</th>
<th>Working (million (\text{sm}^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Senergy base case</strong></td>
<td>349.5</td>
<td>146.7</td>
<td>202.8</td>
</tr>
<tr>
<td>P100</td>
<td>144.8</td>
<td>60.7</td>
<td>82.1</td>
</tr>
<tr>
<td><strong>P90</strong></td>
<td>219.4</td>
<td>94.5</td>
<td>124.0</td>
</tr>
<tr>
<td>P80</td>
<td>249.8</td>
<td>107.9</td>
<td>142.3</td>
</tr>
<tr>
<td>P70</td>
<td>277.0</td>
<td>118.9</td>
<td>157.5</td>
</tr>
<tr>
<td>P60</td>
<td>304.4</td>
<td>131.7</td>
<td>172.8</td>
</tr>
<tr>
<td><strong>P50</strong></td>
<td>335.0</td>
<td>144.5</td>
<td>189.8</td>
</tr>
<tr>
<td>P40</td>
<td>366.0</td>
<td>158.1</td>
<td>207.1</td>
</tr>
<tr>
<td>P30</td>
<td>394.8</td>
<td>171.3</td>
<td>222.2</td>
</tr>
<tr>
<td>P20</td>
<td>428.4</td>
<td>192.2</td>
<td>237.5</td>
</tr>
<tr>
<td><strong>P10</strong></td>
<td>477.1</td>
<td>224.4</td>
<td>257.8</td>
</tr>
<tr>
<td>P0</td>
<td>687.4</td>
<td>310.3</td>
<td>377.0</td>
</tr>
</tbody>
</table>

**Table 5.4: Monte Carlo Simulation: Probability Distribution of Total, Cushion and Working Gas Volumes**
Figure 5.1: Monte Carlo Simulation: Histogram of Working Gas Volume

Figure 5.2 shows which parameters have the most effect on the Working gas volume estimate. Uncertainty in the Base Salt pick contributes 39% to the overall uncertainty, with the ratio of the actual solution mined volume to the planned geometric volume contributing a further 22%. The next four parameters each contribute between 8 and 10% to the overall uncertainty.
5.3 Conclusions

In a base case calculation Senergy estimate Total, Cushion and Working gas volumes of 350, 147 and 203 million m$^3$ respectively. The Working gas volume of 203 million m$^3$ is equivalent to 7.2 bscf, so the base case project could deliver 0.6 to 0.7 bscf/d over a 10 to 12 day production period.

A Monte Carlo simulation investigating the sensitivity of these capacities to the uncertainty in eight key parameters indicates a 50% probability of achieving a Working gas volume of 190 million m$^3$, a 90% probability of 124 million m$^3$ and a 10% probability of 258 million m$^3$.

Examination of the cumulative probability distribution derived from the data in Figure 5.1 indicates that there is a 42.5% probability of achieving a Working gas volume of 200 million m$^3$ and a 1.4% probability of achieving a Working gas volume of 300 million m$^3$.

Senergy considers that there are significant uncertainties in the parameter values used by Geostock in their volumetric calculation which are not reflected in their resulting volumes (i.e. in their single deterministic calculation). Senergy’s probabilistic calculation provides a range of Total, Cushion and Working gas volumes which we feel represents a more realistic view of the uncertainties in relation to the volumetrics inherent in this project.
6 Glossary of Terms

m, m³  metre, metre cubed
BGS  British Geological Survey
bscf  billion standard* cubic feet
bscf/d billion standard* cubic feet per day
SEGY format Society of Exploration Geophysicists open standard for storing geophysical data
m/sec metres per second
bar/m bars per metre
bar/d bars per day
sm³ standard* cubic metre
milliseqs one thousandth of a second
XRD X-Ray diffraction
t/m³ tonnes per cubic metre
Pmin, Pmax minimum pressure, maximum pressure
MPa Megapascal – unit of pressure = 10 bar
* standard conditions are 1 atmosphere (1.01325 bar) and 15 degC

6.1 Additional Terminology

2D seismic Seismic data acquired along a vertical plane
Checkshot Lower resolution VSP that is only able to provide a very coarsely sampled time-depth relationship.
Dip line Seismic line paralleled to dip direction (the direction of steepest angle of descent)
EIS Environmental Impact Statement
Gocad Software used for geological modelling
IPC Infrastructure Planning Commission
Kingdom Software used for the interpretation of seismic data
Monte Carlo Simulation In a Monte Carlo simulation a calculation is repeated multiple times (usually many thousands) using alternative values for some or all of the input parameters randomly selected from their expected distribution and range. The multiple results provide a statistically significant indication of the uncertainty in the overall calculation.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPS</td>
<td>National Policy Statement</td>
</tr>
<tr>
<td>Post-stack migration</td>
<td>Seismic migration done after stacking to attempt to position sub-surface events correctly</td>
</tr>
<tr>
<td>Pseudo-checkshot</td>
<td>Constructed time-depth relationship using multiple data sources.</td>
</tr>
<tr>
<td>SEGY</td>
<td>Format file used to store seismic data. The file is composed of three sections; an ascii header, a binary header and the seismic traces</td>
</tr>
<tr>
<td>Strike line</td>
<td>Seismic line paralleled to the strike direction (direction perpendicular to the dip direction)</td>
</tr>
<tr>
<td>Sub-seismic</td>
<td>The minimum size of geological features that can be observed on the seismic. It is linked to the seismic data frequency content; the higher the frequency content the smaller the geological features that can be resolved.</td>
</tr>
<tr>
<td>TD</td>
<td>The total depth reached by a well</td>
</tr>
<tr>
<td>TWT</td>
<td>The time taken for the seismic signal to propagate from the source downwards, reflect at an interface, and then travel upwards and back to the receiver</td>
</tr>
<tr>
<td>UGS</td>
<td>Underground Gas Storage</td>
</tr>
<tr>
<td>UGSR</td>
<td>Updated Geological Summary Report</td>
</tr>
<tr>
<td>VSP</td>
<td>Vertical seismic profiles (VSPs) are very small seismic surveys with seismic receivers within the well. The VSP provides a seismic image at the well location and a time-depth relationship (seismic data is recorded in the time domain while the well data is recorded in depth).</td>
</tr>
</tbody>
</table>
Appendix 1   KBB Underground Technologies Report
Review and Advise on
Third Party Geomechanical Reports and
Gas Storage Cavern Construction for the
Preesall Gas Storage Project,
United Kingdom

for:
Senergy (GB) Limited
2/3 Queens Terrace
Aberdeen, AB10 1XL
Great Britain

Client Project Code.: A14DEC085A
Client PO Number: 43048
KBB UT Project No.: 2711-881028-K

Author/s: Botho Saalbach
Dirk Zander-Schiebenhöfer

Date: June 19, 2014
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Figure 1  Schematic overview on cavern design and layout parameters  6
1 Introduction

Senergy is currently reviewing the planning documents of Halite Energy Group (HEG) for the creation of salt caverns for gas storage in Lancashire, Great Britain in a concession area near Fleetwood and Preesall.

Within this scope Geostock, France, prepared a Conceptual Design Study describing possible locations and storage volumes of the caverns as well as their possible layout and storage capacity.

KBB Underground Technologies (KBB UT), Germany, was appointed by Senergy to prepare a Third Party review about this conceptual design study of Geostock.
2 Scope of Work

Information about the conceptual design work of Geostock was provided by Senergy by the following documents:

- Halite Energy Gas Storage, Preesall Gas Storage Project, Revision of Cavern field Layout, Report GKF/0/J/0002

General tasks to be performed by KBB UT’s were the following:

- Evaluation of the general methodology (procedure)
- Evaluation of the applied design/assessment criteria and their appropriate limiting values with regard to safety and tightness as well as reliability (risk).
- Risk assessment on realizing the intended storage volume.

The following Chapter 3 describes the findings of KBB UT from evaluation of the general methodology and the application of design criteria as well as the overall assessment of the simulation results. Subsequently a general risk consideration is presented in Chapter 4.

The concluding Chapter 5 highlights the main statements.
3 Evaluation of Methodology and Applied Design Criteria

3.1 General methodology

3.1.1 Applied procedure

The conceptual design study relies on the geological site characterization that was made on the basis of 2D seismic surveys, which were interpreted by the British Geological Survey (BGS) and resulting in maps for top of salt, bottom of salt and salt thickness. These data were used for setting cavern locations in combination with design rules which consider:

- minimum salt roof above the cavern
- minimum length of the cavern neck (distance between last cemented casing shoe and cavern roof)
- minimum salt bottom below the cavern
- minimum salt pillar thickness between caverns
- cavern roof and sump development
- minimum distance to fault zones identified in the rock layers above and below the salt section.
- definition of three different generic type caverns in order to adjust cavern to geological boundary conditions.

In order to estimate the possible volume of the cavern that can be used for gas storage the de-rating factors were taken into account:

- leaching factor describing the percentage of volume that can be leached within the designed shape
- loss of leached volume by the settlement of insolubles (percentage of insolubles and bulking factor)
- reduction of the leached net cavern volume due to brine being in-applicable by debrining

Cavern storage capacity was calculated based on coupled thermodynamic / rock mechanic simulation models in order to recommend minimum and maximum cavern
pressure and limiting withdrawal / injection rates. Intercalated non-salt layers within the cavern section as well as non-salt rock layers above and below the salt section were considered by the simulation models. Initial rock mass stresses were calculated due to the assumption of average densities for the non-salt layers (2.5 t/m³) and the salt (2.26 t/m³). Assessment criteria in order to recommend these layout parameters consider stability and tightness of the caverns. Generally accepted software (SCTS for thermodynamic modelling and ABAQUS for coupled thermo-mechanical modelling) was used. The studied load case considers an operation time period about 20 years.

Based on the conceptual design and layout it was stated that the prospected daily withdrawal / injection capacity of 1 bcf/d is feasible with 19 caverns for a period of 12 days.

### 3.1.2 Evaluation of the general methodology

The overall methodology (procedure) for the conceptual design can be considered as state of the art and therefore appropriate (compare items considered by Geostock (see Chapter 3.1.1) and items addressed in Figure 1). However, the following constraints have to be mentioned:

- It is stated that the geological site characterization takes into account a conservative approach of BGS, but the remaining degree of uncertainty in determining top and bottom layer of the salt is not mentioned. According to our knowledge this uncertainty can make up to 10%. This does not mean that KBB UT doubts the specialists of BGS, but considering a remaining uncertainty will reduce available salt thickness and therefore cavern volume.
- The applied design parameters for cavern location and field design do not consider minimum distances to the boundaries of the concession area. This may be possible due to local legislation, but should be proven. In other countries this is not common practice.
- For the determination of the net leachable volume an average leaching factor is adopted, but is not mentioned how this factor is influenced by the intercalated non-salt layers.
- It remains unclear whether the applied values for insolubles as well as for the rock mass densities rely on site specific data or on general assumptions. The amount of insolubles influences the feasible cavern volume, whereas the density profile has an impact on the limiting cavern pressures.
The conceptual design study considers the leaching phase, gas first fill and storage operation period. Worst case scenarios during operation (e.g. blow out) as well as cavern abandonment are not addressed. Especially, the blow-out case may afford additional pillar thickness as well as salt above the roof and below the sump. The blow-out case is considered to ensure cavern stability even if the cavern pressure was reduced to atmospheric by accident.

Figure 1 Schematic overview on cavern design and layout parameters (reference K.-H. Lux (1984) updated by KBB UT)
3.2 Design and assessment criteria

In the following the design and assessment criteria applied by Geostock in the Conceptual design Study are reviewed and evaluated in detail.

### 3.2.1 Design criteria

Criteria applied by Geostock:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Limiting value</th>
<th>Comment</th>
<th>Consequence</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum salt roof above cavern</td>
<td>1 maximum cavern radius (35 to 50 m)</td>
<td>realistic</td>
<td>higher efforts on overlying rock mass stability</td>
<td>check stability of the above overburden layers</td>
</tr>
<tr>
<td>minimum height of the cavern neck</td>
<td>5 to 15 m depending on cavern maximum radius</td>
<td>optimistic</td>
<td>impairing tightness of the casing shoe, and roof stability</td>
<td>15 to 25 m while increasing salt roof thickness</td>
</tr>
<tr>
<td>minimum salt bottom below the cavern</td>
<td>5 to 15 m depending on cavern maximum radius</td>
<td>optimistic</td>
<td>loss of tightness possible instability of the bottom layers</td>
<td>increase limiting value (increase safety e.g. if salt bottom is inclined)</td>
</tr>
<tr>
<td>minimum distance between caverns</td>
<td>1.4 average diameter of adjacent caverns</td>
<td>optimistic</td>
<td>impairs long-term stability of the salt pillar, reserves for worst case scenarios</td>
<td>increase limiting value</td>
</tr>
<tr>
<td>minimum distance to fault zones</td>
<td>1 maximum cavern diameter (60 to 100 m)</td>
<td>optimistic</td>
<td>influence on homogeneity of the salt (possible local weak zones in terms of tightness)</td>
<td>consider greater distance especially with great cavern diameters</td>
</tr>
<tr>
<td>sump and roof development</td>
<td>cone</td>
<td>domal shape normal lead to better stress conditions</td>
<td>optimization of layout pressures</td>
<td>possible optimization</td>
</tr>
</tbody>
</table>
### 3 Evaluation of Methodology and Applied Design Criteria

Not addressed criterion:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Purpose</th>
<th>Comment</th>
<th>Consequence</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum distance to boundaries of the concession area</td>
<td>guaranteeing equal rights to neighbours</td>
<td>may be negligible due to local legislation</td>
<td>possible restriction while locating caverns</td>
<td>proof of legislation and consideration if demanded</td>
</tr>
</tbody>
</table>

### 3.2.2 Estimates on storage volume

Criteria applied by Geostock:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Limiting value</th>
<th>Comment</th>
<th>Consequence</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>leaching factor</td>
<td>85%</td>
<td>too optimistic</td>
<td>estimated net cavern volume is too high</td>
<td>reduce the value to about 70%</td>
</tr>
<tr>
<td>average amount of insolubles</td>
<td>15%</td>
<td>value based on provided documentation</td>
<td>-</td>
<td>check against site specific values</td>
</tr>
<tr>
<td>bulking factor</td>
<td>1.5</td>
<td>optimistic</td>
<td>estimated net cavern volume is too high</td>
<td>increase the value to 1.8 to 2</td>
</tr>
</tbody>
</table>

Remaining brine after gas first fill | 2% | realistic | - | - |

Not addressed criterion:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Purpose</th>
<th>Comment</th>
<th>Consequence</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavern convergence</td>
<td>estimate on cavern volume during operation</td>
<td>decreases available storage volume</td>
<td>storage potential reduces with time</td>
<td>simulations show small convergence rates during operation, to be checked against observations in the future</td>
</tr>
</tbody>
</table>
3.2.3 Cavern layout

Criteria applied by Geostock:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Limiting value</th>
<th>Comment</th>
<th>Purpose</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>no tension criterion</td>
<td>0 MPa</td>
<td>state of the art tightness of the cavern contour</td>
<td>not strictly applied</td>
<td></td>
</tr>
<tr>
<td>maximum creep strain</td>
<td>5%</td>
<td>realistic</td>
<td>contour stability</td>
<td>met in all cases</td>
</tr>
<tr>
<td>dilatancy criteria for salt</td>
<td>&lt;=1 long term slightly above 1</td>
<td>state of the art (criterion 3b)</td>
<td>estimated net cavern volume is too high</td>
<td>no indications given for consequences when values are above 1</td>
</tr>
<tr>
<td>gas tightness at maximum pressure</td>
<td>tangential rock mass stresses</td>
<td>state of the art</td>
<td>proof of geological tightness</td>
<td>no safety margin addressed, no consideration of near fault areas</td>
</tr>
<tr>
<td></td>
<td>higher cavern pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not addressed criterion:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Purpose</th>
<th>Comment</th>
<th>Consequence</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>long-term stability of the salt pillar</td>
<td>proof of a safety pillar</td>
<td>additional safety for worst case scenarios</td>
<td>increase of pillar dimensions</td>
<td>consideration of worst case scenarios</td>
</tr>
</tbody>
</table>

3.3 Assessment of simulation results

The performed thermodynamic /rock mechanic simulations form the basis for the estimate of the withdrawal / injection potential of the designed caverns.

Essential parameter for this estimate is the working gas volume that is mainly determined by the minimum and maximum cavern pressure. Due to the assessment of Geostock in geomechanical study the minimum cavern pressure should be raised to 0.07 and 0.08 bars/m (type I and III caverns respectively). However, it seems that this assessment relies on salt dilatancy strength data which were taken from the literature. This has to be checked against site specific material data in the future in order to prove that these recommended minimum cavern pressures will be still valid.
There is a mismatch in fulfilling the ‘No Tensile Criterion’ during cyclic operations. If this criterion shall be strictly followed the pressure rates have to be reduced, which results in a decline in delivery potential. The internationally accepted rock mechanical experts do not have a unique view upon the issue whether thermally induced cracks propagate over time.

The tightness of the intercalated mudstone layers within the cavern section is not explicitly assessed. This may lead to reduction of the maximum cavern pressure. So far to KBB UTs knowledge only cores have been tested in the lab and some specific field test results from boreholes. It should be checked, if and how these test results can be applied for the Preesall gas storage project especially to cavern showing maximum diameters of 100 m.
4 Rough Evaluation of General Risks

In the following possible additional risks which may influence the storage potential and that were not mentioned in the Conceptual Design Study of Geostock shall be briefly mentioned.

- **Un-tightness of the last cemented casing**
  
The cementation of the last cemented casing string has to be carried out extremely careful, otherwise the cavern well will be not gastight and not suited for gas storage. If repairing of the un-tight cementation is possible this is besides technical difficulties a costly procedure.
  
  Gas-tight cementation is a technical issue and nearly not related to the cavern site.

- **Un-tightness of the cavern caused by fractures in the salt deposit**
  
The Preesall salt deposit is influenced by faults that can be identified in the overlying and underlying strata. These faults may have generated fracture systems in the salt and may be “touched” during the cavern construction. They are deemed to be closed by salt crystals and tight to brine, but maybe not to gas at high pressure. This implies a possible risk to lose a cavern.
  
  Regarding the total number of 19 caverns the risk is estimated to lose 1 to 2 caverns caused by un-tightness of the cementation or salt fractures.

- **The cavern section is intercalated by non-salt layers (mudstones)**
  
  Even though it can be assumed from similar locations in Cheshire that these mudstone layers are gastight because of small content of salt or because of consolidated conditions, a risk for gas tightness remains unless in-situ tests were successfully performed for the specific location. Due to these test results there may be a need to reduce the maximum cavern pressures.

- **Frequent gas injection and gas withdrawal**
  
  It is planned to operate the caverns at frequent gas injection / withdrawal cycles, so called “huff and puff”-operation. This means frequent pressurization / depressurization of the cavern. The contour stability and tightness may be affected. Finally this may reduce the cavern lifetime.
  
  Because the “huff and puff”-operation just came up during the last few years, no long-time experiences are available at this type of cavern operation.
5 Conclusions

It can be stated generally that the methodology applied by Geostock in the Conceptual Design Study is appropriate. However, it implies some uncertainties that will influence the predicted storage potential in terms of daily withdrawal and injection volumes.

Main items related to the general cavern design, which were identified by KBB UT in this brief Third Party opinion, are the following:

- The degree of uncertainty in the geological model is not stated, although it is stated that the conservative BGS approach is applied. The degree of uncertainty in terms of minimum salt thickness could be provided in order to enable a conservative estimate.
- With regard to all safety dimension of the main load bearing elements it should be taking into account that maximum diameters of 100 m for gas storage cavern are state of the art but more at the upper boundary of experience.
- Possible cavern volumes were calculated by Geostock using a relative optimistic value for the leaching factor and slightly optimistic values for the bulking factor (The average insoluble content could not be checked by KBB UT). Taking into account the assumed leaching factor of 85% alone it can be assumed that the cavern volume available for gas storage will be reduced by about 15%. If the bulking factor turns out to be slightly higher that this reduction tends in the direction of 20%.
- Minimum dimensions of the main load bearing elements in the salt should be slightly increased. With regard to the salt roof and bottom this will lead to smaller cavern volumes. How the revised salt pillars will influence the feasible storage volume depends on the field layout.
- The local rules with regard to minimum distances of the caverns from the boundaries of the concession area have to be clarified. This may affect a number of caverns.

Apart from the cavern volumes, which are recommended by the design, working gas volumes are restricted by thermodynamics and rock mechanical constraints in order to guarantee long-term stability tightness and deliverability.

- Convergence effects seem to be negligible according to the simulations of Geostock, but will have to be checked with future observations. Convergence reduces the storage volume over time (and creates surface subsidence).
• Required minimum cavern pressures maybe slightly higher than proposed by Geostock (as already indicated in the Geomechanical Study) in order to sustain long-term stability of the cavern contour.

• Although the calculated pressure rates of about 5 bars/d in maximum are relatively moderate, the coupled thermo-mechanical analysis shows thermally induced fractures in a small zone of up to 2 m behind the cavern wall. If it cannot be proven that these fractures will not grow during operations and that the cavern contour stability and tightness is not impaired by this occurrence of thermally induced fractures, the permissible pressure rate (mainly the gas withdrawal rates) have to be reduced, which will impair the maximum daily rate and not the overall working gas volume.

Due the short time available for this Third Party review all identified items could only be addressed and the consequences for possible changes in the design or the risk potential only be stated qualitatively. A quantitative statement affords sufficiently more effort.
Review and Advise on
Third Party Geomechanical Reports and
Gas Storage Cavern Construction for the
Preesall Gas Storage Project,
United Kingdom

Addendum 1

for:
Senergy (GB) Limited
2/3 Queens Terrace
Aberdeen, AB10 1XL
Great Britain

Client Project Code.: A14DEC085A
Client PO Number: 43048
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Author/s: Botho Saalbach
Dirk Zander-Schiebenhöfer

Date: June 30, 2014
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4 Statement on Blow-Out Scenario .................................................................... 7
1 Introduction

Senergy is currently reviewing the planning documents of Halite Energy Group (HEG) for the creation of salt caverns for gas storage in Lancashire, Great Britain in a concession area near Fleetwood and Preesall.

KBB Underground Technologies (KBB UT), Germany, was appointed by Senergy to prepare a Third Party review about this conceptual design study of Geostock. This review was already presented to Senergy on June 16, 2014.

The present statement is in response of additional requests of Senergy with regard to subsidence modelling and cavern blow-out (as worst case scenario).
2 Scope of Work

Due to the request of Senergy for commenting on the Halite Energy Groups gas storage project at Preesall with regard to subsidence modelling and worst case scenarios statements/review is given Chapter 3 for subsidence modelling and Chapter 4 for worst case considerations.
3 Review of Subsidence Modelling

3.1 Documentation presented

Senergy provided KBB UT with an extract of

- Updated Geological Summary Report for Preesall Underground Gas Storage Facility, Lancashire written by Mott MacDonald, Chapter 4.7, and page 53-57.

The document describes the procedure of subsidence modelling for the basic design purposes.

3.2 Evaluation

The procedure for subsidence modelling can be summarized from the presented document as followed:

- Processes involved are described by creep closure and roof failure
- SaltSubsid is applied for modelling
- Poor cavern design must be avoided, thus only wide area subsidence is relevant for newly built gas storage caverns, but old ‘unstable’ caverns have to considered in subsidence prediction
- Different kinds of subsidence – wide area (normal) and special point subsidence (due to sinkholes) – is addressed
- The need of on-going monitoring and extension of the existing levelling grid is addressed
- Observations of the existing ICI caverns shall be incorporated
- Improvement of the subsidence model by history matching and coupling of subsidence modelling and rock mechanical modelling is indicated

The presented procedure can be considered as state of the art. However, it has to be make sure that with the proceeding of the project the ‘ifs’, ‘butts’, and ‘shallss’ will be considered accurately.
Two specials item need a detailed review:

- The assumption of input parameters for subsidence modelling, and
- The consideration of safety distances between existing but unstable/collapsed caverns and newly planned caverns for gas storage.

### 3.2.1 Evaluation of input parameters for subsidence modelling

As per Item 4.7.5 it is stated that a cavern convergence of 0.01% per year is assumed according to a Respec Report in 2005. This figure cannot be evaluated on the basis of the presented document.

Basically cavern convergence mainly depends on cavern depth, difference between lithostatic and cavern pressure (e.g. operation period at minimum pressure), creep characteristic of the salt, rock mass temperature, and cavern shape.

Caverns are located at different depths this should be considered in subsidence modelling. Thereby, not the casing shoe depth is the characteristic value but the representative rock mechanical depth, which can be assumed at 2/3 of the cylindrical height or at mid depth for spherical caverns.

Cavern closure rate is assumed with 0.01%/year. Compared to the geomechanical study of Geostock (2014) cavern total convergence is calculated at about 0.5% after 25 years of operation. This would results in an average rate of 0.02%/year, which is in contradiction to the assumption made in the subsidence prediction. It has to be shown that assumed convergence rates are based on assumptions that are specific to the location (material properties, cavern depth, pressure history, etc.).

### 3.2.2 Consideration of existing unstable caverns

It is mentioned that the planned new gas storage caverns are partly in the neighbourhood of existing but partly unstable caverns, where the salt cover in the roof turned out to be too small. The minimum required salt pillar between cavern wall contours of the newly planned gas storage caverns and those old caverns is assumed with 4 times the maximum radius of the two adjacent caverns. This required minimum distance is already mentioned in earlier studies. If pressures in these 'collapsed' caverns cannot be maintained at brine fill level, the pillar stresses will increase and thus (although stability is not impaired) may influence the convergence rate of the adjacent gas storage cavern(s).
3.3 Conclusion

The general procedure for subsidence modelling follows state of the art concepts. Specific data which are valid for the location could not be proven based on the provided document. A rough check with data from other location shows that assumed values for convergence rates are in the range of experience. However, assumed model parameters have to be compared to measurements and observations in future. Compared to the results of the Geomechanical Study of Geostock assumed convergence rates in the subsidence prediction are lower.
4 Statement on Blow-Out Scenario

As worst case scenario for gas storage cavern the blow-out case is generally studied. In this case it is assumed that two safety elements fail at the same time: the subsurface safety valve and the wellhead (e.g. due to a crashing airplane). In the case the stored gas in the cavern will blow-out by unrestrained flow causing both a fast drop in cavern temperature and cavern pressure. Both effects will influence the cavern contour stability considerably. Temperature drops will lead to embrittlement of the salt and decreasing creep ability. The pressure drop to atmospheric pressure increases the load on the surrounding salt. Both effects enhance the possibility of contour instabilities, which increase with duration under atmospheric pressure. If no stabilizing measures will be taken spalling (break-outs at the cavern contour) will occur. This process has to be stopped before pillars between caverns will fail and lead to a chain reaction covering larger parts of the cavern field.

Normally the worst case of a blow-out is performed in order to give answers to the following questions:

- Will instability of the cavern contour occur and if so to which extent.
- For how long may the cavern be under atmospheric pressure and at what point in time after blow-out has a minimum cavern pressure to be re-installed.
- What kind of precautions have to be taken in order to guarantee stability and safety after a blow-out.

The results of such an investigation may in terms of rock mechanical design aspects lead to an enlargement of the minimum salt pillars between caverns.

Wellhead locations have to be checked with regard to the minimum distance to urban areas and/or farm houses, because of the heat radiation during hot blow-out and acoustic emissions.

Emergency plans have to be prepared showing alarm plans for information of the public, the organisation of the emergence management committee. Precautions have to be taken e.g. in order to re-pressurize the cavern, which is normally be recommended to be done by filling the cavern with fresh water or brine, i.e. in this case pumping and water capacity have to be available in the event of emergency.
With regard to the present project phase it can be concluded that the design and layout of the cavern field has to be checked against the recommendations that result from a worst case 'blow-out' scenario.