APPENDIX 4
PROJECT DESCRIPTION

APPENDIX 4.1 OUTLINE CAVERN DESIGN TECHNICAL REPORT

Islandmagee
Storage

Outline Technical Report
on the Proposed Gas Storage Project
at Islandmagee, Northern Ireland

for:

Islandmagee Storage Limited
80 Hill Rise
Richmond, Surrey
TW10 6UB
UNITED KINGDOM

DEEP.-Project-No.: 2905

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Underground Engineering

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Summary

In order to meet the growing demand for gas in Northern Ireland and Ireland, Islandmagee Storage Ltd. ('ISL') is proposing to create caverns for gas storage within a rock salt unit underneath Larne Lough, NE of Belfast, Northern Ireland. In comparison to conventional surface and underground rock cavern storages, the underground storage of gas in caverns in rock salt provides significant benefits and operational advantages as well as high levels of environmental compatibility together with high safety and security provisions. ISL has requested DEEP. Underground Engineering GmbH, Germany to prepare an outline technical report with focus on the feasibility of the construction and operation of gas storage caverns. A storage volume for 500 M Sm^3 of natural gas is required. The scope of the report includes an assessment of the geological situation, its suitability for the development of gas caverns. A preliminary basic design of cavern shape, cavern field layout and essential surface facilities has also been assessed. At the present stage this basic layout is largely based on general practical experiences from comparable projects in the UK, France and Germany.

Information derived from a seismic interpretation and a borehole nearby indicate that the thickness and quality of the Permian salt is sufficient to store the required gas volume in seven underground caverns. A confirmation well at the proposed site will be essential for subsequent more detailed project plannings, the adjustment and refinement of the presented basic design.

A preliminary rock-mechanical design is based on the geological information available at present. With an estimated rock-mechanical envelope of 600,000 m^3 per cavern and an anticipated feasible operating pressures from 90/120 bar to 250 bar a total working gas volume of approximately 77 M Nm^3 can be stored in one cavern. 44 M Nm^3 cushion gas will be required per cavern for storage operations.

An usable volume of 480,000 m^3 per cavern will be created within the rock-mechanical envelope by solution mining. The solution mining of all seven caverns will take approximately four years. The required time for cavern leaching is a function of the maximum leaching rate of 1,000 m^3/h; taking into consideration the technical feasibility of the designed pipelines and leaching plant. The possibility to leach three caverns in parallel for most of the time in two phases is assumed. The resulting average maximum leaching rate per cavern is expected to be 300 m^3/h. An additional cavern will be leached during workovers on the caverns being leached.

Considering the infrastructural and economical point of view, the construction of a natural gas reserve in underground salt caverns is feasible for Northern Ireland. This project would be the first of its kind in Northern Ireland. Several aspects will have to

be thoroughly discussed and implemented into the future detailed design of the facility.

The principal risk concerning the project is related to geological parameters that influence the cavern leaching process. The results of a confirmation well adjacent to the site will provide reliable data and important material properties through laboratory testing and define the depth and thickness of the storage horizon, rock-mechanical properties, total content of insolubles, etc.. These data will allow for a more precise design of the caverns aided by numerical simulations. Rock-mechanical tests on drill cores are required to set up a final rock-mechanical layout. Nevertheless, in consideration of rather conservative assumptions for most of the input data a usable storage volume of 480,000 m^3 per cavern appears to be feasible.

The initial target for the facility by ISL of 500 M Sm^3, with an injection capability of 14 M Sm^3 per day and a withdrawal capability of 24 M Sm^3 per day is achievable with 7 caverns based upon the parameters of the salt interval derived from the Larne-2-borehole and the 3D seismic data acquired by the company in 2007.

An alternative concept with five conventional and three strategic caverns has also been investigated. In case of a national emergency the cushion gas may be withdrawn from the strategic caverns by displacement with seawater. Portland Gas plc. have a patent pending for such a technical situation.

1 Introduction

Islandmagee Storage Ltd. ('ISL') formerly named Portland Gas NI Limited is registered in Northern Ireland and plans to develop underground storage of natural gas in salt caverns at Islandmagee, County Antrim, Northern Ireland. On 1st July 2007 ISL was granted exclusive license by the Crown Estate to create caverns to store natural gas below Larne Lough within an area of approximately 2.75 km^2 located east and south of the Ballylumford power station, Islandmagee. ISL is planning to construct the surface facilities south-east of the Ballylumford power station (Enclosure 1-1). In total, 7 caverns are planned to be constructed. All cavern wells will be drilled from an onshore location close to the power station.

Currently, there are no storage facilities for natural gas in Northern Ireland but the gas market in this region has been significantly growing over the recent years. Northern Ireland relies solely on the gas supply from Scotland via the Scotland-Northern Ireland pipeline (SNIP). The creation of a storage volume in the form of salt caverns will add to the markets stability since it represents an ideal option to ensure and optimise the delivery of gas. It might be an important tool for balancing network supplies, supporting the growth of the gas market and providing trading opportunities within the GB market. ISL identified the Larne region to be the most prospective area in Northern Ireland for the creation of storage caverns in rock salt.

From drilling activities in 1981 (Larne-2), it is known that below Larne, a 113 m thick sequence of Permian salt is present at a depth of approximately 1,690 m. ISL initiated a 3D seismic survey that was conducted in October-November 2007 and is interpreted in combination with the results from the borehole 'Larne-2'. A rock salt section with a thickness of 210 to 240 m has been identified in a depth range from 1,380 to 1,530 m below Larne Lough (Enclosure 1-2).

The present report for the underground facilities and the conceptual design for the surface installations is based on the mentioned geological assumptions and estimations which are summarised in the respective chapters. It has to be stated that the estimated design parameters do bear a certain range of error that may lead to deviations from the present report in the course of the realization of the project. With increasing knowledge, especially on the geological situation, the uncertainties will be reduced. A confirmation well (such as the proposed 'Ballylumford-1') in particular will provide more reliable data that will enable for a more detailed planning of the whole project.

2 Project Outline

ISL intends to develop underground gas storage in seven salt caverns at Larne Lough with a physical storage volume of 3 M m^3. ISL requested DEEP. to perform a pre-feasibility study with the aim to develop a preliminary technical concept for both the subsurface and the surface facilities including rough estimates on time scheduling. An alternative storage concept with 5 conventional and 3 strategic caverns has also been investigated.

2.1 Project Site

From the vertical geothermal test well 'Larne 2' it is known that the area of Larne Lough geologically belongs to the Larne Basin and is underlain by a thick Permo-Triassic succession. The Upper Permian consists of a rock salt thickness of 0 m to ~ 250 m and is the primary target for the construction of salt caverns. Upper Triassic units comprise of a 951 m thick unit of shales, siltstones and thin sandstones with three major halite units ('Ballyboley, Carnduff and Larne halite'). These layers may be regarded as the secondary target horizons. The geology of the area is described in detail in the Chapter 3.

The presence of saliferous beds of such thicknesses and depths, the proximity of the site to the onshore part of the SNIP as well as to the gas power plant gives an appropriate indication of a good potential for the construction of salt caverns as storage site for natural gas in this area.

2.2 General Concept

In order to fulfil the basic project requirements as given by ISL, seven underground salt caverns will have to be constructed applying solution mining technology. An usable cavern volume of 480,000 m^3 will be created (Enclosure 2-1), according to the knowledge from the test well 'Larne-2'.

Engineering and construction of the cavern volume and the required facilities will be completed in the shortest possible time span; i.e. in approximately five years. The time required for the provision of the seven caverns is a function of the feasible maximum leaching rate. As it is planned to leach three caverns in parallel during a first phase and additional three caverns during a second phase respectively, the resulting average maximum leaching rate will be 300 m^3/h. In addition, one cavern will be leached during downtimes during leaching operations of both phases; e.g. caused by workover.

The brine produced during leaching operation will be disposed to the sea.

2.3 Scope of Work

The present report examines the general feasibility of the construction and subsequent operations of an underground natural gas storage project at Larne Lough, County Antrim, Northern Ireland. All assumptions are made within the framework of ISL’s technical and commercial demands and under consideration of the geological constraints of the local setting. Generally, it has to be kept in mind that all input and output data stated are preliminary and will be subjected to adjustments according to the results of the planned confirmation well adjacent to the site (proposed ’Ballylumford-1‘ well).

The evaluation reviewed all relevant data, particularly geological data (borehole ‘Larne 2’ and 3D seismic survey). Special emphasis is focussed on the geological parameters (e. g. depth range and thickness of the evaporate sequence, amount of salt vs. content of insolubles, rock-mechanical strength and gas tightness of the rock). These are essential for rock-mechanical demands, leaching parameters and operational procedures.

A preliminary cavern design is presented and includes specification of cavern depth, cavern height, geometrical volume, shape and possible internal pressures for gas operation. The cavern design is based on a leaching scenario regarding the local setting as well as experiences from comparable salt cavern projects. A basic cavern field layout for seven conventional gas caverns is proposed.

Technical specifications for drilling and well completion related activities include the layout of the well pad, drilling and completion programmes, a description of primary and secondary mechanical integrity tests (MITs) together with gas first fill and snubbing procedures. The conceptual design of surface installations comprises of the general layout of the leaching plant inclusive freshwater intake, brine disposal, pipelines, well site, and the gas facilities.

An operational schedule is given. Anticipated basic design parameters for all evaluations are summarized in Enclosure 2-2.

3 Geological Framework

The area of interest is located in the Larne Basin that is situated in the Midland Valley terrain between Northern Ireland and the SW of Scotland. It is part of the Larne Basin (Enclosure 3-1). The SW portion of the Larne Basin lies onshore on Northern Ireland. The sedimentary fill of the basin comprises deposits of Carboniferous to Tertiary age, predominantly Permo-Triassic. It is non-compliantly resting on Ordovician and Silurian basement rocks of the Longford Down Inlier/Southern Uplands Massif (both Caledonian).

The evolution of the Larne Basin supposedly began with several phases of crustal extension in association with synsedimentary faulting, half-graben development and sporadic volcanism during the Carboniferous.

Permo-Triassic NE-SW extension, subsequent to significant erosion of Carboniferous clastic deposits due to regional inversion tectonics at the end of the Variscan Orogeny, led to the development of a complex arrangement of half grabens and normal faults. This extension resulted in the Larne Basin in a largely continental deposition of Permo-Triassic strata of up to 3,000 m in thickness. Lower Permian sandstones and conglomerates (potential reservoirs for hydrocarbons) are contributing up to 440 m to the thickness. These sediments are covered by Upper Permian limestone, shales, marls and evaporates, some of which may laterally vary in thickness and facies. The evaporates including the basal Magnesian Limestone are members of the Belfast Harbour Evaporate Formation (BHE) which is regarded as an equivalent of the Zechstein. This formation is the primary target of the Larne Lough gas storage project for the construction of the storage caverns. The evaporates are covered by the Permian Connswater Marl Formation (CMF). For stratigraphically equivalent sediments in the East Irish Sea, a deposition of alluvial fanglomerates passing basinwards into fluvial and aeolian sandstones at the basin margin is suggested. These are inferred to grade further into basin centre shaley and evaporatic playa lake deposits [1].

During the Mesozoic, the ongoing subsidence of the basin led to fluvial and aeolian accumulation of units of the Lower Triassic Sherwood Sandstones Group (SSG). The sedimentation of these sandstones was followed by the deposition of shales, siltstones and thin sandstones of the Upper Triassic Mercia Mudstone Group (MMG). The latter are interbedded with three major halite sequences, Ballyboley, Carnduff and Larne Halites (in order of decreasing age).

Rapid uplift and erosion during the Jurassic and Cretaceous are probably responsible for insignificant thicknesses or absence of sedimentary formations in the Larne Basin. Onshore, lower shallow marine Jurassic mudstones and subordinately limestones are overlying Triassic deposits in many places. These units are generally 25 to 100 m thick.

Sporadic relicts of thin karstified beds of Late Cretaceous chalk have been reported. They are in many places capped by Paleocene basalt lava extrusions up to 800 m in thickness (British Tertiary Igneous Province; BTIP). The volcanic activity is understood to be the result of an uplift, and again, NE-SW extension and faulting. NW-SE (WNW-ESE) extensional faulting is imaged on seismic from the onshore and offshore Larne Basin. The basalt extrusions comprises of a Lower Basalt Formation, an Interbasaltic Formation and the Upper Basalt Formation. Maximum preserved thickness of the Lower Basalt Formation area of up to 530 m was recorded in the Lough Neagh. An unknown amount of basalt has been removed by erosional processes. Onshore Northern Ireland Tertiary dykes are predominantly oriented NW-SE whilst offshore they display rather NNW-SSE to N-S trends.

A phase of compression caused regional uplift and erosion during the Miocene. In the Larne Lough area an axis of uplift is centred on the Lough itself where the Permian salt is most thickly developed. The uplift resulted in the erosion of the basalts which results in a clearer resolution of the salt sequence on seismic data below Larne Lough (Enclosure 1-2).

Parallel to the adjoining Highland Boundary Fault Zone (HBF) and Southern Upland Fault Zone (SUF) normal faults in the south of the Larne Basin dip generally to the E (Variscan or Tertiary trend), those in the north dip to the NW striking WSW-ENE (Caledonoid) [2]. They are featuring strike slip elements.

3.1 Evaporatic Formations in the Vicinity of Larne Lough

The Larne Basin yields a potential for hydrocarbon exploration mainly due to the two reservoir-seal couplets, Lower/Upper Permian and Lower/Upper Triassic. For this reason, there are seismic lines and a few boreholes in the area which are of great assistance in the exploration for evaporatic sequences suitable for salt cavern construction.

Salt mine development in the Carrickfergus area were located in the saliferous beds of the Triassic MMG.

3.1.1 Larne No. 1 Well

The Larne No. 1 well was drilled in the centre of Larne in 1962/1963 to a depth of 1,283.5 m [3]. Lower Liassic mudstones of 51.5 m in thickness are underlaid by some 987 m of mudstones, siltstones, evaporates and subordinate sandstones of the MMG. They are subdivided into Collin Glen Formation, Port More Formation, Knocksoghey Formation, Glenstaghey Formation, Craiganee Formation and Lagavarra Formation. The Larne Halite which belongs to the Glenstaghey Formation consists of approximately 480 m of massive halite beds. These beds are often containing pockets and bands of red and green mudstone and doleritic intrusions (approximately 330 m of pure rock salt). In the section assigned to the Craiganee Formation, the borehole penetrated beds of the Carnduff Halite and the Ballyboley Halite. The Carnduff Halite comprises of approximately 15 m of halite interbedded with some 26 m of mudstone. The Ballyboley Halite consists of 12 bands rock salt, totalling to 13 m interbedded with approximately 13 m of mud- and siltstones. Members of the SSG were proven down to TD with a minimum thickness of 208 m.

3.1.2 Larne No. 2 Well

The Larne No. 2 well is the nearest well to the area of interest. It was drilled 650 m E of well Larne No. 1. The vertical geothermal test well was drilled by the British Geological Survey (BGS) in 1981. Below a Quaternary cover of approximately 9.4 m, 951 m of the MMG were penetrated (Table 3-1). The Larne Halite contains three major halite sequences of up to 30 m in thickness divided by thinner beds (1.5 – 5 m thick) of mudstone, siltstone and halite. The Carnduff Halite comprises five halite sequences of more than 5 m thickness, the greatest being 70 m thick. The Ballyboley Halite contains four principal halite beds of less than 7.5 m thickness. The base of the MMG is characterised by mud-, silt- and sandstones of the Lagavarra Formation (55.2 m thick). The borehole section between 957.7 m and 1,606 m (below MSL) is dominated by sandstones of the SSG. It is underlain by units of the Upper Permian (207 m, inclusive of magnesian limestone), Lower Permian Sandstone (440.7 m) and Lower Permian Volcanics (> 616.6 m). The Upper Permian in well Larne No. 2 consists (from top to base) of mudstone and siltstone (66.1 m in thickness) and anhydrite (4.6 m in thickness) of the CMF, a siltstone (< 2 m in thickness), a rock salt sequence (about 113 m in thickness), a Magnesian Limestone (14 m in thickness excluding associated intrusions) with a dolomitic cap, all belonging to the BHE.

The rocksalt/halite sequence is reported to be very uniform, homogeneous and pure with virtually no interstitial clay or anhydrite. In appearance it may be similar to bedded Permian salt observed in locations in the Netherlands (Enclosure 3-2). The Lower Permian Sandstone was encountered at 1,813 m and a significant gas show is reported from this section [4]. The well bottomed in Lower Permian Volcanics at 2,870.3 m. The thick sequence of lavas and tuffs represents an important phase of volcanicity, possibly associated with rift initiation. These olivine-pyroxene basaltic lavas and tuffs have been isotopically dated at 245 ± 13 Ma [5], suggesting an age to young to be assigned to the Lower Permian.

The structural weakness of the saliferous beds gave rise to the emplacement of Tertiary dolerite dykes and sills majorly ranging from 2 to 7 m in thickness.

Table 3-1: Stratigraphic column of the Larne No. 2 Well (after [5])

	from depth below MSL [m]	to depth below MSL [m]	vertical thickness [m]
Quaternary	**- 2.6**	**6.8**	**9.4**
undifferentiated	- 2.6	6.8	9.4
Triassic	**6.8**	**1,546.3**	**1,539.6**
Mercia Mudstone Group	**6.8**	**957.7**	**951.0**
Knocksoghey Fm.	6.8	134.1	127.4
Knocksoghey Fm. (u. p.)	6.7	103.3	96.6
Coolmaghra Skerry	103.3	110.0	6.7
Knocksoghey Fm. (l. p.)	110.0	134.1	24.1
Glenstaghey Fm.	134.1	471.5	337.4
Glenstaghey Fm. (u. p.)	134.1	257.0	122.9 [1]
Larne Halite	257.0	460.9	203.9 [2]
L. Glenstaghey Fm. (l. p.)	460.9	471.5	10.6
Craiganee Fm.	471.5	902.5	431.0
Craiganee Fm. (u. p.)	471.5	618.1	146.6
Carnduff Halite	618.1	798.0	179.9
Craiganee Fm. (m. p.)	798.0	861.7	63.7
Ballyboley Halite	861.7	902.5	40.8
Lagavarra Fm.	902.5	957.7	55.2
Sherwood Sandstone Group	**957.7**	**1,606.0**	**648.3**
U. Sherwood Sandstone	957.7	1,243.6	285.9
Sherwood Upper Siliceous	1,243.6	1,546.3	302.7
Sherwood Lower Siliceous	1,546.3	1,606.0	59.7
Permian	**1,606.0**	**2,870.3**	**1,264.3**
Upper Permian	**1,606.0**	**1,813.0**	**207.0**
Connswater Marl Fm.	1,606.0	1,672,1	66.1
U. Permian Marls	1,606.0	1,672.1	66.1
Anhydrite	1,672.1	1,676.7	4.6
Belfast Harbour Fm.	1,676.7	1,813.0	140.9
Siltstone	1,676.7	1,678.2	1.5
Halite	1,678.2	1,791.3	113.1
Magnesian Limestone	1,791.3	1,813.0	21.7 [3]
Lower Permian	**1,813.0**	**2,870.3**	**1,057.3**
Lower Permian Sandstone	1,813.0	2,253.7	440.7 [4]
Lower Permian Volcanics	2,253.7	2,870.3	616.6 [5]
Total Depth		**2,870.3**	

u. p.: upper part; m. p.: middle part; l. p.: lower part.
Contribution of Tertiary intrusive rocks to thickness: [1] 25 m, [2] 14.3 m, [3] 7.6 m, [4] 9.8 m, [5] 4 m.

3.1.3 Newmill No. 1 Well

The well was drilled in 1971 in the context of hydrocarbon exploration on the south-western shore of Larne Lough to a depth of 1,981 m. This well was located on a surface anticline and proved a thick Permo-Triassic sequence including potential reservoirs in the Triassic Sherwood Sandstone Group and Lower Permian Sandstones. No significant indications for hydrocarbons were noted. The MMG contains four halite zones (with thicknesses of 24 m, 77 m, 86 m and 74 m). The second can be correlated to the Larne Halite. The BHE is only present in form of shale, anhydrite and dolomitic shaley anhydrite between 1,562 and 1,572 m. The major halite horizons of the Larne No. 2 well are absent, which may be due to faulting [4][6], but following the interpretation of the 3D seismic survey in Larne Lough a more likely explanation is that the well is outside the area of deposition centred to the north (Enclosure 1-2).

3.1.4 Seismic Surveys

A challenge to seismic surveying in the vicinity of Larne Lough is the avoidance of areas with Tertiary basalt cover that have a significant influence on the quality of the data produced. Furthermore, the uncertain and independent distribution of low density halite and high density igneous intrusives (frequently associated, Chapter 3.1.2) is evoking inaccuracies that may lead to misinterpretations.

A Vibroseis survey was carried out in 1981 between points 6.5 km WSW of Carrickfergus Castle and 11.5 km NNW of Larne, respectively. Reflecting horizons, top Larne Halite, top SSG and top Magnesian Limestone were tied to the wells Larne No. 1, Larne No. 2 and Newmill No. 1. Calculated bulk velocity figures are compatible with specific velocities from downhole logs of Larne No. 2 and the airgun survey of Newmill No. 1 (McCANN, 1990). In combination with results from the drillings, the seismic results delineate a general dip of Mesozoic and Permian strata to the north from Belfast to Carrickfergus to Newmill No. 1 and across Larne Lough to the Larne wells.

Portland Gas NI Limited (now ISL) acquired a 3D-seismic programme using IMC Geophysics during October-November 2007. Two 2D seismic tie lines where also acquired to allow a correlation of the survey with the Larne No. 2 well. During the interpretation of survey by GEO International Ltd., regional gravity and high resolution aeromagnetic survey data were also considered. The interpretation indicates an extension of the Permian salt sequence from the Larne No. 2 well underneath Larne Lough into the area of the exploration license (Enclosure 3-3). The top as well as the base of the Permian salt provide strong seismic reflections. As a result of this interpretation the top of the Permian salt could be contoured and is displaying a principal dip to the NW within the area of seismic investigation. This lithological interface is at depths of about 1,340 m to 1,630 m. The accuracy of the interpreted depths of the top of the Permian salt is estimated to be within 20 – 30 m. As evident from the maps (Enclosure 3-3 and 3-4), there are faults affecting the salt interval, but the area proposed for caverns under the Larne Lough is not affected.

The shallowest depth of the top of the Permian salt was recorded along the south-eastern boundary of the 3D seismic area.

A further result of the interpretation of the seismic campaign is an isopach map (Enclosure 3-4) illustrating the thickness of the Permian salt. The salt sequence basically seems to be thinning out towards the edges of Larne Lough, and thus is characterised by a lenticular geometry. The variation of the formation thickness inferred from the 3D-seismic survey is significant as the thickness ranges between 0 m and approximately 240 m. The survey results are placed in a regional context in Enclosure 1-2.

3.2 Proposed Confirmation Well Ballylumford-1

With the objective to confirm the interpretation from the seismic data, the proposed confirmation well (Ballylumford-1) is planned for 2010 as part of the Front-End-Engineering and Design ('FEED') for the project. The sequence of the Permian salt will be cored in its entity to allow the determination of leaching and rock mechanical properties of the evaporates. The properties are required to design caverns and surface facilities in more detail. The trajectory of the well is planned to follow the seismic inline 65 for some 234 m towards the SW (azimuth 237°) to penetrate an undisturbed sequence of the Permian salt. From this seismic line a geological forecast for the well has been established [7] (Enclosure 3-5).

4 Rock-Mechanical Cavern Design

Storage caverns have to maintain serviceability and long-term stability of the surrounding rock mass during each mode of operation (leaching, gas injection, gas storage and gas withdrawal). To achieve these requirements, the geological formation and the rock-mechanical design have to be met. Tests on core samples give information about the geo-mechanical properties as well as creep behaviour of the storage horizon and contiguous strata. The following parameters have to be defined:

- the section within the halite sequence suitable for solution mining and subsequent gas operations,
- the depth of last cemented casing shoe (LCCS),
- the length of required cavern neck in the top portion of the storage horizon,
- the depth and shape of cavern roof,
- the maximum allowable height and diameter of the cavern,
- the sufficient safety pillar between caverns,
- the sufficient spacing of several wells in the cavern field,
- the sufficient thickness of rock salt in the hanging wall and foot wall of the cavern, and
- the feasible storage operation pressures.

4.1 Design Parameters

One objective of this pre-feasibility study is the definition of basic rock-mechanical design parameters or at least their estimation.

A feasible rock-mechanical design of salt caverns relies on a thorough geological understanding of the salt sequence in the vicinity around a cavern well and comprehensive laboratory tests on salt and non-salt cores, as well as on numerical calculations of the mechanical properties of the salt from the results of these tests. A new well adjacent to the site will be required to obtain the core material required to undertake this work. Thus, the following preliminary design is based on historical data and experiences from the dimensioning and positioning of other gas storage caverns in comparable settings and in the context of the geological framework provided by the Larne-2-borehole and the 3D seismic data.

Preliminary assumptions on these design parameters, which have been estimated in cooperation with the Institut für Gebirgsmechanik (IfG), are summarised in Table 4-1 and displayed in Enclosures 4-1.

Table 4-1: Estimated basic design parameters for future gas caverns at Larne Lough

Cavern geometry		
top of storage horizon	ca. 1,440	m
base of storage horizon	ca. 1,670	m
thickness of storage horizon H6	ca. 230	m
depth range of cavern interval	ca. 1,500 - 1,660	m
roof shape	ellipsoidal	
maximum cavern height	160	m
maximum cavern diameter	80	m
volume of rock-mechanical envelope	600,000	m^3
net volume	480,000	m^3
gross volume	300,000	m^3
depth of last cemented casing shoe	1,480.0	m
well spacing	300	m
Operating parameter		
maximum pressure @ last cemented casing shoe	250	bar
minimum pressure (1 month/ 5 months)	90/120	bar
working gas volume per cavern	77,000,000	Nm^3
cushion gas volume per cavern	44,000,000	Nm^3

4.1.1 Cavern Shape and Dimensioning

Gross height vs. net height are referring to the thickness of the total section of rock salt to be solution mined and the height of the resulting cavern available for gas storage, respectively. The net height is estimated by consideration of the loss of height due to insolubles accumulating in the cavern sump. Consequently, the gross height of the cavern reduced by the height of the sump is equal to the net height. Accordingly, the terms gross volume and net volume are used for the total cavern volume and for the cavern volume without sump (Enclosure 2-1).

The gas storage caverns are planned to be solution mined within a rock-mechanical envelope of 160 m in height, 80 m in diameter and with an ellipsoidal roof shape. The total volume within the rock-mechanical boundary is 600,000 m^3. The leaching programme (Chapter 7.2) has to consider the limits given by the rock-mechanical envelope to guarantee long-term stability of the caverns in operation.

4.1.2 Well Spacing

Stress distribution around an individual cavern is not as complex as for a cavern cluster which is in the domain of stress interaction. The distance (D) between two gas cavern axes (well spacing) is constrained by the minimum pillar width, for which stability of the neighbouring caverns operated at P_{max} is guaranteed in case of a total loss of cavern pressure of a single cavern ('blow-out-scenario'). The distance (D) generally equals to three times the cavern diameter (d). In a first approach the rock-mechanical experts recommend to assume D = 300 m for the cavern cluster dimensioning (Table 4-1).

4.1.3 Operating Parameters

The minimum and maximum operating pressure have to be defined for every individual cavern to avoid fracturing of the surrounding rock mass, the bonding between the casing cementation and the host rock, as well as volume loss due to convergence. The pressure values have to guarantee the stability of the cavern during all different modes of operation or loading conditions.

The depth of the casing shoe of the last cemented casing is the benchmark depth for the determination of the maximum operational pressure. The minimum operational pressure is limited by stability concerns (large difference in pressure between formation pressure and storage pressure) and volume losses due to cavern convergence. Minimum pressure limits are time-depended and proposed to avoid damaging of the cavern in form of e.g. convergence. P_{max} is a function of depth of LCCs and the lithostatic pressure gradient inferred from formation densities of the overburden rock. The cushion gas volume remains in the cavern when minimum pressure is reached and is not to be withdrawn during conventional cavern operation. The assumptions on the maximum and minimum operational pressure are summarised in Table 4-1.

4.2 Future Steps

The preliminary design outlined above demonstrates the basic feasibility of the planned project. The basic design parameters need to be confirmed or specified in course of the following steps of the project realisation.

4.2.1 Re-Evaluation of Pre-Design Parameters

Once the confirmation well has been drilled and log data and rock cores are available, the following items will be prepared to re-evaluate the general feasibility of the project:

- Confirmation of depth and thickness of the salt sequence,
- Evaluation of core material from the storage formation to confirm suitability for cavern construction,
- Basic rock mechanical tests on core material to determine parameters such as strength and deformation behaviour (strain rates, convergences and subsidence) of the relevant formation,
- Numerical calculations on the dimensioning of the storage caverns,
- Adjustments of cavern field layout, and
- Adjustments of subsurface completions as well as adjustments to surface facilities.

The results will assess the basic design parameters of the planned storage facility e.g. the storage size, storage volume and operating pressures.

4.2.2 Final Design of Storage Caverns after Drilling Wells

The final design will be based on data achieved from drilling operations of cavern wells. This data will be evaluated to adjust the dimensioning of the single cavern. A more precise definition of maximum and minimum pressures for gas operation will be provided. This will include limitations during which the caverns may be operated at minimum pressure levels as well as limitations on gas injection and withdrawal rates.

After the drilling of the cavern wells, further input is needed for the final design from:

- Comprehensive rock mechanical test programme on core material (core diameter of 100 mm) to quantify parameters such as strength and deformation behaviour of the relevant rock salt formation, and
- Complementary numerical calculations and refinements of the existing model for the final dimensioning of the storage caverns.

4.3 Surface Subsidence

The material properties of rock salt are characterised by visco-elastic/visco-plastic behaviour. Owing to this behaviour and because internal cavern pressure will always be below lithostatic pressures a salt cavern will shrink or converge over its lifetime. The resulting loss of salt volume will be conveyed one-to-one to the surface, where a very gentle subsidence bowl of a volume equivalent to the total volume loss of salt will form. The diameter of the subsidence bowl is a function of the depth of the cavern. In case of a cavern field, the individual subsidence bowls will overlap and surface deformation (vertical and horizontal movements with a compressional component in the centre and an extensional component at the margins) will add up to a total surface subsidence across the cavern field. The surface deformation and slope angles to be expected above cavern fields are very small. A study on the subsidence pattern to be expected under Larne Lough will be undertaken after a decision regarding the well pad area/cavern field layout (Chapter 6.1) has been made.

5 Drilling and Casing of Cavern Wells

The present chapter comprises of a description of the drilling and completion procedure of the cavern wells. The layout of the casings and tubings (leaching completion and gas storage completion) is described.

5.1 Requirements for Well Casing and Gas Completion

The diameter and the setting depth of the last cemented casing shoe (LCCS) are the key parameters for a cavern well design. The LCCS isolates the cavern from the formation above and its quality is crucial for the tightness of the cavern. Criteria for the design and the dimensioning of the LCCS are the required flow rates that persists through all the tubings installed therein, the maximum internal pressure in the well and the maximum horizontal stress in the formation. Under consideration of the desired leaching rates and a predefined gas production rate, a gas-tight 13 ⅜“ last cemented casing is proposed for each of the cavern wells. A feasible casing scheme (Enclosure 5-1) would be:

- 36” conductor casing,
- 26” safety casing,
- 18 ⅝” anchor casing, and
- 13 ⅜”/14” last cemented casing.

This dimension allows the use of a large-sized 9 ⅝" gas completion (Enclosure 5-1) with a subsurface safety valve (SSSV). The cavern well is to be completed with a 10 ¾” outer leaching string and a 7” inner leaching string for the leaching operation (Enclosure 5-1). With gas as blanket medium, the 10 ¾” outer leaching tubing does not have to be gas-tight and can be equipped with standard connections. For the corresponding hydraulic calculations see Chapter 7.2.

5.2 Trajectories of Cavern Wells

5.2.1 Limitations for Cavern Well Trajectories

Generally, the design of a well path necessitates the consideration of a number of different factors beyond the avoidance of collision with adjacent wells and beyond reaching the target. These factors include parameters related to the drilling procedure, well completion and other possible well operations. Fundamental parameters apart from the required step-out distance from surface position to the target are the position of the kick-off point (KOP), the position of the end of drop section (EOD) and the acceptable maximum dog leg severity.

Based on experiences of comparable cavern projects some limitations on the well trajectories are recommended to be considered.

In order to prevent difficulties during the implementation of the casings of the planned diameters the dog leg severity is suggested to be limited to 3°/30 m for build and drop sections.

Cavern wells have to be planned to be vertical within and at approximately 100 m above the depth interval envisaged for cavern construction, which demands an S-shaped well path. The placement of the EOD at approximately 100 m above the planning depth of the last cemented casing appropriates to the prevention of problems while tripping the leaching strings.

During the installation of the leaching and gas completion, in particular the setting of packer systems, the maximum inclination should be as low as possible (less than 30° at best). These planning mechanisms reduce the potential for problems induced by possibly high torque and drag.

The above requirements need to be taken into account in the design of the layouts of cavern fields. Such directional drilling of cavern wells is common in Europe.

5.2.2 Possible Trajectories of Cavern Wells

The top of the Permian salt is expected at true vertical depths of 1,400 and 1,500 m. Under consideration of required roof pillar section of 40 m of rock salt above all caverns (Chapter 3.1), the EOD will supposedly be in the true vertical depth range of 1,340 to 1,440 m. According to step-out distances of up to 580 m the KOP has to be placed as shallow as possible.

Assuming a KOP as shallow as 150 m below MSL (approximately 170 m below ground level) the maximum inclination will be between 14° and 34° for the respective cavern wells arranged in form of the cavern field layout proposed in Chapter 6.1.

The set of seismic data suggest that the base of the Permian salt will be at true vertical depths between about 1,630 and 1,710 m below ground level.

5.3 Indicative Drilling and Casing Programme

The conductor pipes of 36” in diameter are recommended to be pre-set by air drilling or hammering.

The drilling rig will start drilling with a bit size of 30” or 32” into the top of the mudstone of the Glenstaghey Formation (MMG). A surface casing of 26” will be run and cemented to surface. The fresh water/native clay mud may be exchanged for an oil-base mud or upgraded to an salt saturated inhibitive water-base mud system to drill the saliferous bed of the MMG. After drilling out of the casing and cement a steerable bottom hole assembly with a 23” bit will allow to build inclination. In order to establish well integrity prior to drilling the 17 ½” section the 23” section will be drilled to the base of the MMG (approximately 900 m TVD) and cased with an anchor casing with a diameter of 18 ⅝”. The 17 ½” section will range over the SSG and the Upper Permian lithologies including the target horizon of the Permian salt.

Depending on the results from coring of the salt section in the confirmation well (proposed Ballylumford-1) at least five drill cores (4” in diameter) are recommended to be recovered from the salt section from each of the cavern wells. The core material allows the determination of rock-mechanical and leaching parameters at depths of the last cemented casing shoe, the cavern roof, the upper and lower third of the cavern interval and the planned cavern sump. Those parameters are required to plan in detail the leaching process and to constrain operational limitations based on rock-mechanical behaviour for each individual cavern (Chapter 4.1).

After the base of the Permian salt is reached (Chapter 3.1), a bridge plug is recommended to be set to ensure the successful installation and cementation of the last cemented casing with diameters of 13 ⅜” down to the casing shoe of the anchor casing and 14” from the shoe of the anchor casing down to 40 m below the top of the Permian salt (roof pillar). This casing has to be gas tight and is suggested to be installed with welded connections.

6 Possible Site Layout

According to the information available at present a basic design of surface and subsurface installations and facilities has been developed.

6.1 Cavern Field Layout

For the design of a cavern field, geological and rock mechanical parameters need to be considered as well as requirements from engineering, drilling procedures, casing characteristics and completion techniques.

The thickness of the Permian salt will be decisive for the height and volume of the future caverns. Thus, areas will be preferred, for which larger thicknesses are indicated by the isopach map from the seismic survey (Enclosure 3-4).

Preliminary rock mechanical considerations are suggesting a minimum distance between the planned cavern wells of 300 m and a maximum feasible cavern diameter of 80 m. This usually results in a more or less hexagonal grid of storage caverns.

In consideration of these requirements and limitations for cavern well trajectories suggested in chapter 5.2.1 a preliminary layout of the possible cavern field at Larne Lough has been established (Enclosure 6-1). It is designed to be developed from a well pad neighbouring the gas plant at Ballylumford. According to this field layout and the interpretation of the seismic data the expected depths of the top of the Permian salt for the seven respective caverns ranges from 1,400 to 1,495 m. The isopachs of the Permian salt show that salt thicknesses at the locations of the well targets are estimated to be between 210 and 240 m. From both, the top of the Permian salt, and the salt thickness, the base of the target horizons corresponds to depths from 1,640 to 1,710 m at the respective target coordinates. Assuming the positioning of the kick-off point at 150 m below MSL, the maximum inclination of the seven cavern wells will be below 35° in the proposed layout. The above assumptions are the base of the evaluation in this report.

A possible alternative site has been identified for the construction of the well pad, situated approximately 800 m SSE of the area neighbouring the gas plant. An alternative cavern field layout has been developed (Enclosure 6-2). From the interpretation of the seismic survey the depths of the top of the Permian salt for the seven respective caverns is to be expected to range from 1,340 to 1,440 m. From the isopach map of the Permian salt, thicknesses of the Permian rock salt are to expected to also vary between 210 and 240 m at the target locations. Presuming a feasible kick-off point 150 m below MSL for this alternative cavern field layout, the maximum inclination of the seven cavern wells is estimated to ba also less than 35°.

A very simplified block diagram illustrates the proportions of the proposed caverns and is displayed in Enclosure 6-3.

6.2 Plant Layout

The location of the above ground facilities are illustrated in Enclosures 6-4. Due to the topography the surface facilities will be distributed in three areas at different elevations. The three areas will be secured by fences for safety and security reasons. The areas have to be accessible by newly constructed roads.

Enclosure 6-5 shows the above ground facilities (cavern pad, leaching plant, and gas plant) in detail. The area most proximate to the shoreline of Larne Lough will serve as well pad with an elevation of approximately 17 m, unless the alternative area further down the side of the Lough is chosen. The gas plant with compressors and drying units will be constructed at an elevation of approximately 46 m adjacent to the SNIP pipeline compound. The gas plant will consist of an operations building, a transformers and frequency converter building, a compressors building, gas coolers, gas heaters as well as gas dehydration. The entrance will be from the east side of the site (Chapter 10). The leaching plant will be constructed in a third area just NE of the Ballylumford Road at an elevation of approximately 60 m. All existing buildings in the site envisaged for the construction of the leaching plant will be removed. The leaching plant is planned to consist of a pump station, an operation building and an electrical substation. All three areas will be accessible via newly constructed roads (Chapter 8).

The brine disposed site is planned to be constructed along the north-eastern coast of the Islandmagee (Enclosure 6-4). A number of potential points for intake of sea water are being considered.

Brine pipelines are required to connect the leaching plant with the well pad. Whilst the gas pipelines need to be installed to connect the well pad with the gas storage plant. These pipelines are supposed to connect the gas storage plant with the local gas transmission network at the SNIP above ground installation at Ballylumford, adjacent to the planned gas storage plant.

6.3 Well Pad Layout

The design of a well pad has to meet requirements for the drilling, leaching and gas operations, some of which will overlap in time to allow for a most efficient scheduling of project steps (Chapter 11). The well pad has to provide space for the drilling rig under consideration of a required minimum distance between the rig and the existing overhead HV-line from the nearby power plant, in the case of the well pad option adjacent to the power station (Enclosure 6-6).

The seven well heads will be arranged in single row centred in a rectangular well pad approximately 110 m long and 45 m wide. The cavern well heads will be aligned parallel to contour lines to minimise constructional work necessary for the levelling of the site.

An equal spacing between the drilling slots of the planned seven wells and the size of the cavern cellars has to allow a safe installation of the preventer stack and cavern well heads as well as for safe skidding of the drilling rig.

Sufficient distances between the conductor casings/well heads and to the walls of the cavern cellars facilitate the installation of fittings and connection of the cavern heads to the brine and gas pipelines.

For security reasons it is desired to place the cavern well heads below the surface of the well pad. This results in a cavern cellar depth of approximately 5.5 m below the surface of the concrete foundation. Three of the cellars will include two well heads; one cellar will include a single well head.

A low voltage distribution will be required.

7 Cavern Construction

The storage volume is created by circulating seawater through the leaching strings during the cavern leaching phase. Two different ‘leaching modes’ are applied:

- ‘direct mode’ or ‘bottom injection’ (injection through the inner leaching string), and
- ‘reverse mode’ or ‘top injection’ (injection through the annulus between inner and outer leaching string).

By switching between these leaching modes, the cavern will be shaped within the boundaries of the rock mechanical envelope. Further activities such as the changing of the setting depth of the leaching strings as well as the moving of the blanket level will continuously design the cavern shape and dimension development. The cavern roof will be protected with the implied non-leachable blanket medium with a lower density compared to the brine that is produced in the cavern. Nitrogen is planned to be used as blanket medium in this project.

The cavern development will be recorded in a conceptual leaching programme which lists the operating parameters and the sequence of actions against a realistic time frame. The leaching concept results from considerations of many different factors. These factors are the geology of the salt deposit, physical, chemical and mineralogical parameters, rock mechanical constraints and design parameters as well as technical and logistical requirements and restrictions. Some of these constraints can have a major influence; others may have only a limited influence on the development of the gas storage caverns. The preliminary leaching programme, the timing for an individual cavern and an assessment of its feasibility is presented in the following chapter.

7.1 Leaching Model

The leaching programme is always adjusted to the present geology of the salt deposits as well as the desired and the feasible cavern shape. The realisation of the cavern volume within the rock mechanical envelope, i.e. the theoretical boundaries that shall not be exceeded by the leaching process at any time (Chapter 4) is obligatory. For an ideal cylindrical leaching model a diameter smaller than the maximum of 80 m has to be selected to yield a most realistic result. A ellipsoidal shape of the cavern roof provides geo-mechanical conditions of the greatest stability.

Preliminary values and preconditions regarding properties of the salt deposits were estimated prior to the preparation of a leaching programme. The following characteristics have to be experimentally determined:

- horizontal and vertical leaching velocity of the rock salt,
- chemical/mineralogical composition of salt,
- content of insolubles in the rock salt,
- vertical distribution of the insolubles within the salt,
- loosening factor of insolubles in the cavern sump, and
- salt density.

Additional investigations are necessary to verify or modify the assumed parameters. Detailed laboratory tests (leaching tests) on core material to be recovered from the confirmation well (proposed Ballylumford-1) will be required to adjust the input data and to refine the leaching concept.

In addition to these preconditions, several time dependent variables are used to set-up an operational leaching concept. These parameters are basically:

- depths of leaching strings,
- blanket level depth,
- leaching rates, and
- leaching method (direct/ reverse circulation).

The leaching of a single cavern takes a duration of approximately two to three years. It is intended to perform the leaching of the projected cavern volume within the shortest time frame and effective costs. This is most likely to be achieved with a fine-tuned balance of high brine saturation and high flow rates according to the feasible leaching hydraulics. In order to change the operational parameters several leaching-related activities (workovers, sonar surveys, blanket adjustments) will be applied. The number and sequence of these activities will be scheduled and planned to assure a safe construction of the cavern within a reasonable frame of time and costs.

With the geological data and some assumptions regarding cavern temperature and salinity of leaching water, a 3D leaching simulation software is used to model the cavern development. The assumed input parameters for the leaching model are listed in Table 7-1. In many years of experience with this software, the results of the simulation have always proved to be very reliable when later compared to the actual leaching progress. At this stage of the project the simulation relies on many assumptions. The simulation will be subject to stepwise refinements by the substitution of assumptions and estimations of data from future drillings (proposed confirmation well 'Ballylumford-1').

Table 7-1: Input data for leaching model

content of insolubles (average)	5	vol-%
estimated loosening factor for insolubles	1.7	
average leaching velocities, horizontal	13.0	mm/h
average leaching velocities, vertical	18.7	mm/h
temperature in cavern	40	°C

7.2 Cavern Leaching Programme

The output of the 3D leaching simulation is a conceptual leaching programme which lists the operating parameters (flow rates, circulation modes etc.) and the sequence of actions (workovers, sonar surveys etc.) against a realistic time frame. The cavern construction is performed stepwise in a pre-defined three-stage leaching concept comprising the sump, main and roof leaching phases, respectively. The phases are described in Chapter 7.2.1 and 7.2.2. Further simulation results are:

- the concentration of the produced brine,
- the dissolved and produced amount of salt,
- the net cavern volume,
- the volume of insolubles in the cavern sump, and
- the 3D development of the cavern.

These output data will always be visualised and used for further evaluations. The result of the preliminary leaching simulation is shown in Enclosures 7-1 and 7-2. As shown in Enclosure 4-1, the cavern dimensions are within the rock mechanical limits of d_{max}= 80 m and fit within the ellipsoidal shape of the cavern roof. Net leaching time to create the cavern will be approximately 670 days (22 months). Gross operational time (including workovers, perforations, and sonar and blanket surveys) will amount to approximately 700 days. Additional downtime due to operational delay is not included.

7.2.1 Sump Leaching Phase

Based on the geological preconditions and the desired shape of the cavern, it is necessary to develop the desired diameter of 80 m during the sump leaching phase. The sump leaching phase will take approximately two months. The blanket level will remain fixed throughout sump leaching. Flow rates of 100 to 200 m³/h will be realized during this stage and will achieve a geometrical volume of about 20,000 m³. During the sump leaching phase the mining mode will be direct (bottom injection). In order to keep up with the rising sump level and to prevent the leaching strings from getting plugged with insolubles, one workover will be performed (lifting of the inner leaching string). By the end of the sump leaching phase with an injection rate of approximately 200 m³/h the brine concentration will reach approximately 180 g NaCl/l (Enclosure 7-2).

7.2.2 Main and Roof Leaching Phase

During the main leaching phase the mining mode will be reverse (top injection) to achieve a good cavern shape development. The leaching rate will be around 300 m^3/h (nominal flow) for the whole remaining time of the leaching process. At the beginning of the main leaching phase, the leaching strings will be adjusted and the blanket level will be risen for approximately 50 m above the previous level.

During the roof leaching phase the blanket position will be modified in small steps to facilitate the development of an ellipsoidal cavern roof. The brine concentration will gradually increase to a maximum of about 312 g NaCl/l, close to saturation, towards the end of the process (Enclosure 7-2).

By the end of the main and roof leaching phases, a geometrical cavern volume of about 480,000 m³ will be realized. The cavern volume and shape will be checked by a final sonar survey before the leaching completion will be retrieved.

7.3 Leaching Hydraulics

Following the sump leaching phase with a production rate of 100 m³/h, it is intended to subsequently operate the caverns at a maximum rate of 300 m³/h. The leaching pumps are, in terms of injection pressure and power requirements, designed to allow such a flow rate, while leaching three caverns in parallel.

Using nitrogen as blanket medium, the pressure at the last cemented casing rises with increasing depth of the brine-blanket interface. At every stage of the leaching process this pressure has to be kept below the maximum operation pressure. The most critical point is reached when the blanket level is at its deepest position and the brine is saturated.

Due to the great depth of the caverns, a high pressure difference will develop between the leaching strings (i.e. the blanket annulus and the brine annulus) at the well head. Thus the pipe's wall stability against collapse under biaxial stress has to be verified.

Based on the maximum flow rate of 300 m³/h, suggested for the leaching concept, and the friction losses to be expected for the depths of the caverns a last cemented casing of 13 ⅜"/14" is proposed (Chapter 5.3). The typical leaching string combination appropriate in this casing is 10 ¾" x 7".

The hydraulic calculations are based on situations with the deepest pipe settings, the deepest blanket level and the longest well path for the deviated well (horizontal deviation of 700 m). In the further phases of the leaching process the blanket will be raised stepwise; therefore the hydraulic conditions will be less critical.

The input parameter and the results of the hydraulic calculation for the leaching process are shown in Table 7-2.

Table 7-2: Results of hydraulics calculation for the leaching process

leaching rate	300	m³/h
injection pressure at well head	111	bar
pressure at casing shoe of last cemented casing	243	bar
maximum pressure at casing shoe of last cemented casing	252	bar
brine pressure at well head	10	bar
blanket pressure at well head	206	bar
power requirements for high pressure leaching pump	3 x 1.3	MW

The brine pressure at the well heads is proposed to be 10 bar because of the change in deviation between the caverns pads and the brine tanks (Chapter 6.2).

8 Leaching and Brine Facilities

Leaching systems in general consist of the water supply, leaching station, brine disposal system, diluting system, blanket system and pipelines.

A flow diagram of the leaching operation is shown in Enclosure 8-1. The main field lines for seawater, brine and blanket medium run from the leaching station to the cavern pad. The leaching will start with cavern 1 to 3. Each cavern will be leached through one borehole with concentric tubings.

Table 8-1: Key parameters for the leaching facilities

number of caverns	7	
number of leached caverns in parallel	3-4	
leaching flow per cavern for sump leaching	100	m^3/h
max. leaching flow per cavern	300	m^3/h
cavern volume net	480,000	m^3
leaching well head pressure	110 +/- 5	bar
brine discharge	into the sea, NE coast of Islandmagee	
blanket medium	nitrogen	
power supply	110	kV

Enclosure 8-2 shows a plot plan of the leaching facilities. The buildings and units which are to be built at the site are:

- operation building,
- pump station,
- electrical substation (power supply),
- Tanks,
- blanket unit,
- car park, and
- storage area.

8.1 Operation Building

The operation building (Enclosure 8-2) will be located next to the main gate and is to serve as the security checkpoint, central control room and administration. In general, the leaching plant will be operated from the central control room in the operation building which has to technically equipped to be capable of controlling the whole operations for the entire storage plant. The control room will be manned 7 d/24 hrs.

It is supposed to house all necessary offices for the plant management, administration, HSE- and all other engineers. The operation building will also contain social and dressing rooms as well as sanitary facilities.

8.2 Pump Station

Two leaching pumps and two brine pumps will be arranged inside the pump building (Enclosure 8-2). The seawater for leaching will be taken from the sea at a distance of 2.5 km (Enclosure 6-4). The leaching pumps will be driven by variable speed electric motors. All pumps will work on one pipeline with the same speed and flow. The basic design parameters for each pump are listed in Table 8-2.

Table 8-2: Basic parameters for a single leaching pump

flow required	450	m³/h
min. suction pressure	2	bar
head	1,100	m
motor design	2	MW
voltage	690	V

The leaching pumps will inject the leaching water into the cavern via the leaching water pipe system with a required pressure of approximately 110 bar. A main field pipeline will supply all caverns with leaching water. As a compromise between availability and cost, the system of two pumps each producing 50 % of the total flow was chosen. If one pump has to be maintained or repaired for a certain period of time, the other pumps will be capable to produce 50 % of the total flow. This will suffice to leach two caverns simultaneously.

8.3 Electrical Substation

The electrical substation will lie in immediate vicinity to the pump house (Enclosure 8-2). It is supposed to contain the power supply of the pumps transformers and switchboards. For this study, it is assumed that power will be supplied to the plant from an existing 110 kV feeder. A transformer will supply the 11 kV switchgear. Again, this switchgear will supply the two transformers for the leaching pumps and the transformer for the 0.4 kV supply of the leaching plant. In case of power failure of the public grid, the power supply for the control system and medium voltage system will be kept operational by a battery backup device.

8.4 Water Intake and Brine Disposal Station

The water intake station (Enclosure 6-4) will be constructed in a concrete cellar near the water intake which will be connected to the sea by water intake lines. The possibility to remove the equipment with a crane for maintenance should be given. A few different sites are currently being reviewed, including one close to the proposed brine disposal site to the north-east of Islandmagee.

During the construction of salt caverns by application of solution mining techniques nearly-saturated brine is produced, whereby 1 m³ solution mined underground volume represents approximately 8 m³ brine. Correspondingly, the construction of a cavern with a volume of 480,000 m³ generates approximately 3.8 M m³ of brine that needs to be disposed. Three brine transport pumps are planned to transport the brine to the site of brine disposal north-east of the Islandmagee on a distance of approximately 2.5 km.

8.5 Field lines

The seawater field lines as well as the brine and diluting/nitrogen field lines will be constructed from carbon steel with a general corrosion allowance of 5 mm.

8.6 Well pad

All caverns will be leached from one well pad (Enclosure 6-6). The well heads will be placed below the surface of the cavern pad. A container to be located on the cavern pads will be planned for local electrical installations. The buildings and equipment will be designed to meet the noise limitations in the area.

9 Completion and Gas First Fill

Subsequent to the leaching process several activities have to be planned before the cavern is ready for gas operations. Besides the technical activities, e. g. the installation of the gas production tubing, the tightness of the cavern has to be tested before the cavern can be filled with gas while brine is withdrawn from the cavern with a debrining string, that will be snubbed out afterwards. All activities necessary before the start of routine gas operations will take more than a year. A time of approximately 8 months will be necessary to fill the single cavern with gas.

9.1 MIT (Mechanical Integrity Test)

An important prerequisite for assuring a secure and reliable operation of storage caverns is the verification of mechanical integrity of the cased and cemented borehole against the surrounding formation, particularly at the casing shoe of the final cemented casing. The testing has to prove that leakage will not result in an uncontrolled escape of flammable storage products to surface or the contamination of drinking water resources.

A first hydraulic test is usually performed at least 4 weeks after cementing the final casing prior to leaching. The decisive second test (for historical reasons named ‘primary test’) will be conducted subsequent to solution mining before installation of the gas completion. The following paragraphs describe this second test, a common gas interface test.

Interface tests have been developed world-wide to a standard method by injecting a limited volume of test gas. By evaluating parameters such as head pressure and interface depth, it is possible to draw conclusions on the tightness of the well.

In practice, the commonly applied MIT method is the in-situ balance method (ISB). After pressurising the cavern with brine, gas is injected into the annulus to a level below the casing shoe of the final cemented casing in order to set a gas/brine interface in the open borehole. Prior to starting the test, a waiting period is necessary to allow short-term pressure and temperature fluctuations to approach equilibrium.

In order to achieve a quantitative determination of the leakage rate, the wellbore geometry (cross sectional area vs. depth) down to the planned interface depth has to be determined, which is usually known from wireline logging.

At the start and the end of a test interval, the following measurements are necessary:

- well head pressure of test gas,
- interface depth (using Pulsed-Neutron-Gamma-Logs), and

- well temperature from Pulsed-Neutron-Gamma-Logging.

The duration of the tests is normally approximately 1 to 2 weeks. The measurement data will be recorded and evaluated by aid of a computer software. The final assessment of the cavern and well integrity is based on long-term experiences from various projects since there are no generally accepted criteria for the assessment of technical tightness.

9.2 Gas Completion

The proposed gas completion consists of a permanent packer with a ratch-latch connection, a 8 ⅝" tail pipe with landing nipples, and a 9 ⅝" threaded production string. A subsurface safety valve (SSSV) will be implemented.

For the gas completion, a system with a pre-stressed production string is recommended. This can be described as a standard completion. Enclosure 9-1 shows the general configuration.

According to the state of the art, two different SSSV systems are necessary. These systems will be a wireline retrievable SSSV and a tubing mounted SSSV. The latter is an integral part of the 9 ⅝" production string, whereas the WR-SSSV can be removed during possible well operations but has a smaller internal diameter.

9.3 Gas First Fill, Snubbing

During gas first fill, the gas will be injected at the well head into the cavern through the annular space between the debrining string and the gas production string. The brine will be displaced from the cavern through the debrining string. The maximum filling and debrining rate are subject to the static and dynamic pressure losses during the filling process. The injection rates and the resulting filling time, are restricted by the geometry, the maximum operating pressure and the maximum compressor capability.

For gas first fill operations, a 4 ½" debrining string and a 7" tail pipe is presently considered.

Calculations have been performed to estimate the maximum gas injection rate and resulting duration for the gas first fill. The calculations are based on the longest well path for the deviated well.

The results of the hydraulic calculation for the gas first fill are summarised in Table 9-1.

Table 9-1: Results of hydraulic calculations

	4 ½" debrining string	
maximum filling rate	21,000	Nm³/h
maximum debrining rate	105	m³/h
filling time	238	days

The hydraulic calculation of the maximum filling and debrining rate is based on operating at the maximum pressure at the casing shoe (250 bar). Assuming a 4 $^{1}/_{2}$" debrining string, a maximum filling rate of about 21,000 Nm³/h is possible. For this case a filling time for one cavern is expected to take some 238 days.

The gas/brine interface will be levelled down to the shoe of the debrining string. Subsequently, the debrining string is to be snubbed out to make the cavern ready for gas operations.

10 Gas Operations and Facilities

It is planned to perform the leaching of the seven caverns in two phases. The time needed for gas first fill is approximately 8 months. 3 caverns need to be first filled with gas at the same time at the end of the first leaching phase and 4 caverns at the end of the second leaching phase. This requires to have 2,000,000 Nm³ gas per day available for filling the caverns while extracting the brine.

The compressors should be able to fill one cavern with 21,000 Nm³/h, respectively four caverns with 84,000 Nm³/h. Because this flow can not be realised by use of the planned centrifugal compressors without recycling, separate smaller compressors will be installed for first gas fill only.

In total 5 to 6 years from the beginning of the leaching operation are estimated to be required to connect all 7 caverns to the gas transmission network (Enclosure 11-1).

10.1 Injection and Withdrawal Scenarios

Following limitations and requirements were considered for the planning of gas operations as well as of gas facilities:

- Maximum total gas flow injection of 555,000 Nm³/h.
- Maximum total gas flow withdrawal of 950,000 Nm³/h.
- Pressure changes in the cavern must not exceed 10 bar per day to ensure rock mechanical integrity of the cavern. This limitation is implying a maximal gas flow of 200,000 Nm³/h per cavern.
- Minimal cavern pressure is 90 bar for a duration of one month or 120 bar for a duration of five months.
- Maximal cavern pressure is 250 bar.
- Gas withdrawn from the caverns has to yield pressures exceeding 60 bar to feed the national pipeline net (with a pressure of 60 bar), otherwise produced gas may have to be compressed to supply the pipeline net.

Enclosure 10-1 shows a flow diagram of the gas operations. Procedural parameters (gas volume, flow rate, cavern pressure and gas flow velocity) during gas operations are illustrated in the Enclosure 10-2. All these parameters refer to one of the 7 caverns. Starting the gas injection at the minimum cavern pressure of 90 bar (cushion gas volume: 44 x 10^6 Nm³ per cavern, 302 x 10^6 Nm³ per 7 caverns), a gas injection flow of approximately 80,000 Nm³/h per cavern would increase the cavern pressure for 4 bar per day. After 40 days the cavern pressure would reach its maximum value of 250 bar. Total stored gas volume at the maximum cavern pressure might be 120 x 10^6 Nm³ (840 x 10^6 Nm³ in 7 caverns), corresponding to a maximum working gas volume of 77 x 10^6 Nm³ (538 x 10^6 Nm³ in seven caverns). This would comfortably meet the ISL target working gas volume of 500 x 10^6 Nm³. After a certain shutdown time (duration to be specified by IfG) gas withdrawal may be operated with a maximum gas flow of 136,000 Nm³/h per cavern, resulting in a daily decrease of cavern pressure of 7 bar. At this maximum withdrawal rate the cavern pressure will drop down to 120 bar after approximately 19 days and further down to the minimum pressure of 90 bar after 5 further days. Gas velocity at well head during gas injection might be between 3 and 8 m/s and during gas withdrawal between 5 and 15 m/s.

The pressure losses between compressors and pipelines and between compressors and well heads were estimated to be 5 bar, respectively. The gas will need to be compressed from 55 to 90 bar as minimum or to 230 bar as a maximum pressure difference. Both compressors have to be designed for these ranges.

For the injection the following scenario is proposed:

- 1. Phase: 277,500 Nm³/h with 1 compressor, and
- 2. Phase: 555,000 Nm³/h with 2 compressors.

The gas to be stored in the caverns will enter the plant at the station inlet equipped with filter and metering systems. Compression will be attained by two electrically driven centrifugal compressors. A suction scrubber protects the compressors from liquids, entrained in the gas. Each compressor train consists of two compressor casings with intermediate- and after-cooler. The gas injection will have a capacity of 2 x 277,500 Nm^3/h with two compressor trains to a maximum cavern well head pressure of approximately 230 bar. The gas will be pressed into the caverns via the field pipeline system.

For the withdrawal operations the following parameters have been selected for the design of gas facilities:

- 1. Phase: 410,000 Nm³/h with one pressure reduction and dehydration unit, and
- 2. Phase: 950,000 Nm³/h with two pressure reduction and dehydration units.

With the completion of the second unit the full capacity can be realized. Especially for the withdrawal of gas a redundant system should be foreseen to avoid delivery problems for the customer.

Feasible injection and withdrawal rates are summarized in Enclosure 2-2. A plot plan of the gas plant is displayed in Enclosure 10-3.

10.2 Well Head Pressures during Gas Withdrawal

The aim of the calculations is the estimation of the resulting well head pressure during gas withdrawal operations. The operator needs to know whether the resulting well head pressure will still remain above the pressure level of the local gas transmission network under consideration of pressure losses in the surface gas plant.

The pressure change during withdrawal along the well consists of:

- a static share (weight of gas column) depending on the true vertical depth (TVD) of the production string and
- a dynamic share (friction losses) depending on the measured depth (MD) of the production string.

In order to investigate the resulting well head pressure during gas withdrawal for the planned gas storage project pressure losses have been calculated for various parameters:

- constant cavern pressures: 90 to 250 bar.
- withdrawal rates: 20,000 to 136,000 Nm³/h per cavern.

Table 10-1: Well head pressures for various cavern pressures and withdrawal rates

withdrawal rate	**cavern pressure**		
Nm³/h	**90 bar**	**170 bar**	**250 bar**
20,000	79 bar	150 bar	221 bar
80,000	77 bar	149 bar	220 bar
136,000	72 bar	146 bar	218 bar

Calculation results compiled in the Table 10-1 are including dynamic and static shares. Pressure losses are largely depending on static pressures. In all cases considered in the calculations the well head pressure is by far in excess of the pressure required for injection into the local gas transmission network of 60 bar.

The pressure drop coinciding with increase of the withdrawal rate is not the only limitation on maximum withdrawal. Depending on pressure and gas composition as well as the rate of gas decompression hydrates may form, if gas temperature dropped to the formation temperature of gas hydrates during withdrawal. The formation of gas hydrates may provoke plugging of well and/or surface piping.

The results of the preliminary pressure loss calculations show that, even at the maximum withdrawal rate of 136,000 Nm³/h per cavern, pressures do not limit the withdrawal capacity. However, the large pressure drop during the ascent from the cavern to the well head will instantaneously cause a significant drop in gas temperature. Therefore, low initial gas temperatures will limit gas withdrawal long before reaching critical pressures.

10.3 Gas Storage Plant

The gas storage plant is planned to consist of two injection and two withdrawal trains. Its main equipment is described hereunder.

An intake separators will be installed to prevent the intake of liquids from the pipeline, and thus, to protect the compressors from damage.

For gas compression, an electrically driven centrifugal compressor will be installed per injection train (Table 10-2). Each compressor will be a centrifugal LP and HP compressor with electrical variable speed drive.

Table 10-2: Technical data per compressor

	proposed		remarks
total flow max.	277,500	Nm³/h	
suction pressure	55	bar	
discharge pressure	max. 230	bar	
required power	17	MW	
drive	20	MW	electric motor

During the first gas fill gas two compressors of smaller capacity will be required to control smaller gas flows. They may be temporarily installed for the time of the first gas fill. Proposed technical specifications for these compressors are listed in Table 10-3.

Table 10-3: Technical data of temporary compressors required for gas first fill

	proposed		remarks
total flow max.	2x 42,000	Nm³/h	
suction pressure	55	bar	
discharge pressure	max. 200	bar	
required power	2 x 2.4	MW	
drive	5	MW	electric motor

Basic parameters for manifolds and piping are proposed to facilitate a most flexible operation of the gas plant. These are listed in the Table 10-4 and Table 10-5.

Table 10-4: Parameter for manifolds

operating temperature gas pipelines	0 to 50	°C
design pressure low pressure section	84	bar (ANSI 600)
design pressure high pressure section	250	bar (ANSI 1500)

Table 10-5: Piping classes

High pressure section	ANSI 1500 (cavern: API 5000)
Low pressure section	ANSI 600
Piping material	carbon steel

The field gas pipeline will connect the gas operating facility with the cavern pad. An additional pipeline from the gas operating facility to the cavern pad will have to be installed to allow the gas first fill of caverns while first complete caverns are already in gas operation.

Pipelines are designed with the following specifications:

- field pipeline to cavern pad: DN 250/ANSI 1500 PN 250.
- pipelines on cavern pad: DN 150/ANSI 1500 (well head API 5000) PN 250.
- pipeline for first gas fill: DN 200/ANSI 1500 PN 250.

The gas withdrawal trains are recommended to be equipped with TEG (Triethyleneglycol) technology for gas dehydration. Two separator trains will enable a continuous gas supply during gas withdrawal, if one separator needs to be serviced.

To prevent the formation of gas hydrates during withdrawal the gas needs to be heated prior to cooling caused by decompression to pipeline pressure. The heating will be attained with heat exchangers working with hot water circuits. The water will be heated by gas fired water bath heaters (Enclosure 10-3).

The piping of the cavern pad will connect the cavern heads to the gas field pipeline. A hydraulic operated emergency shut down valve (ESD) will be installed to enable a safe shut off of this connection.

A tank system to handle condensates, separated liquids and diesel is needed.

The plant will be supplied with power from an existing 110 kV line nearby. A low voltage distribution will supply buildings and equipment of the gas plant (i. e. lighting, receptacles, motors, cathodic protection).

In case of power failure the control and safety systems can be continuously operated by supply from an uninterruptible power supply (UPS). The withdrawal equipment and other consumers can be supplied by a diesel generator.

A process control system will facilitate the control of the plant from the control centre in the operation building (Enclosure 10-3). A permanently manned operation is planned only for the initial stage of the gas operation. Finally, the plant will be operated fully under automatic control with devices still permitting local control of the entire plant as well as of single plant units.

In case of emergency (fire, leakage, line breakage etc), an emergency shut down command will close down all equipment and shut off the cavern wells and the in and outlet of the gas storage plant with fail safe valves.

The following buildings and facilities will be necessary for the gas plant (Enclosure 10-3):

- operation building (preferably close to exit road),
- transformers and frequency converter building,
- nitrogen and air utilities,
- compressor buildings
- water bath heaters
- gas dehydration
- gas metering and pig trap

Size and construction of the buildings needs to be further specified in the detailed design to follow.

11 Time Schedule

Based on assumptions and estimations on the sequence and duration of single project steps and from experiences from comparable projects a time schedule has been established (Enclosure 11-1). Drilling of the confirmation well and evaluation of the drilling result as well as the subsequent design adjustment are not included in the time schedule. The time schedule starts with the basic engineering (including tendering, procurement, delivery/construction) for the

- construction of infrastructure and cavern pad,
- construction of pipelines for water intake and brine disposal,
- drilling and completion of cavern wells, and
- construction of leaching plant.

A time period of approximately one year is estimated to be required for civil works and site preparation. The leaching facilities and the well layout need to be designed at a very early stage to avoid interruptions caused by long delivery times to be anticipated for certain items. Drilling of the first cavern well is expected to commence about six months after the onset of the preparative works. All seven boreholes will be drilled one after another. It is anticipated that the drilling of a single cavern well will take approximately two months. After the well head completion and installation of the leaching strings, the drilling rig will move on to the next location. The drilling process will continue while the first leaching operations will start. In this context, problems may arise from the limited space on the well pad and the short distances between the individual well heads. The drilling and preparation of all cavern wells for the leaching operation is expected to be completed within 14 months.

As displayed in the project time line (Enclosure 11-1), the construction of the leaching plant must be completed before the leaching of the first cavern. The estimation for the duration of the leaching operation is based on the assumption of a leaching rate between 100 and 300 m^3/h per cavern. The cavern field will be developed in two phases with 7 cavern wells in total drilled from one well pad. Due to the limitation of total sea water supply to 1,000 m^3/h for the leaching process, a maximum of three caverns can be leached simultaneously. Caverns 1, 2 and 3 (Enclosure 11-1) will be leached more or less in parallel during the first phase and caverns 5, 6 and 7 during the second leaching phase, respectively. The leaching process for each cavern is anticipated to take approximately 22 months, including downtime required for workovers, blanket adjustments and sonar surveys. Cavern 4 (Enclosure 11-1) will be leached during downtimes during the leaching operation of both phases. A period of approximately 3 ½ years is estimated to be required for the leaching of this cavern. In total, the completion of the leaching operations of all 7 caverns is expected to last approximately 4 years.

After the required cavern volume is realised, approximately 2 months are necessary for integrity testing and simultaneous arrangement and completion of the gas facilities for the gas first fill. The caverns will be completed for gas injection one by one and filled with gas in parallel. The gas first fill will take about 8 months per cavern. After snubbing of the debrining string the caverns will be ready for gas operation. All 7 caverns will be in gas operation after approximately 6 years.

12 Alternative Storage Concept with 5 Conventional and 3 Strategic Caverns

A storage concept with 5 conventional and 3 strategic caverns has been investigated. The basic design parameters for this storage concept are outlined in Enclosure 12-1. The set of data is based on geological assumptions to be confirmed by the confirmation well (proposed Ballylumford 1) in terms of expected salt thicknesses and salt purity as well as pressure induced by the overburden.

The two types of caverns to be designed allow for different modes of gas operations. The three strategic caverns are projected to sustain a certain gas supply in case of a national emergency by displacing the cushion gas by the injection of seawater into the caverns. Only a limited number of storage cycles will be possible, because during each storage cycle the cavern volume will be increased by leaching with seawater. In this scenario is planned to reach the maximum permissible volume of the strategic caverns after three turnovers with seawater. After these turnovers, the resulting caverns are henceforward only available for conventional gas storage with a fixed cushion gas volume.

To permit sufficient gas withdrawal rates during compensation with seawater each of the strategic caverns have to be connected via two wells. Both well are to be equipped with surface controlled subsurface safety valves (SCSSSV).

Two different modes of gas withdrawal for this assembly of strategic and conventional caverns are theoretically outlined below.

Portland Gas plc. have a patent pending for the above storage concept.

12.1 Possible Mode of Conventional Gas Withdrawal

Starting the gas withdrawal at the maximum fill of all eight caverns at cavern pressures of 250 bar would allow 19 days of supply with a total withdrawal rate of 950,000 Nm³/h down to a pressure of 120 bar (Enclosure 12-2 a). Below that pressure the well head pressure of the three strategic caverns would drop below 60 bar and surface compression would be necessary to maintain injection into the gas transmission network at the withdrawal rates required. Alternatively, the five conventional caverns might be able to compensate for the reduction of the withdrawal rate of the strategic caverns for about four more days. After the conventional caverns would be emptied down to the minimum pressure of 90 bar (allowed for the duration of one month) the three strategic caverns together may be producing 135,000 Nm³/h for another four days.

12.2 Possible Mode of Gas Withdrawal with Subsequent Seawater Compensation

Starting the gas withdrawal at the maximum fill of all eight caverns at cavern pressure of 250 bar would allow 12 days of supply with a total withdrawal rate of 950,000 Nm³/h down to a pressure of 170 bar (Phase I; Enclosure 12-2 b). At this pressure it may be necessary to stop the withdrawal from the strategic caverns in case there may be a need for a later seawater compensation. To sustain the required withdrawal rates the five conventional caverns might together contribute 950,000 Nm³/h for further five days (Phase II; Enclosure 12-2 b) down to a pressure of 120 bar (allowed for the duration of five months). They are not to be operated down to 90 bar at that stage as it is unlikely that they may be refilled within a month to 120 bar in a situation that led to the decision for seawater compensation.

The capacity of the planned leaching pumps is permitting a gas withdrawal rate from the three strategic caverns of 153,000 Nm³/h over a period of 42 days (Phase III; Enclosure 12-2 b).

It is supposed that the two types of caverns are designed to be operated independently.

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[3] Manning, P. I.; Wilson, H. E. (1975): The stratigraphy of the Larne Borehole, County Antrim. - Institute of Geological Sciences, bulletin of the BSGS, No. 50, Her majesty's stationary Office, London, 37pp.

[4] McCann, N. (1990): The subsurface geology between Belfast and Larne, Northern Ireland. – Irish Journal of Earth Sciences, 10, 157 – 173.

[5] Penn, I. E. (1981): Larne No. 2, Geological Well Completion Report. – Institute of Geological Sciences, Natural Environment Research Council, 59 pp.

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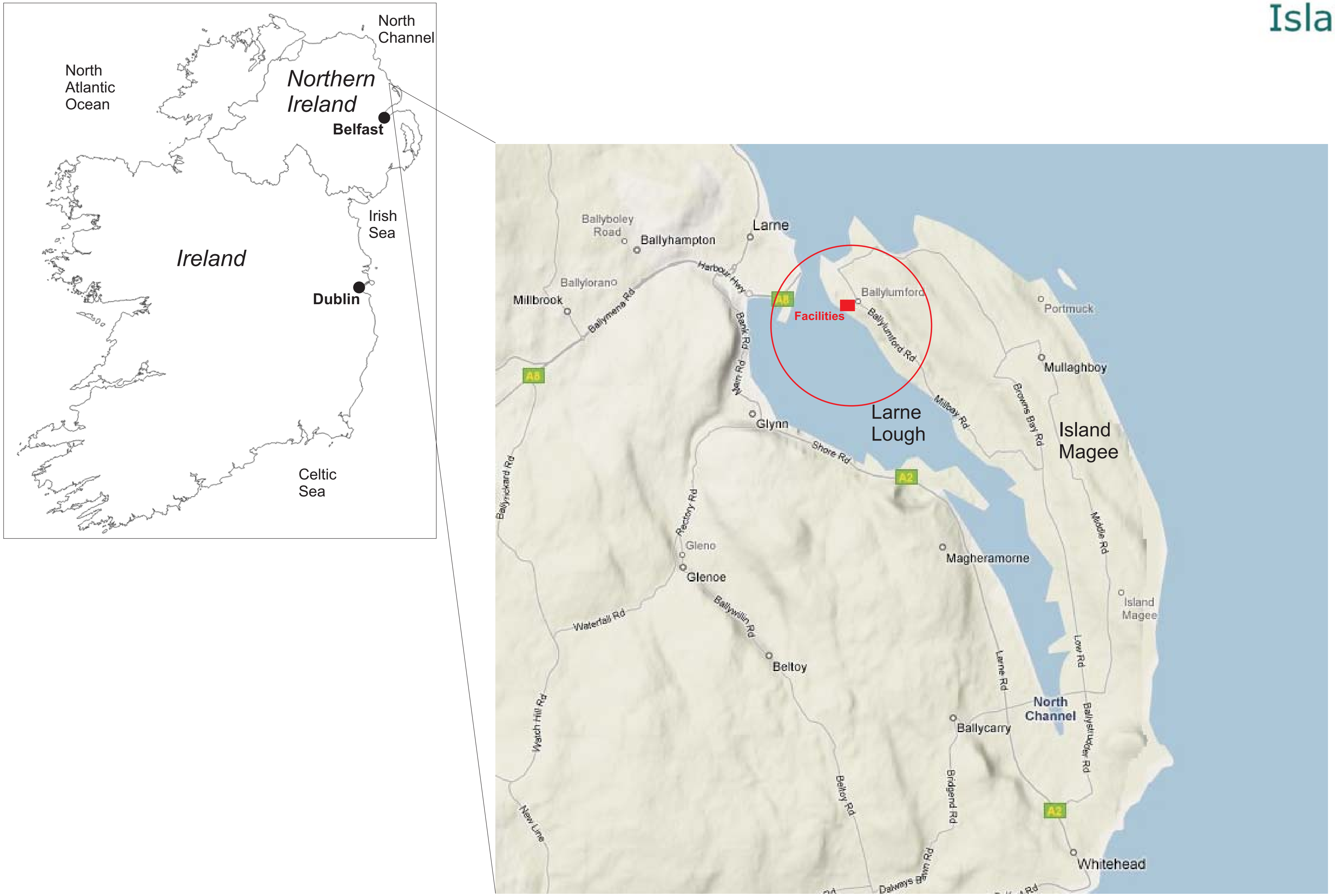
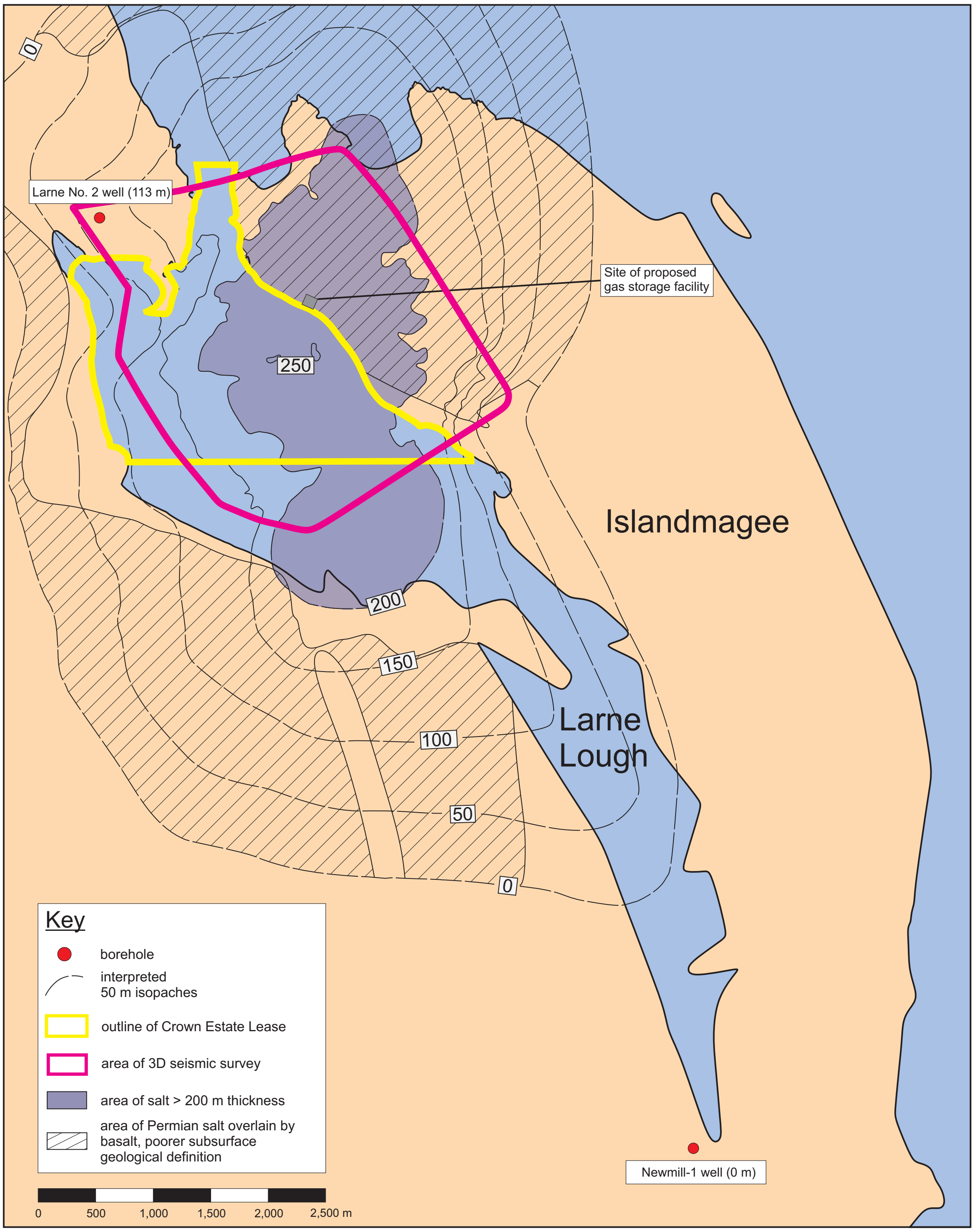
[7] Portland Gas NI Ltd. (2009): Ballylumford-1, Drilling Programme. – pp. 51.

List of Enclosures

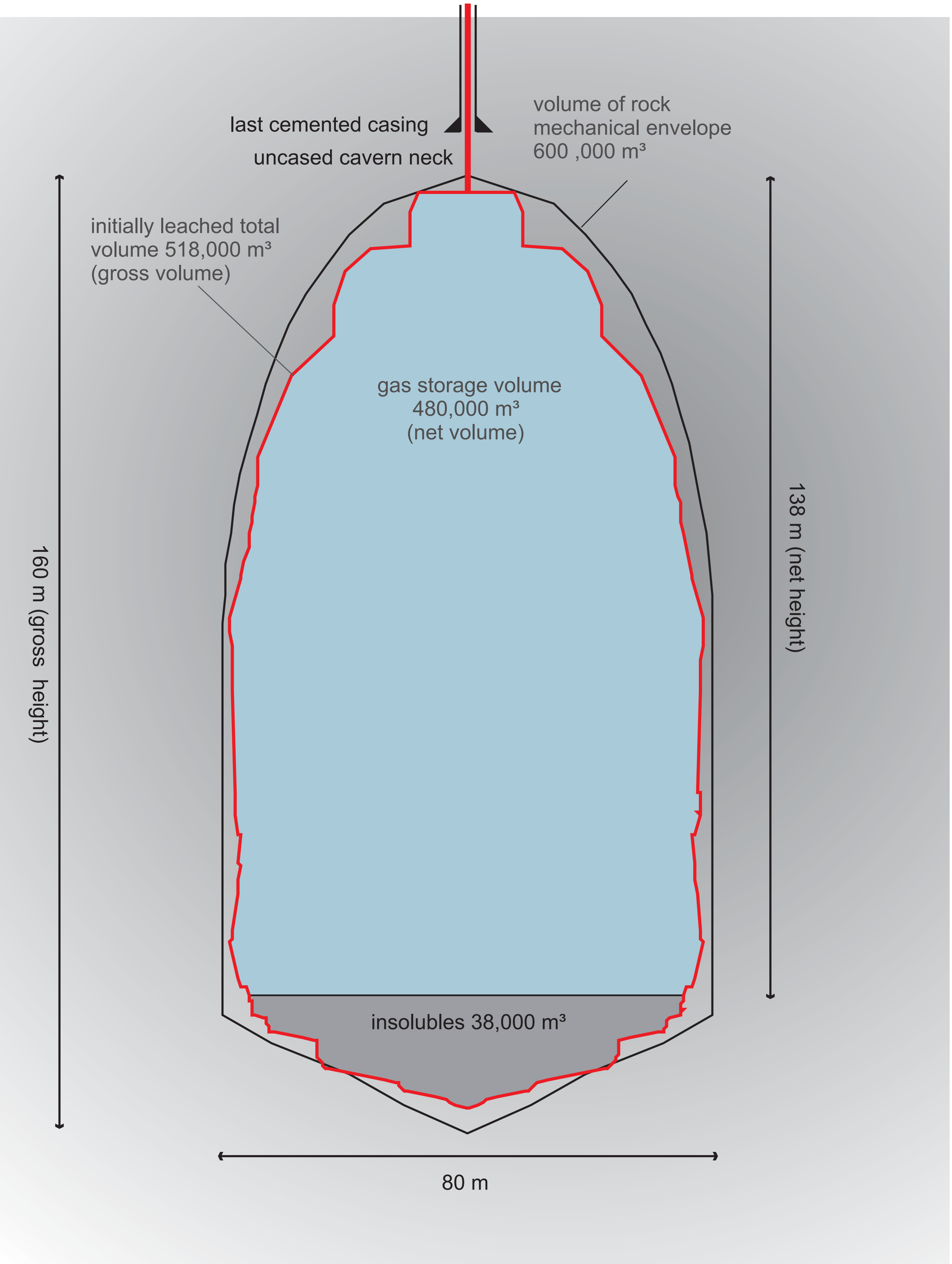


Enclosure 1-1: General location map



Enclosure 1-2: Regional isopach map for Permian salt in the vicinity of Larne Lough

PN 2905
090609_Regional_Isopach_Map.des



Enclosure 2-1: Definition of cavern volumes

PN 2905
090504_cavern_shape_parameters_v00.des/YF

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GENERAL DESIGN PARAMETER

item	value	unit	value	unit
Total storage volume, required	500,000,000	Sm^3	474,000,000	Nm^3
Max. gas flow injection, required	14,000,000	Sm^3/d	555,000	Nm^3/h
Max. gas flow withdrawal, required	24,000,000	Sm^3/d	approx. 950,000	Nm^3/h
GAS OPERATIONS				
Max. gas pressure in cavern	250	bar		
Min. gas pressure in cavern (1 month / 5 months)	90 / 120	bar		

PROJECT BASICS

item	value		unit
Total cavern volume required	3,000,000		m^3
Rock mechanical envelope	600,000		m^3
Geometrical volume per cavern (total of 7) (net volume for gas storage)	480,000 (x 7 = 3,360,000)		m^3
Total number of caverns / wells in the field	7 / 7		
Working gas volume per cavern (total of 7)	77	(x 7 = 538)	x 10^6 Nm^3
Cushion gas volume per cavern (total of 7)	44	(x 7 = 302)	x 10^6 Nm^3
DRILLING AND CASING			
OD of last cemented casing	13 $^3/_8$ - 14		inch
LEACHING			
Number of caverns leached in parallel	3-4		
Leaching flow, sump leaching phase	100 - 200		m^3/h
Leaching flow, main and roof leaching phase	300		m^3/h
Total water/brine flow (incl. gas first fill)	1,000		m^3/h
OD outer leaching string	10 ¾		inch
OD inner leaching string	7		inch
Leaching time per cavern (@ 300 m^3/h)	22		months
GAS OPERATIONS			
OD of gas injection/production string	9 $^5/_8$		inch
Gas injection (per cavern)	80,000		Nm^3/h
Gas withdrawal (per cavern)	136,000		Nm^3/h
Duration of gas injection (between 250 and 90 bar)	40		days
Duration of gas withdrawal (between 250 and 90 bar)	24		days

Enclosure 2-2: Overview of estimated basic design parameters

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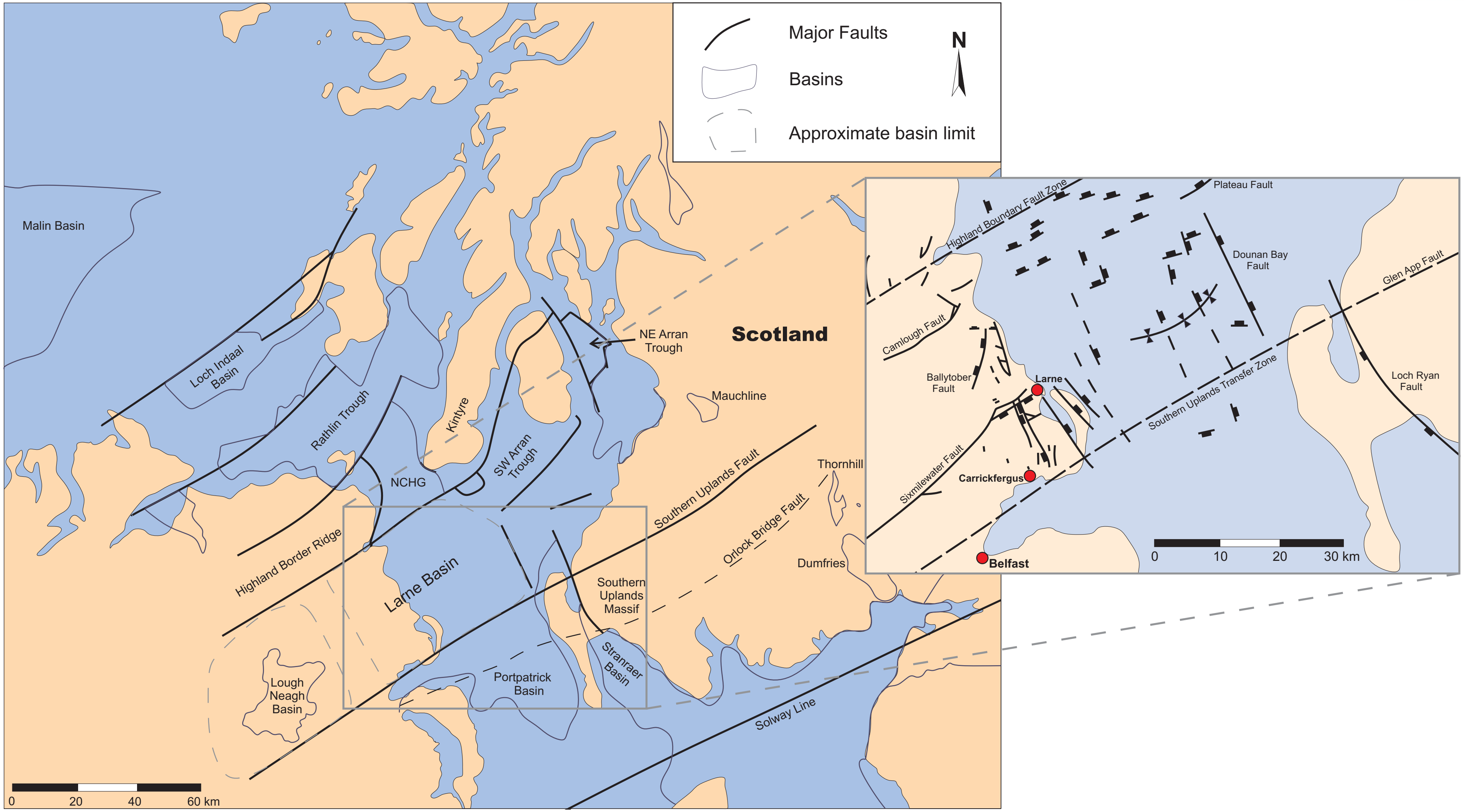
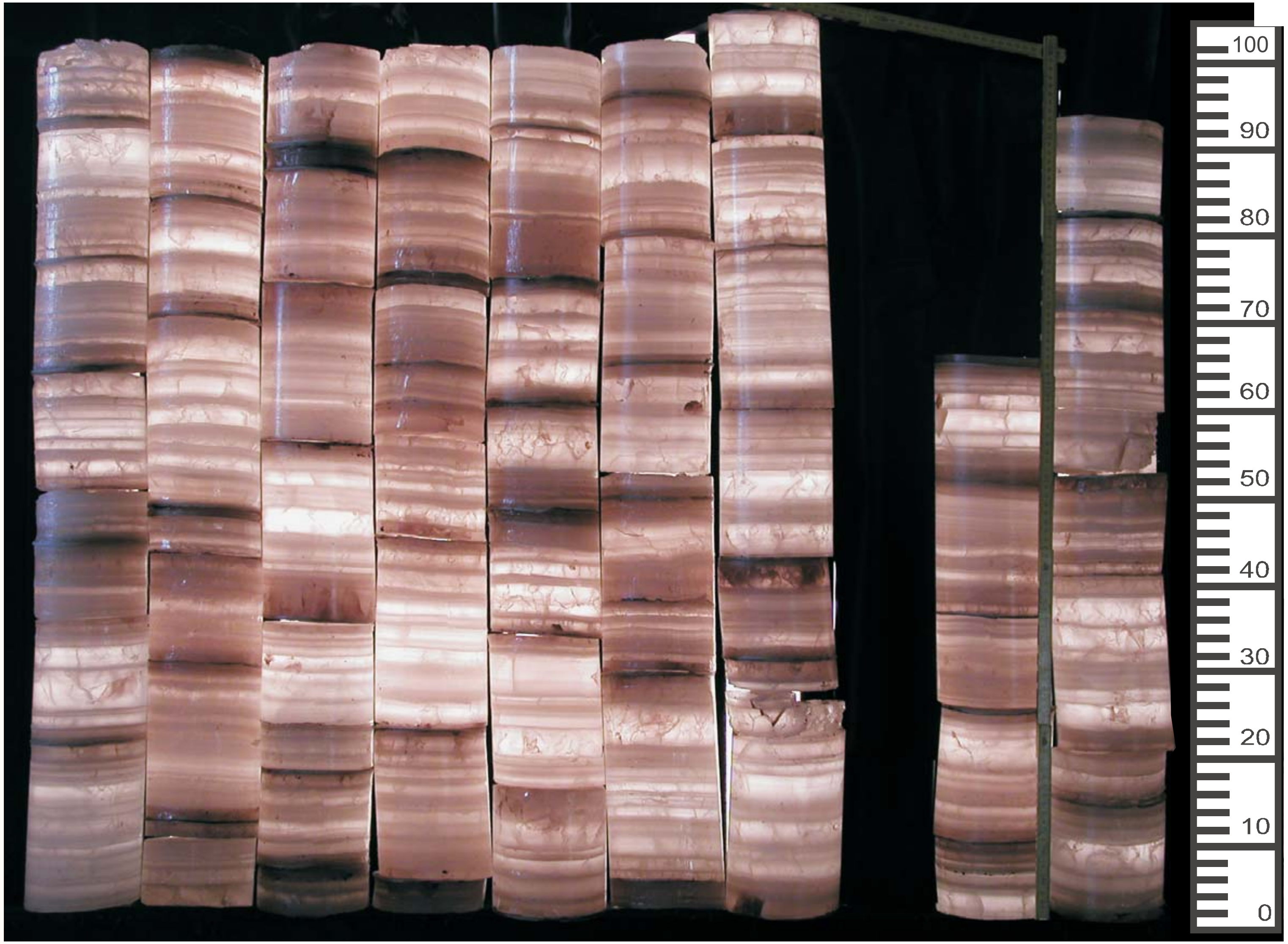
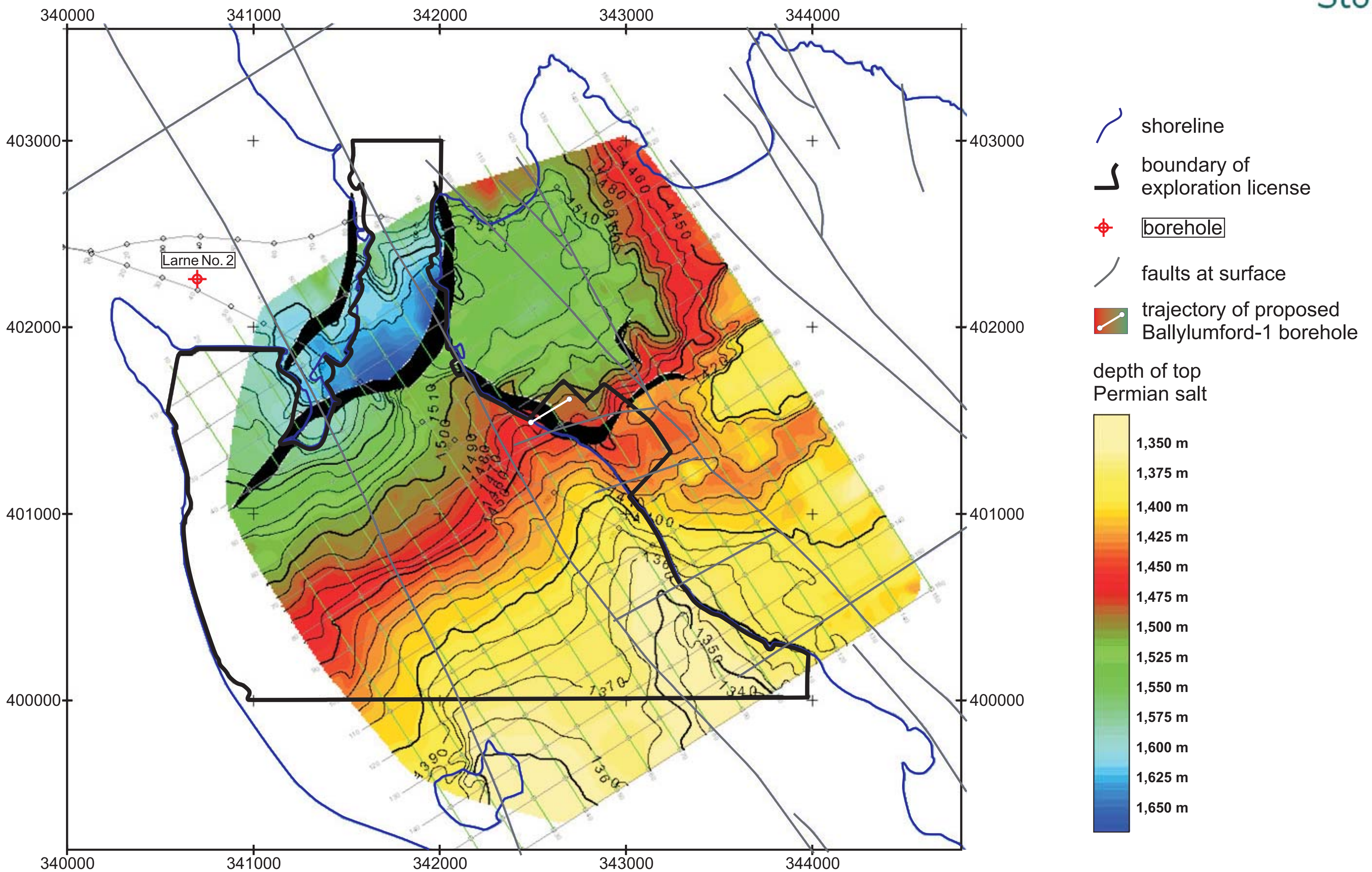


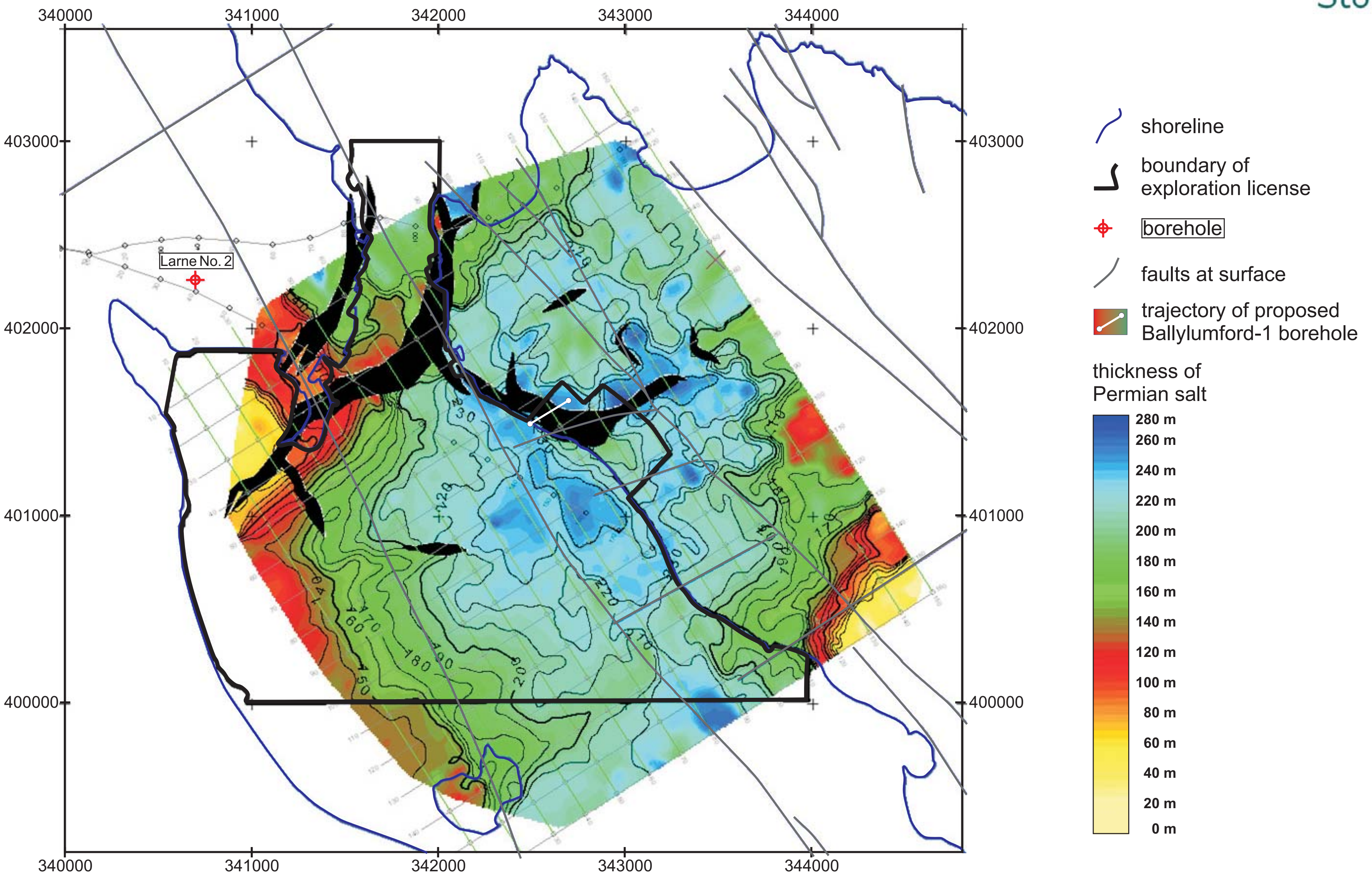
Enclosure 3-1: Location map showing the Larne Basin and major Caledonian faults; structural insert map based on seismic data and published geological maps (modified after Shelton, 1997).



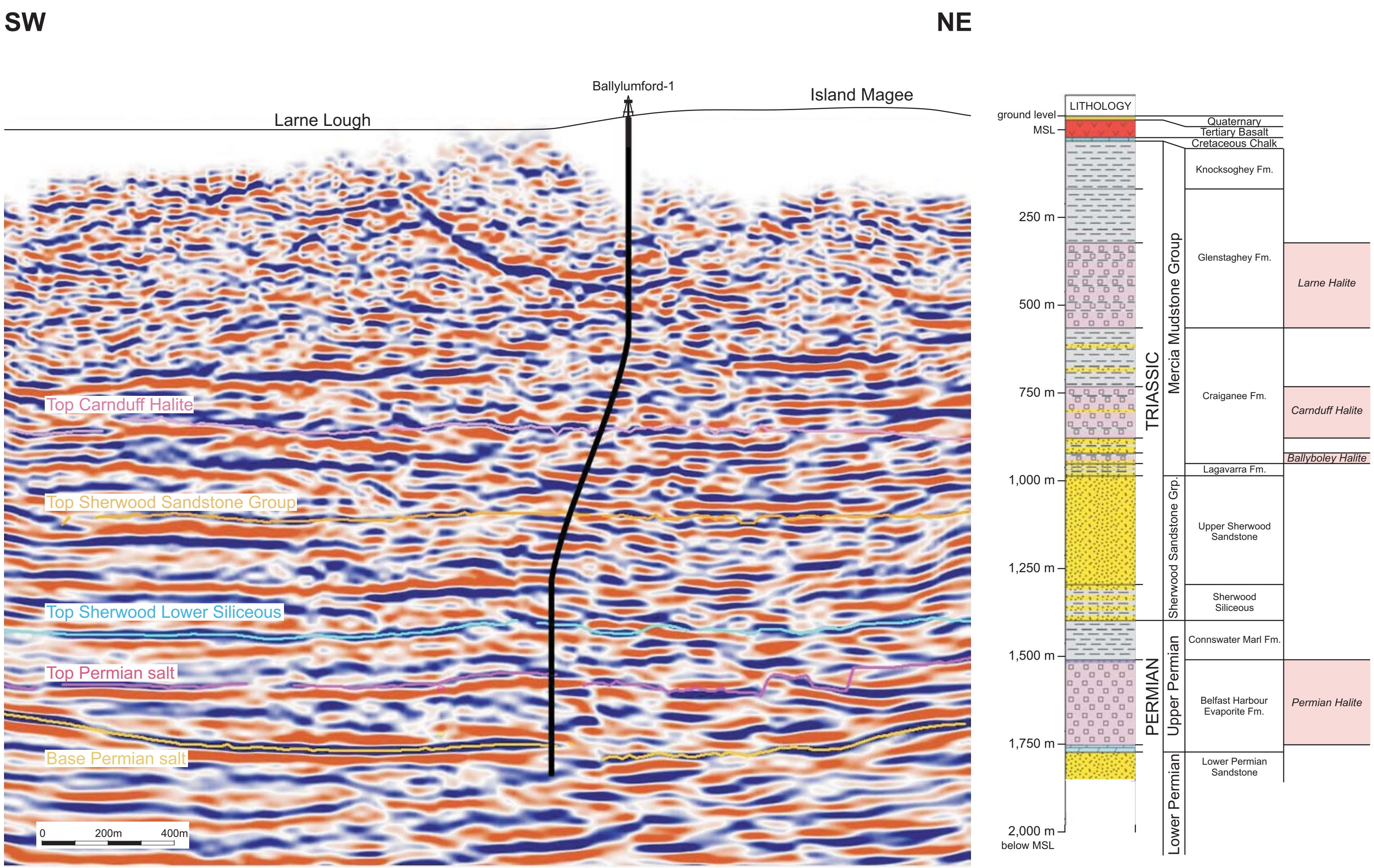
Enclosure 3-2: Bedded Permian salt from a location in the Netherlands



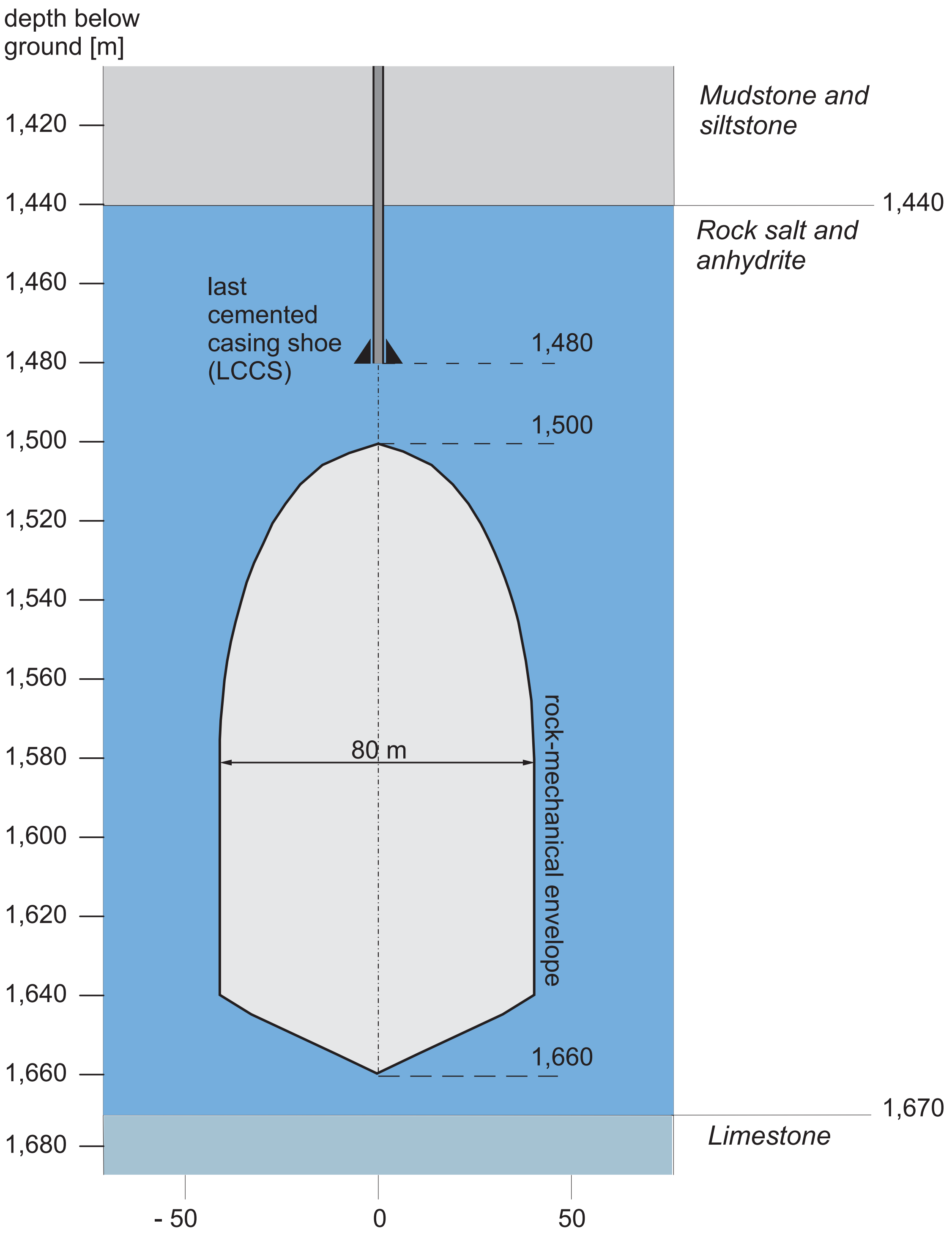
Enclosure 3-3: Depth map of the top of the Permian salt from 3D-seismic survey acquired in 2007 (GEO International Ltd.).



Enclosure 3-4: Isopach map of the Permian salt from 3D-seismic survey acquired in 2007 (GEO International Ltd.).



Enclosure 3-5: Inline 65 of the 3D-seismic survey acquired in 2007 with well trajectory and geological prognosis for the proposed confirmation well Ballylumford-1 (modified after Portland Gas NI Ltd., 2009).



Enclosure 4-1: Rock-mechanical layout

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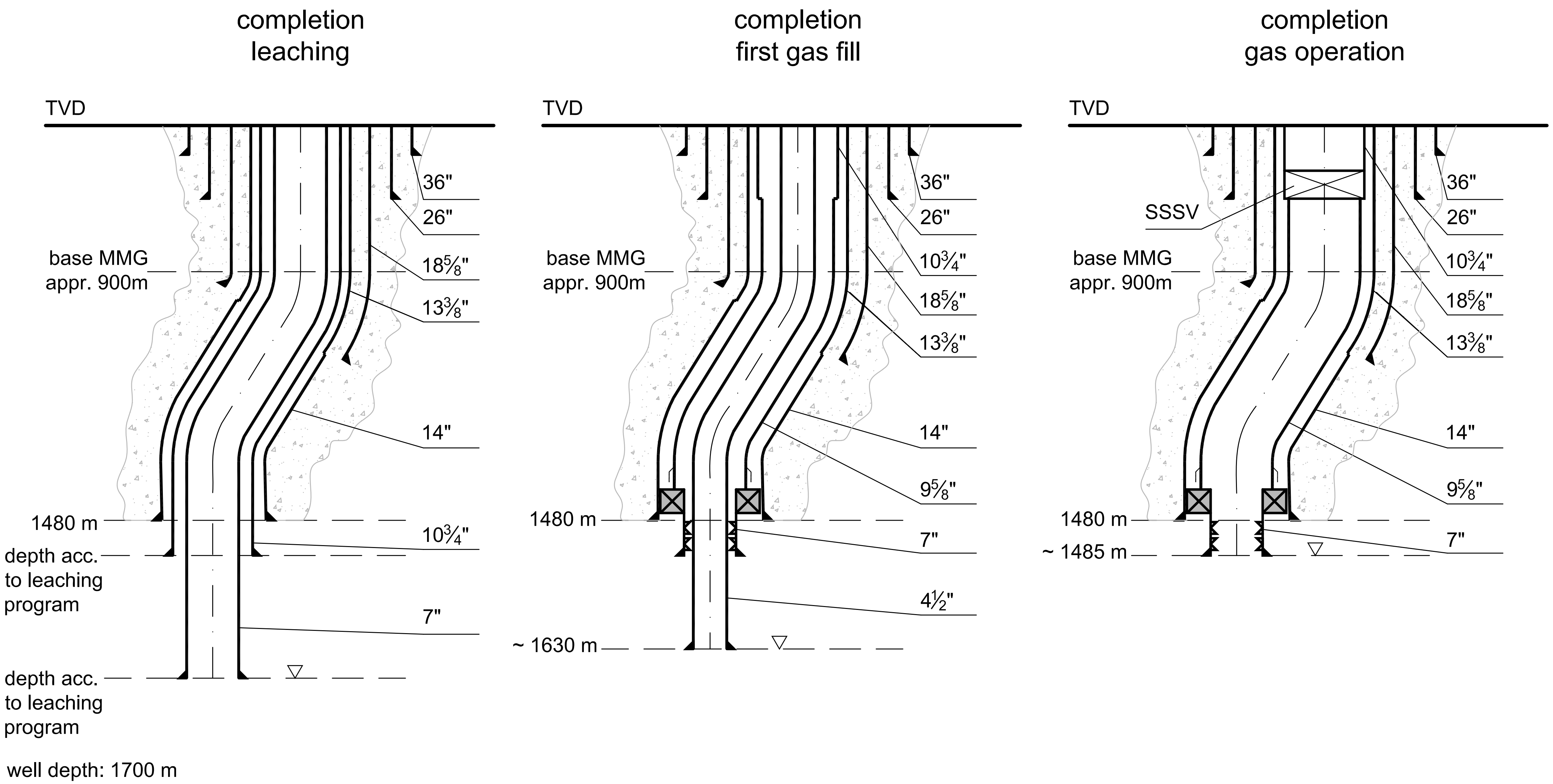

Enclosure: 5-1: Well completion conventional storage method (Draft)

PN: 2905
File: 08072301 Well completion conventional storage method rev01e.dwg

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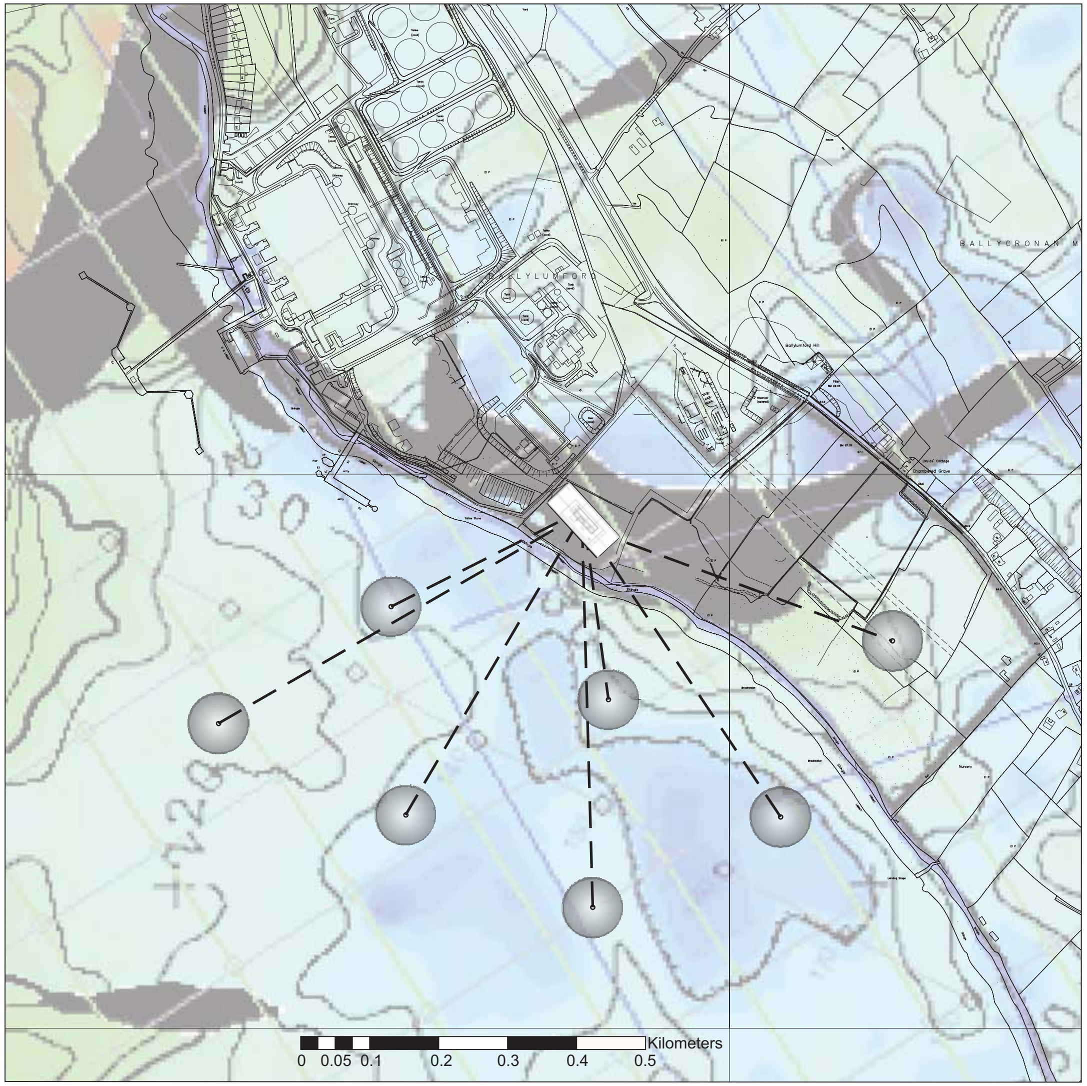

Enclosure 6-1: Possible cavern field layout, Larne Lough,
minimum distance between cavern wells: 300 m, diameter of caverns: 80 m

PN 2905
080414_Preliminary_Layout_Cavern_Field_Larne_Lough.des/SW

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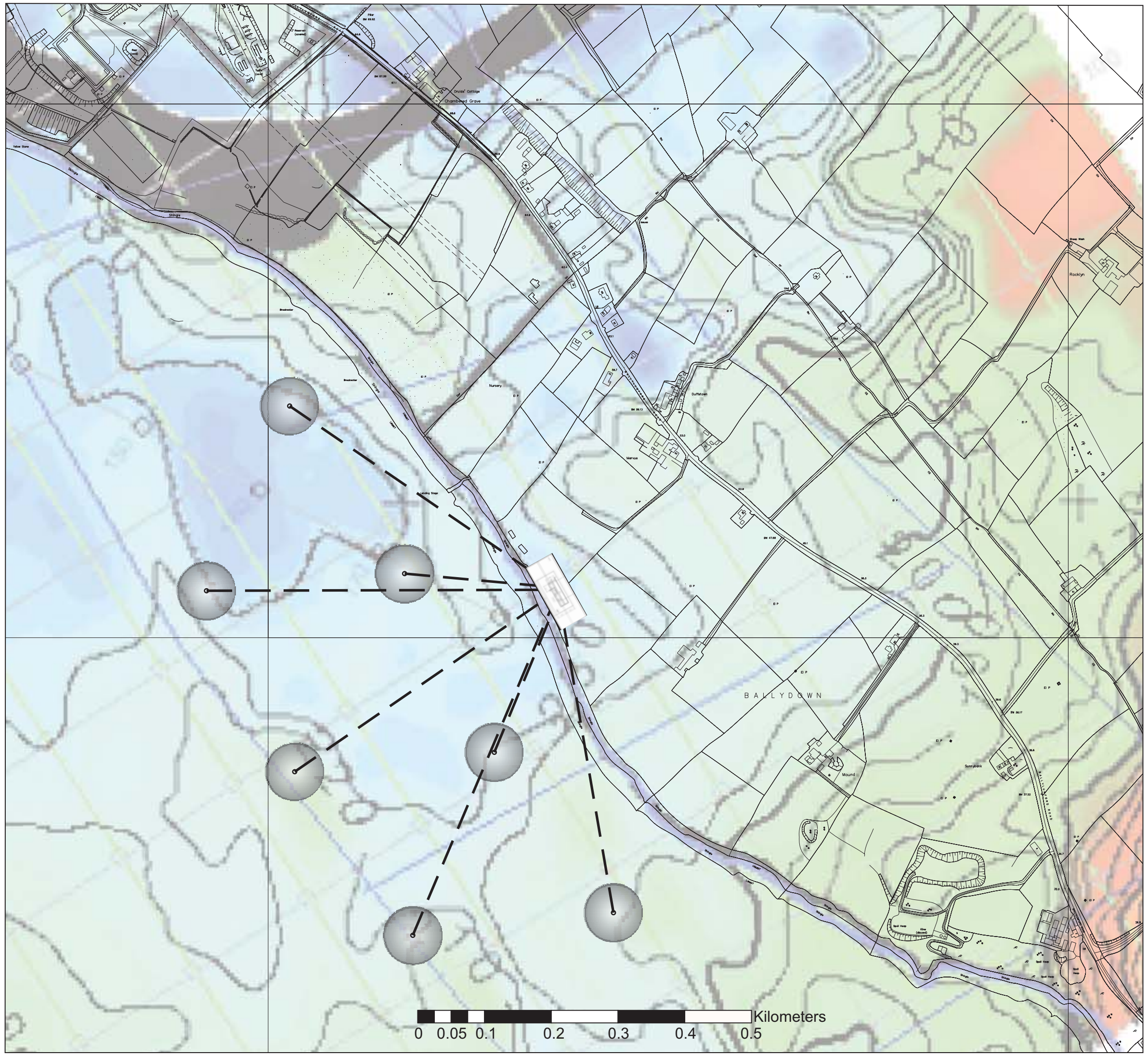
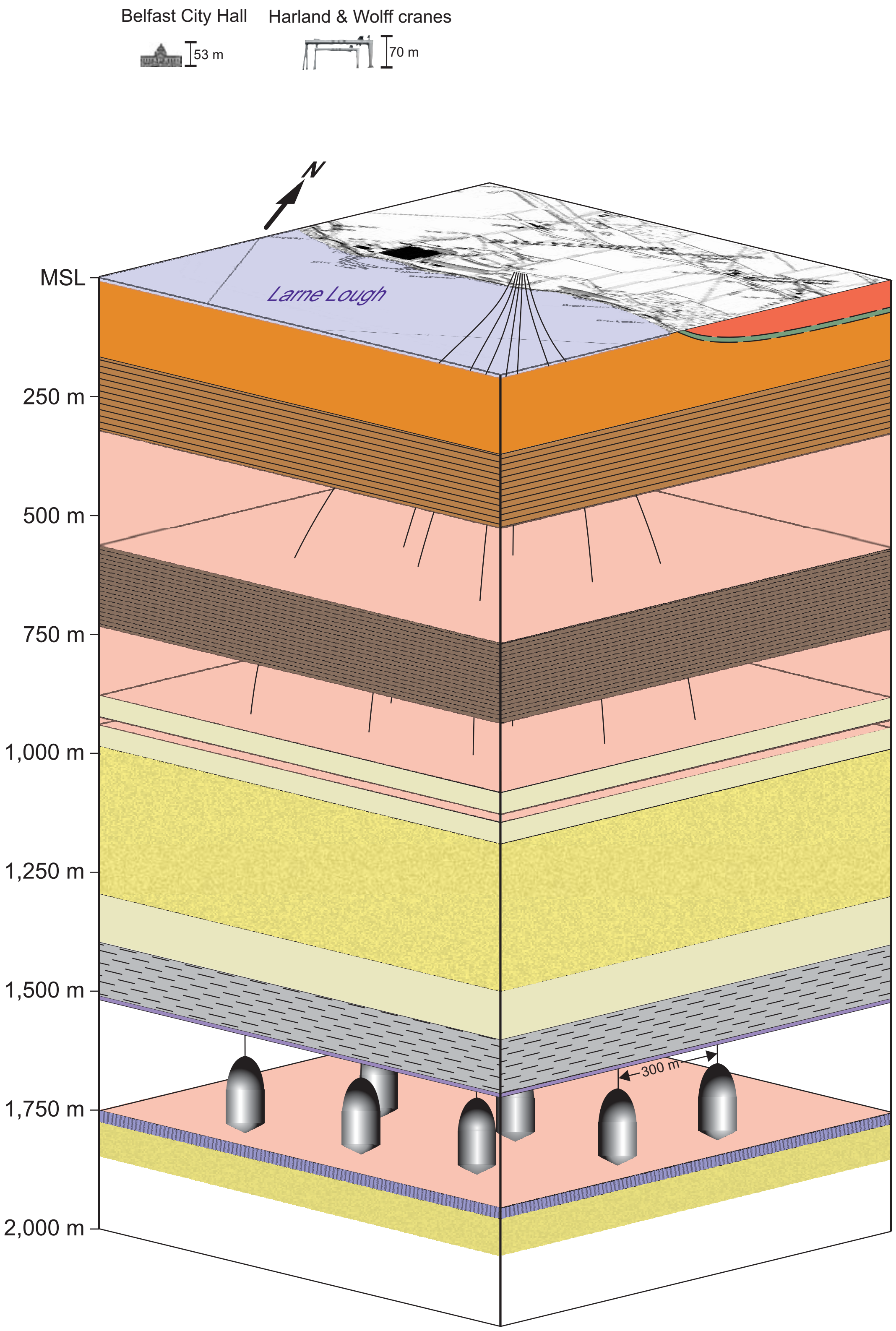


Enclosure 6-2: Possible cavern field layout (alternative well pad area), Larne Lough, minimum distance between cavern wells: 300 m, diameter of caverns: 80 m



Enclosure 6-3: Very simplified block diagram illustrating the proportions of the proposed caverns

PN: 2905
090603_Block_diagram_Cavern_field.des/SW

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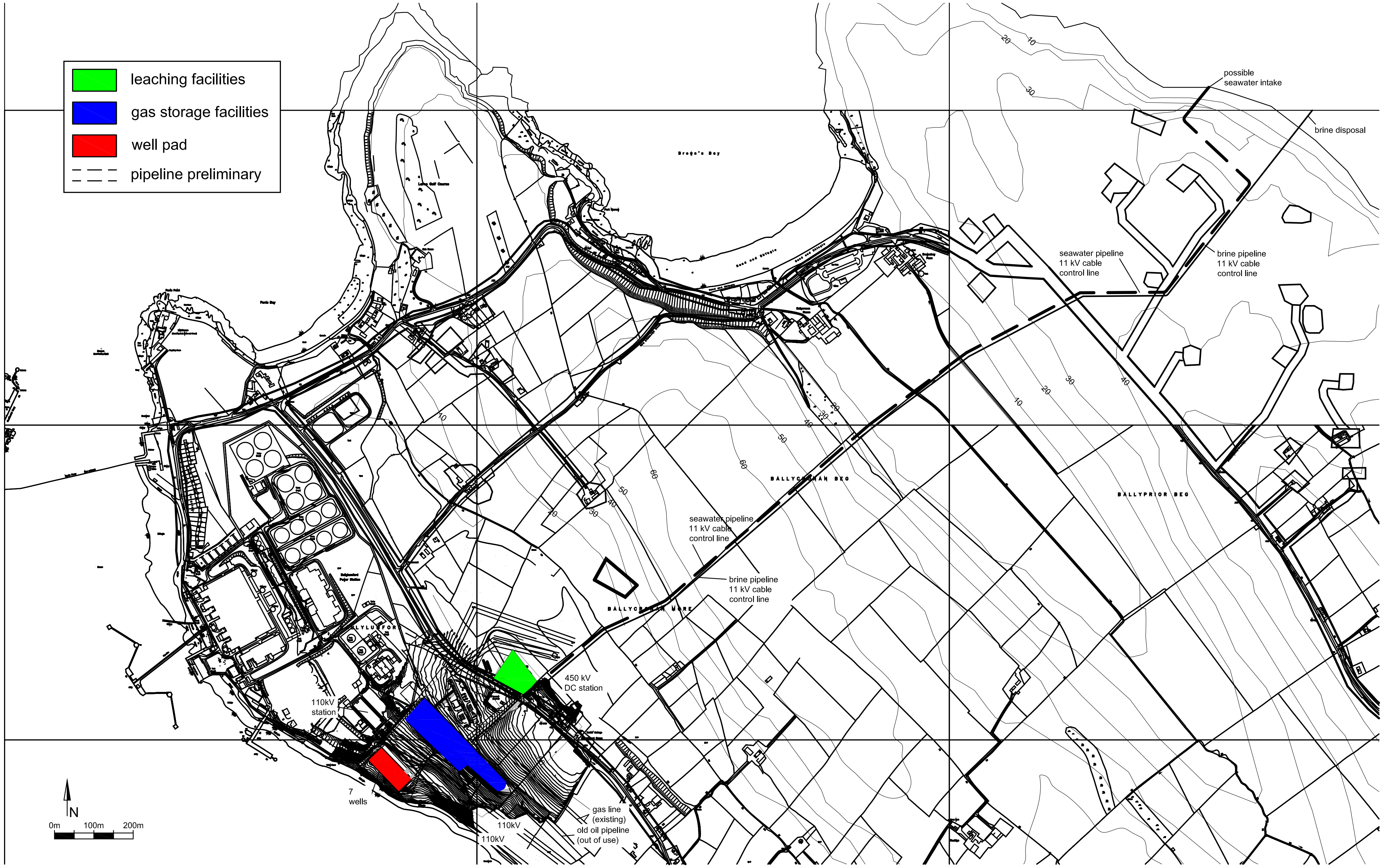

Enclosure 6-4: General layout plan

PN: 2905
File: 07091101 Layout plan rev09b.dwg

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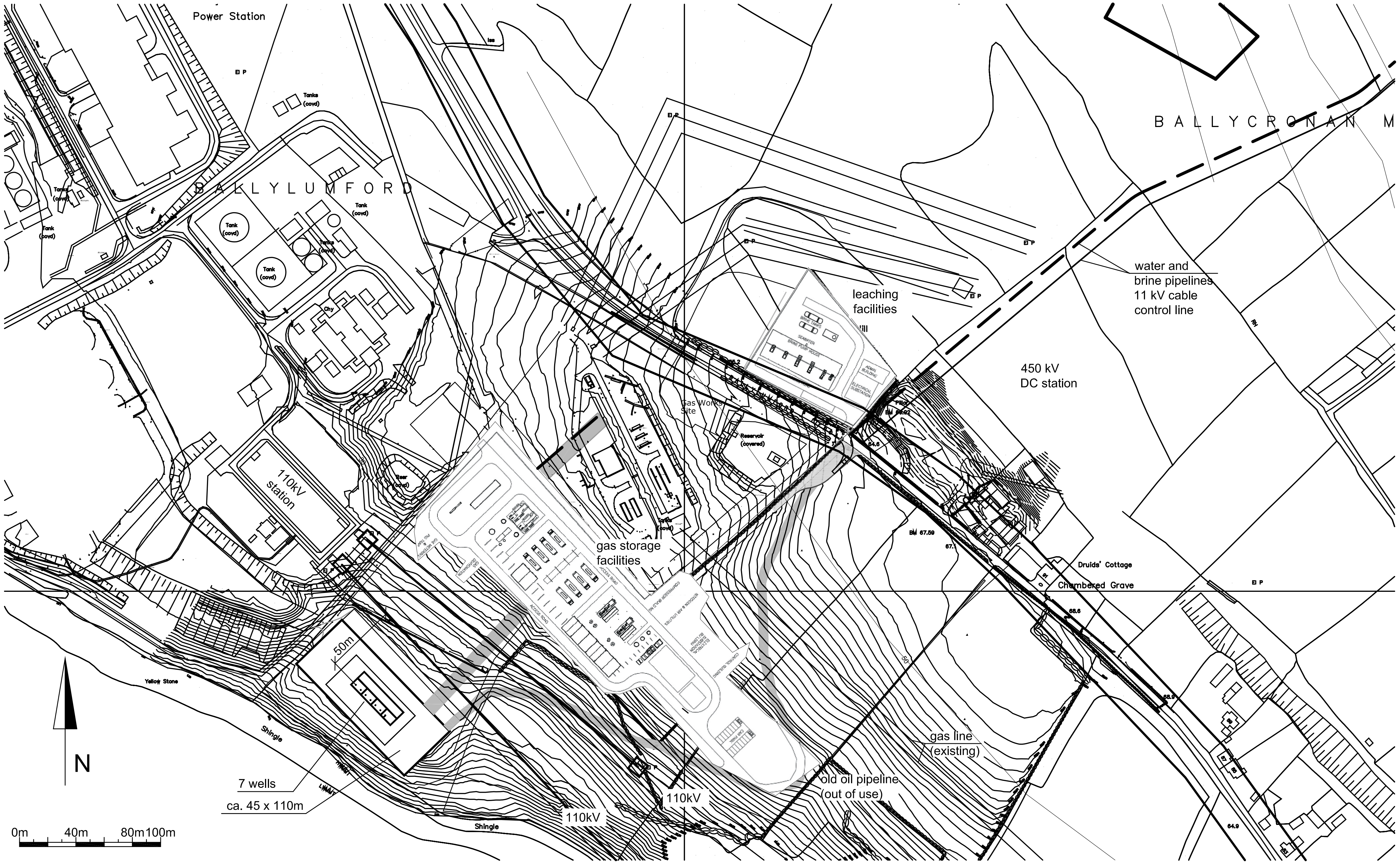

Enclosure 6-5: Detailed layout plan; according to the gas storage facilities and leaching facilities layouts by CB&I

PN: 2905
File: 07091102 Layout plan rev08a.dwg

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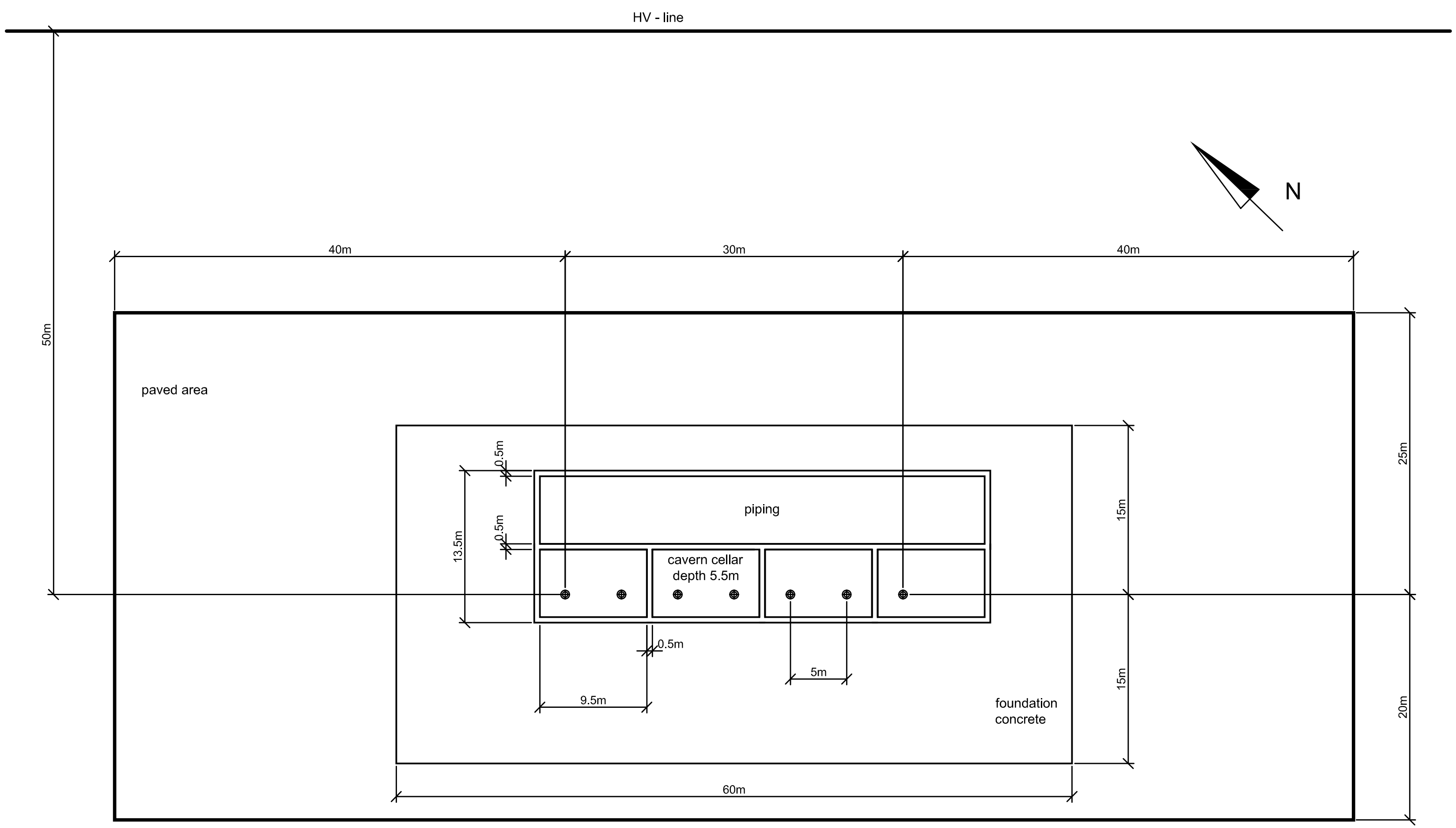
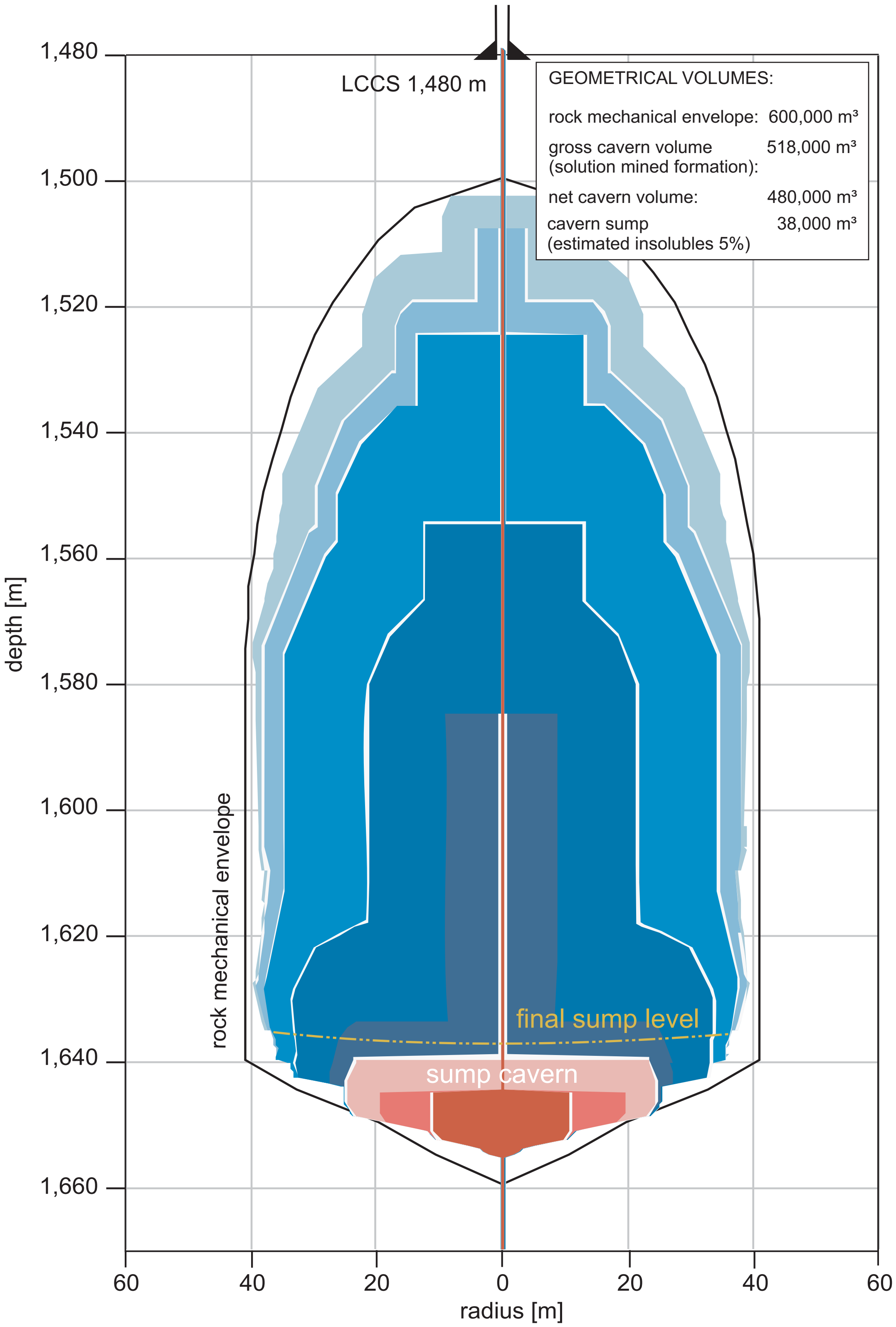
Underground Engineering



Enclosure 6-6: Possible design of well pad

PN: 2905
File: 09051301 Typical well pad 1 rev01c.dwg



Enclosure 7-1: Cavern shape development from leaching simulation

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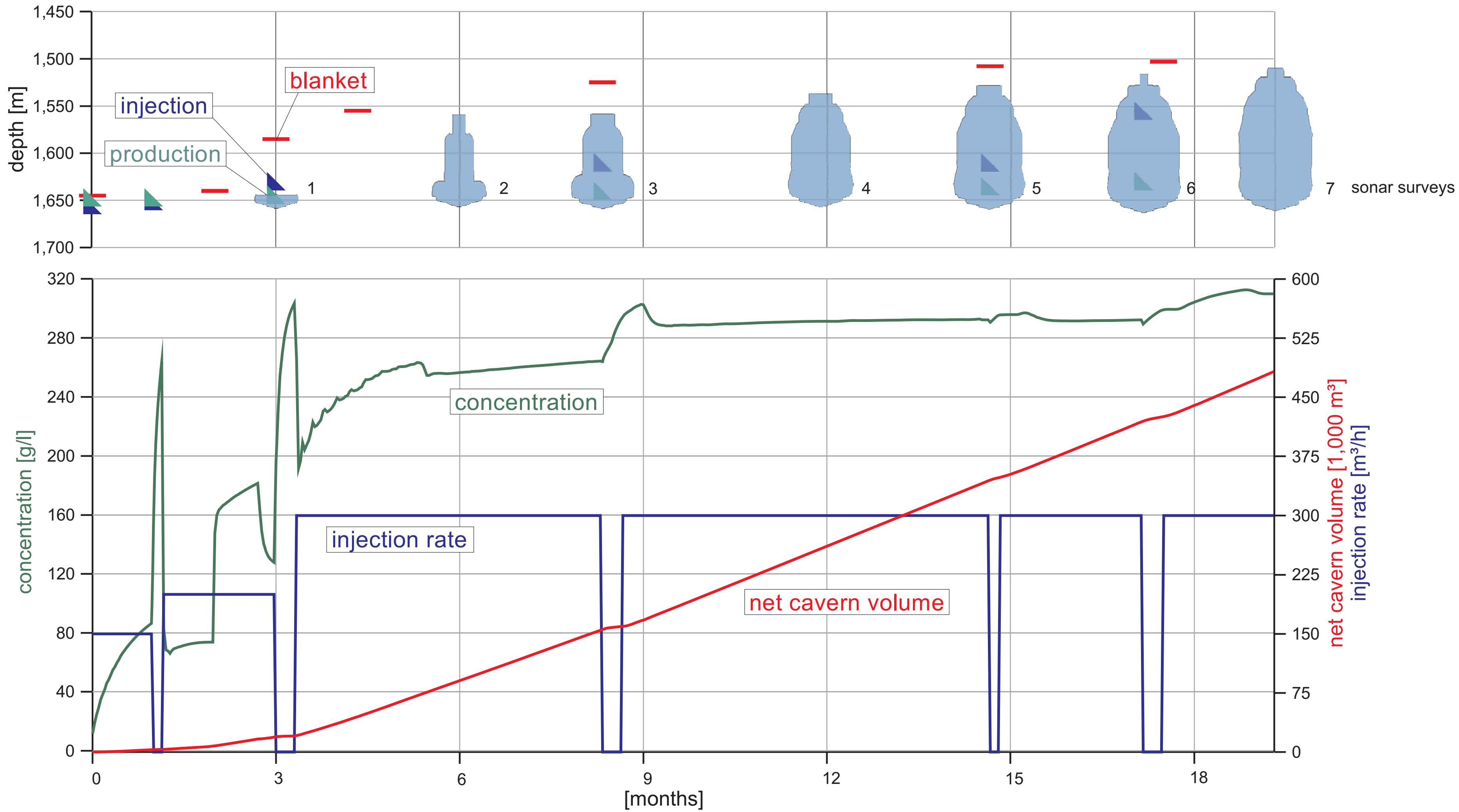
DEEP. Underground Engineering



Enclosure 7-2: Leaching settings and development of brine saturation and geometrical volume

PN 2905
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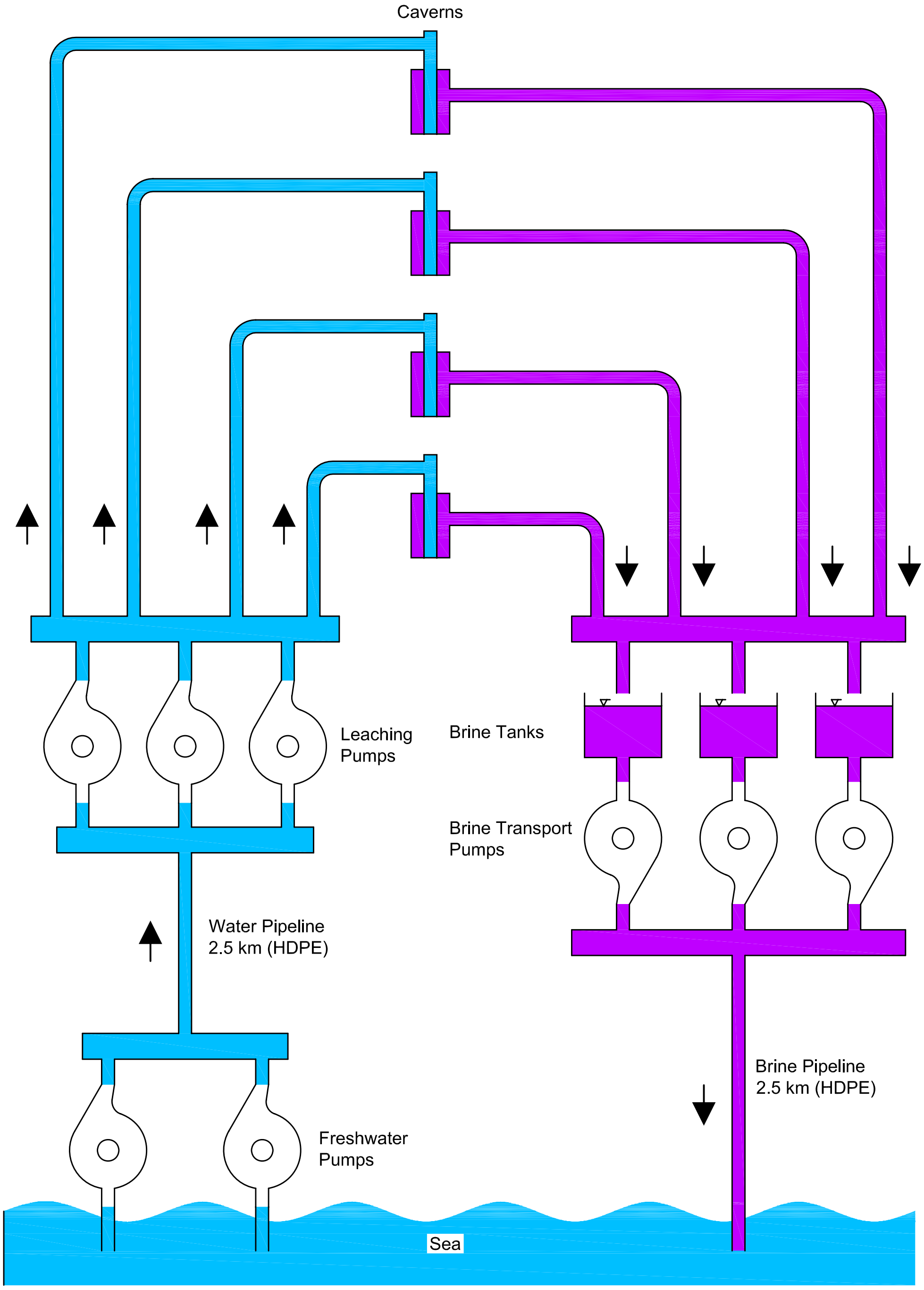

Enclosure 8-1: Flow diagram for leaching operation

PN: 2905
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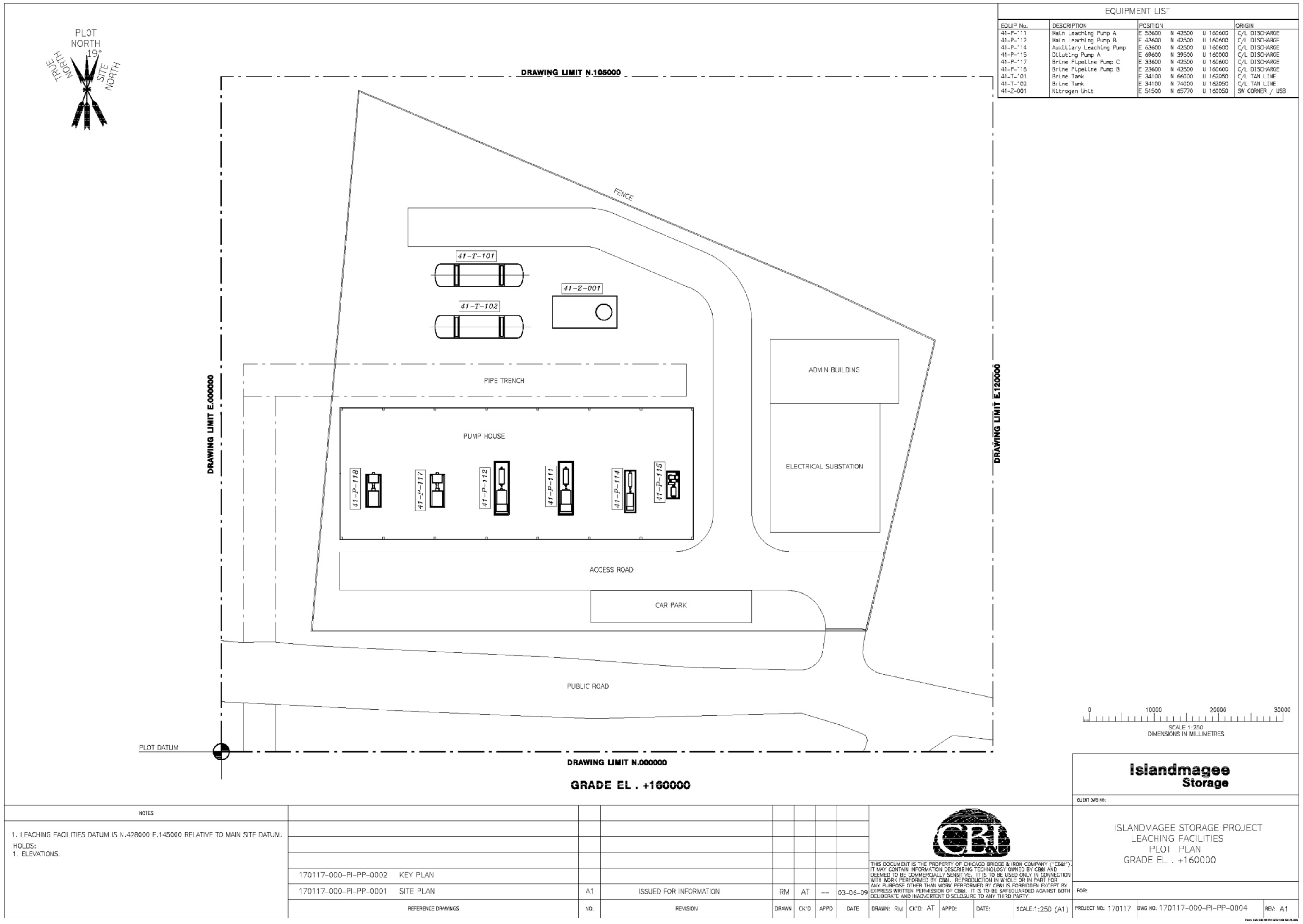
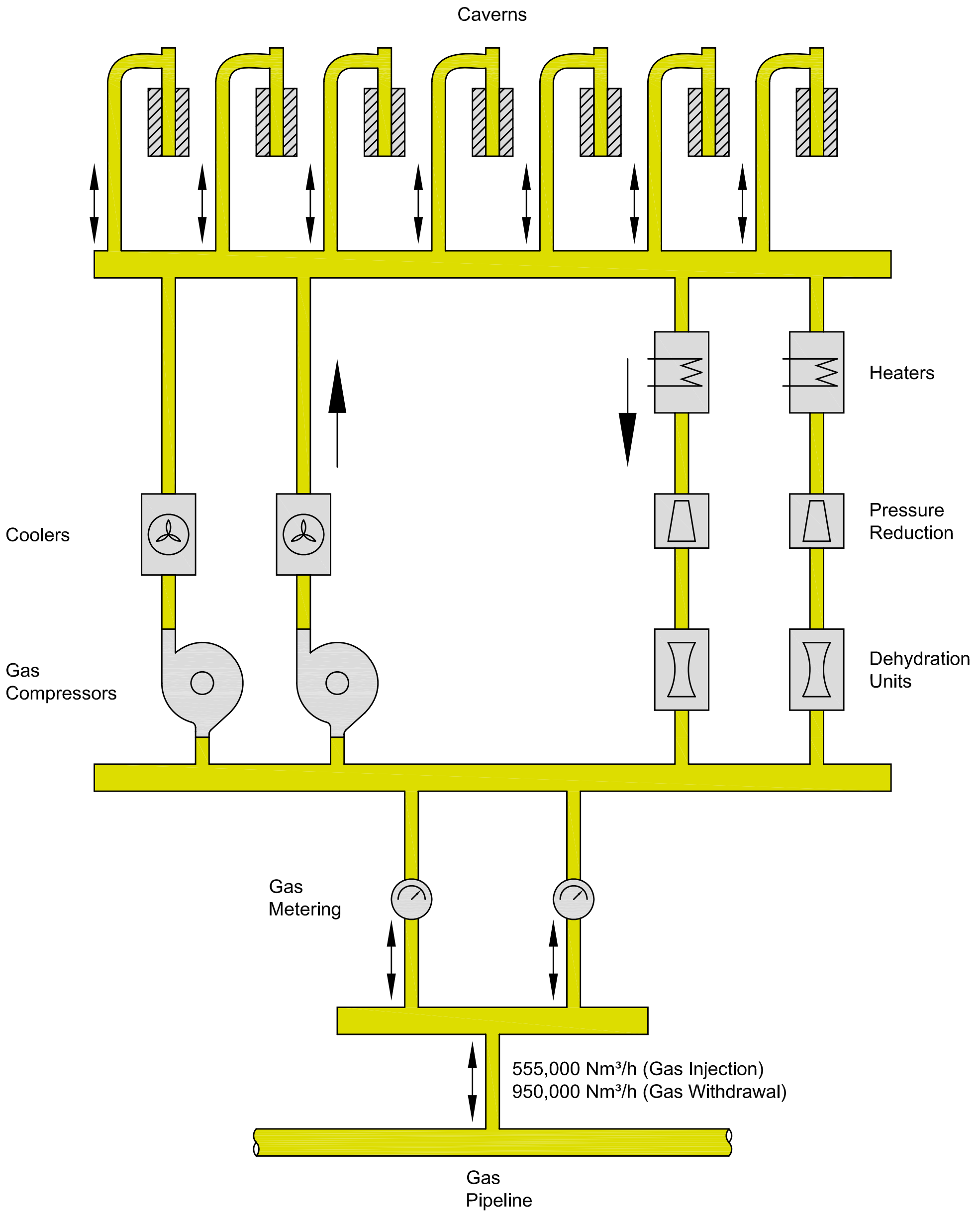


EQUIPMENT LIST

EQUIP No.	DESCRIPTION	POSITION			ORIGIN
41-P-111	Main Leaching Pump A	E 53600	N 42500	U 160600	C/L DISCHARGE
41-P-112	Main Leaching Pump B	E 43600	N 42500	U 160600	C/L DISCHARGE
41-P-114	Auxiliary Leaching Pump	E 63600	N 42500	U 160600	C/L DISCHARGE
41-P-115	Diluting Pump A	E 69600	N 39500	U 160000	C/L DISCHARGE
41-P-117	Brine Pipeline Pump C	E 33600	N 42500	U 160600	C/L DISCHARGE
41-P-118	Brine Pipeline Pump B	E 23600	N 42500	U 160600	C/L DISCHARGE
41-T-101	Brine Tank	E 34100	N 66000	U 162050	C/L TAN LINE
41-T-102	Brine Tank	E 34100	N 74000	U 162050	C/L TAN LINE
41-Z-001	Nitrogen Unit	E 51500	N 65770	U 160050	SW CORNER / USB

Enclosure 8-2: Plot plan of leaching facilities by CB&I

PN 2905
090618_Encl.8-2_leaching_plant.des



Enclosure 10-1: Flow diagram for gas operations

PN: 2905
File: 09030603 Block Diagram gas facilities rev01a.dwg

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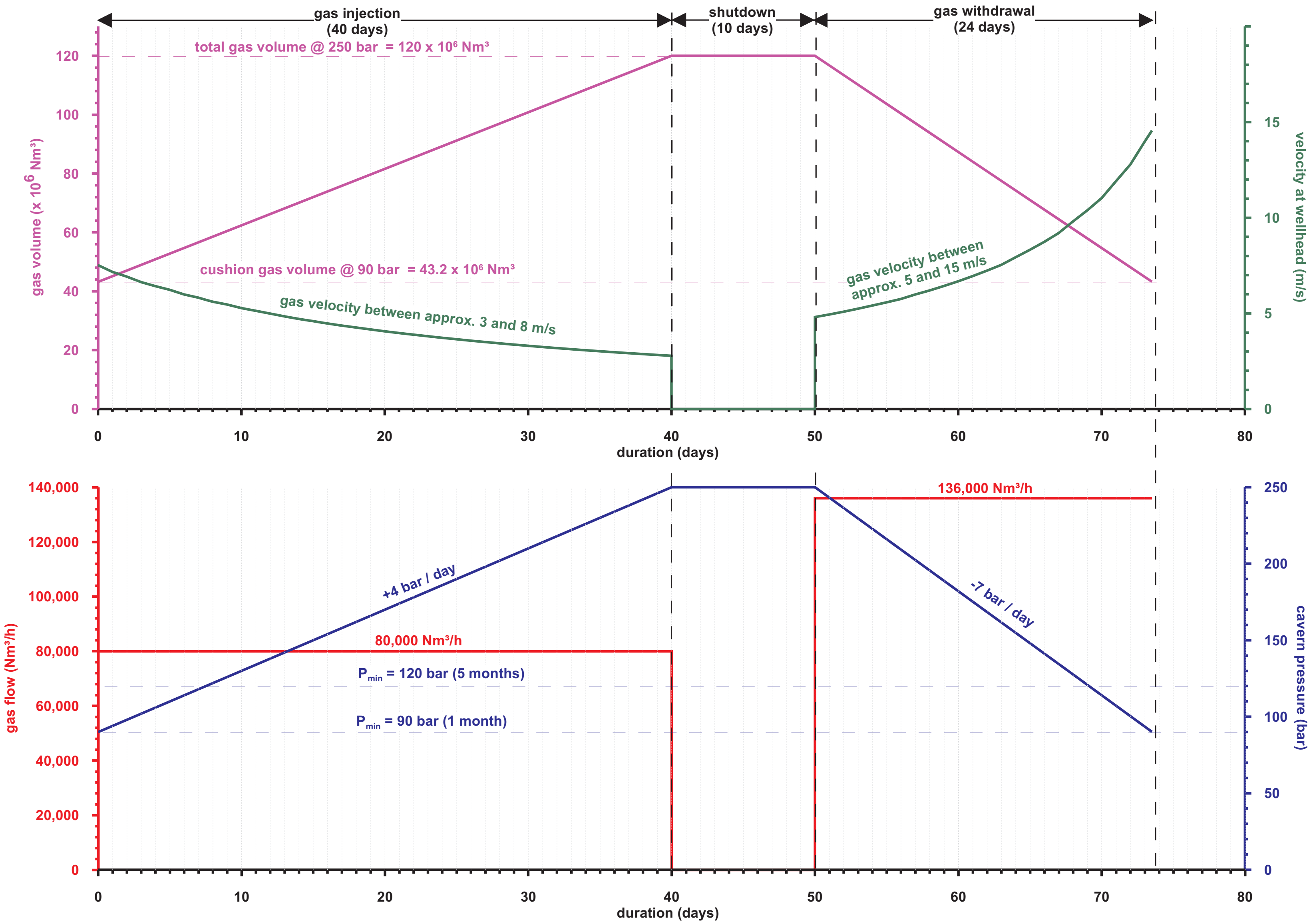

Enclosure 10-2: Procedural parameter during gas operation of 7 conventional caverns, for a single cycle of injection and withdrawal (gas volumes and flow rates for a single cavern)

PN 2905
090519_Encl.10-3_procedural_parameterp.des
IBE0096/EIS01/March '10

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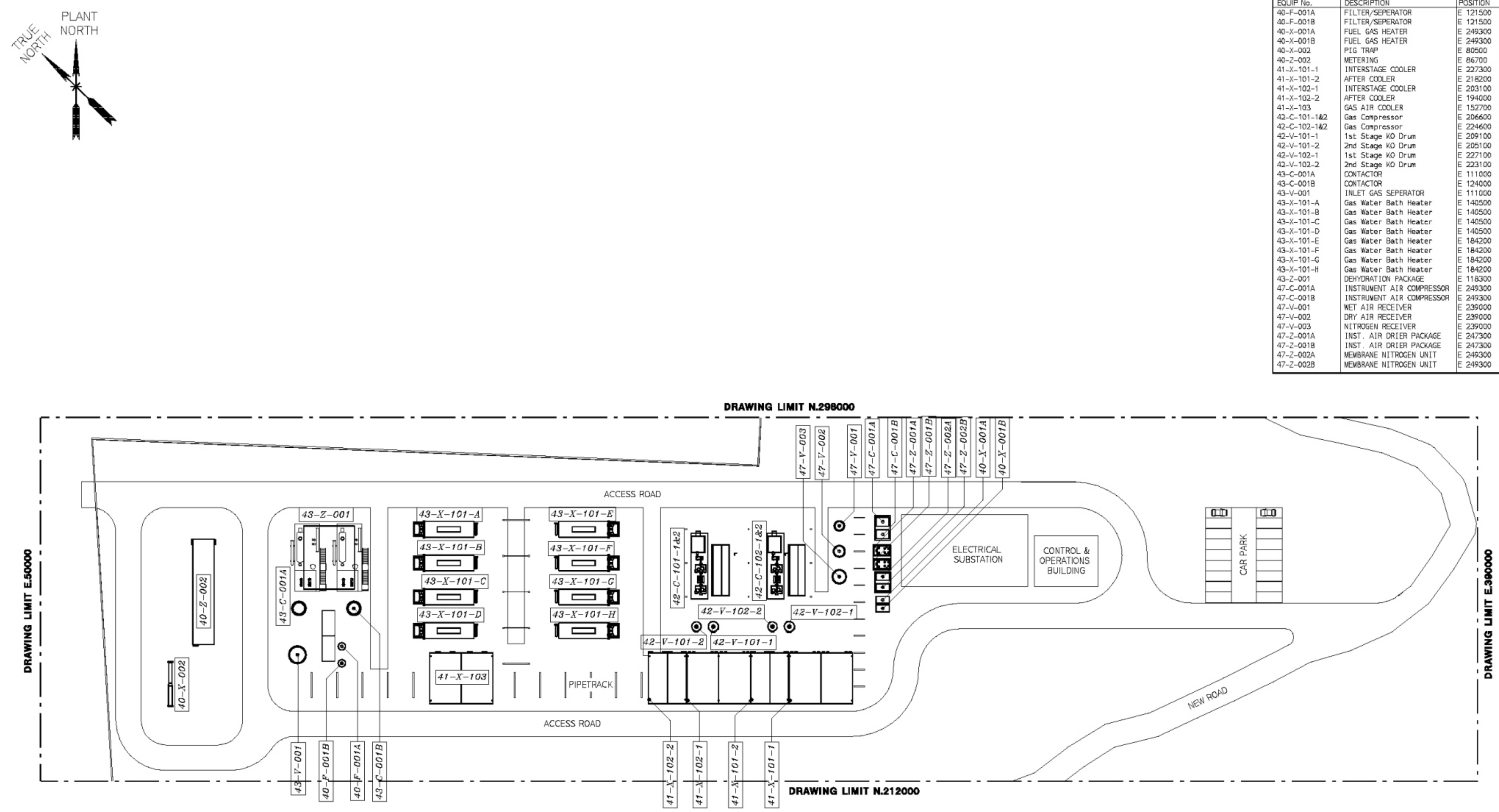
RPS



EQUIPMENT LIST

EQUIP No.	DESCRIPTION	POSITION	ORIGIN
40-F-001A	FILTER/SEPERATOR	E 121500 N 244000 U 143100	C/L LOWER TAN LINE
40-F-001B	FILTER/SEPERATOR	E 121500 N 240000 U 143100	C/L LOWER TAN LINE
40-X-001A	FUEL GAS HEATER	E 249300 N 254900 U 140000	SW CORNER / USB
40-X-001B	FUEL GAS HEATER	E 249300 N 252900 U 140000	SW CORNER / USB
40-X-002	PIG TRAP	E 80500 N 240200 U 143500	C/L LOWER TAN LINE
40-Z-002	METERING	E 86700 N 244000 U 142500	SW CORNER /USB
41-X-101-1	INTERSTAGE COOLER	E 227300 N 231000 U 146900	SW CORNER / USB
41-X-101-2	AFTER COOLER	E 218200 N 231200 U 146900	SW CORNER / USB
41-X-102-1	INTERSTAGE COOLER	E 203100 N 231000 U 146900	SW CORNER / USB
41-X-102-2	AFTER COOLER	E 194000 N 231200 U 146900	SW CORNER / USB
41-X-103	GAS AIR COOLER	E 152700 N 236300 U 148000	SW CORNER / USB
42-C-101-1&2	Gas Compressor	E 206600 N 265500 U 142000	C/L DISCHARGE
42-C-102-1&2	Gas Compressor	E 224600 N 265500 U 142000	C/L DISCHARGE
42-V-101-1	1st Stage KO Drum	E 209100 N 248500 U 144855	C/L LOWER TAN LINE
42-V-101-2	2nd Stage KO Drum	E 205100 N 248500 U 144855	C/L LOWER TAN LINE
42-V-102-1	1st Stage KO Drum	E 227100 N 248500 U 144855	C/L LOWER TAN LINE
42-V-102-2	2nd Stage KO Drum	E 223100 N 248500 U 144855	C/L LOWER TAN LINE
43-C-001A	CONTACTOR	E 111000 N 253000 U 147200	C/L LOWER TAN LINE
43-C-001B	CONTACTOR	E 124000 N 253000 U 147200	C/L LOWER TAN LINE
43-V-001	INLET GAS SEPERATOR	E 111000 N 242000 U 144400	C/L LOWER TAN LINE
43-X-101-A	Gas Water Bath Heater	E 140500 N 271500 U 145250	C/L TAN LINE
43-X-101-B	Gas Water Bath Heater	E 140500 N 263500 U 145250	C/L TAN LINE
43-X-101-C	Gas Water Bath Heater	E 140500 N 255500 U 145250	C/L TAN LINE
43-X-101-D	Gas Water Bath Heater	E 140500 N 247500 U 145250	C/L TAN LINE
43-X-101-E	Gas Water Bath Heater	E 184200 N 271500 U 145250	C/L TAN LINE
43-X-101-F	Gas Water Bath Heater	E 184200 N 263500 U 145250	C/L TAN LINE
43-X-101-G	Gas Water Bath Heater	E 184200 N 255500 U 145250	C/L TAN LINE
43-X-101-H	Gas Water Bath Heater	E 184200 N 247500 U 145250	C/L TAN LINE
43-Z-001	DEHYDRATION PACKAGE	E 118300 N 264900 U 141100	SW CORNER / USB
47-C-001A	INSTRUMENT AIR COMPRESSOR	E 249300 N 273400 U 140000	SW CORNER / USB
47-C-001B	INSTRUMENT AIR COMPRESSOR	E 249300 N 270400 U 140000	SW CORNER / USB
47-V-001	WET AIR RECEIVER	E 239000 N 272400 U 141600	C/L LOWER TAN LINE
47-V-002	DRY AIR RECEIVER	E 239000 N 266400 U 141600	C/L LOWER TAN LINE
47-V-003	NITROGEN RECEIVER	E 239000 N 260400 U 142000	C/L LOWER TAN LINE
47-Z-001A	INST. AIR DRIER PACKAGE	E 247300 N 267600 U 140000	SW CORNER /USB
47-Z-001B	INST. AIR DRIER PACKAGE	E 247300 N 264400 U 140000	SW CORNER / USB
47-Z-002A	MEMBRANE NITROGEN UNIT	E 249300 N 260400 U 140000	SW CORNER / USB
47-Z-002B	MEMBRANE NITROGEN UNIT	E 249300 N 257900 U 140000	SW CORNER / USB

GRADE EL . +140000

0 10000 20000 30000 40000
SCALE 1:500
DIMENSIONS IN MILLIMETRES

Islandmagee Storage

ISLANDMAGEE STORAGE PROJECT
PROCESS AREA
PLOT PLAN
GRADE EL . +140000

NOTES

REFERENCE DRAWINGS		NO.	REVISION	DRAWN	CK'D	APPD	DATE
170117-000-PI-PP-0002	KEY PLAN						
170117-000-PI-PP-0001	SITE PLAN	A1	ISSUED FOR INFORMATION	RM	AT	--	02-06-09

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CLIENT DWG NO:
FOR:
DRAWN: RM | CK'D: AT | APPD: | DATE: | SCALE:1:500 (A1) | PROJECT NO: 170117 | DWG NO: 170117-000-PI-PP-0003 | REV: A1

Enclosure 10-3: Plot plan of gas facilities by CB&I

PN 2905
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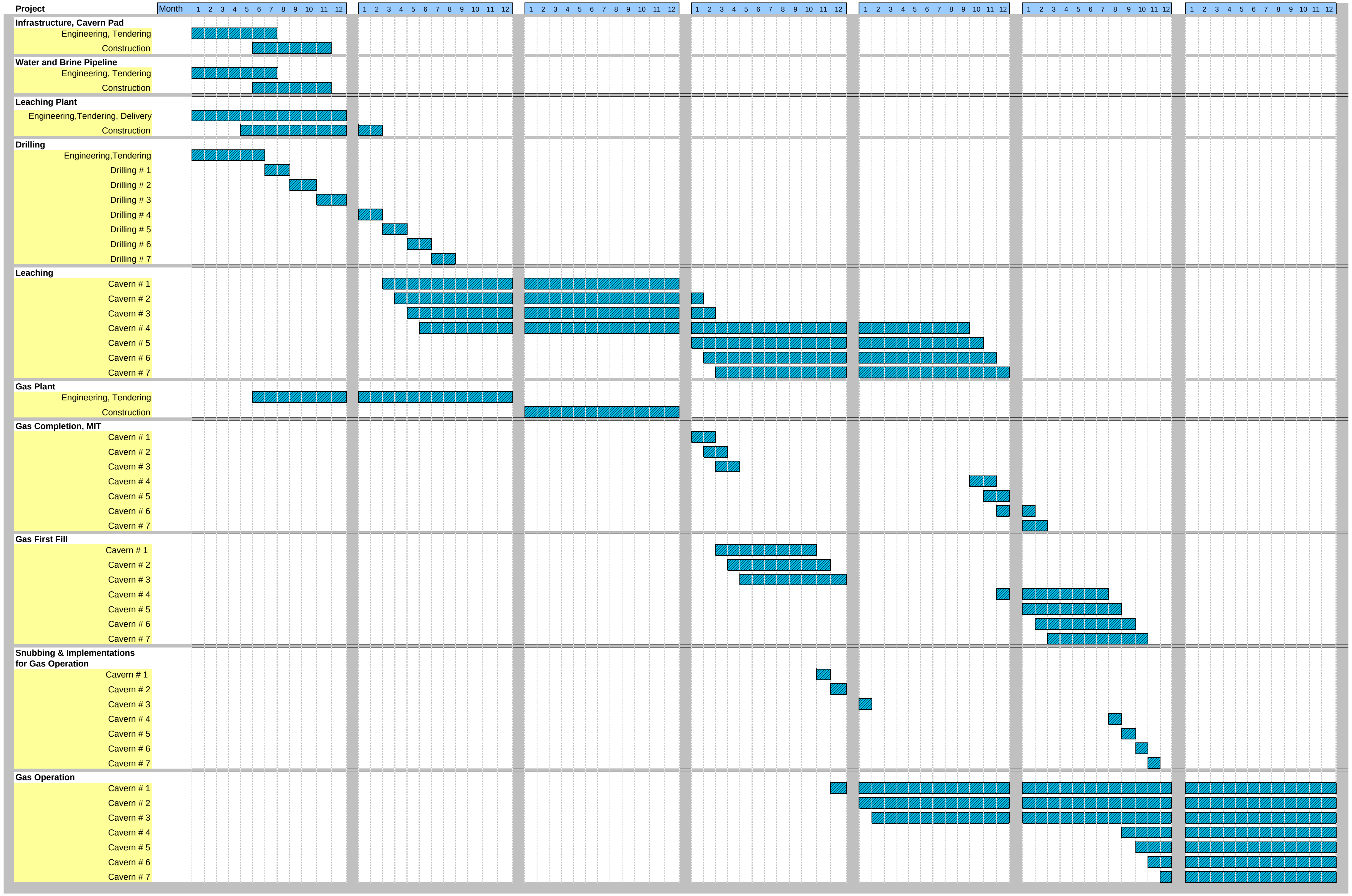

Enclosure 11-1 : Time schedule for the construction of 7 caverns

PN 2905
090526_Time_Table.xls

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(a) General design parameter and project basics for conventional caverns

GENERAL DESIGN PARAMETER				
item	**value**	**unit**	**value**	**unit**
Total storage volume, required	500,000,000	Sm^3	474,000,000	Nm^3
Max. gas flow injection, required	14,000,000	Sm^3/d	555,000	Nm^3/h
Max. gas flow withdrawal, required	24,000,000	Sm^3/d	approx. 950,000	Nm^3/h
GAS OPERATIONS				
Max. gas pressure in cavern	250	bar		
Min. gas pressure in cavern (1 month / 5 months)	90 / 120	bar		

PROJECT BASICS		
item	**value**	**unit**
Total cavern volume required	3,000,000	m³
Rock mechanical envelope	600,000	m³
Geometrical volume per cavern (net volume for gas storage)	480,000 (after 3 turnover per strategic cavern)	m³
Total number of caverns / wells in the field	8 / 11	
LEACHING		
Number of caverns leached in parallel	4	
Leaching flow, sump leaching phase	100	m^3/h
Leaching flow, main and roof leaching phase	300	m^3/h
Total water/brine flow (incl. gas first fill)	1,000	m^3/h

CONVENTIONAL CAVERNS		
Number of caverns / wells	5 / 5	
Geometrical volume per cavern (total of 5)	480,000 (x 5 = 2,400,000)	m^3
Working gas volume per cavern (total of 5)	76.8 (x 5 = 380)	x 10^6 Nm³
Cushion gas volume per cavern (total of 5)	43.2 (x 5 = 216)	x 10^6 Nm³
DRILLING AND CASING		
OD of last cemented casing	13 $^3/_8$ - 14	inch
LEACHING		
OD outer leaching string	10 ¾	inch
OD inner leaching string	7	inch
Leaching time per cavern	22	months
GAS OPERATIONS		
OD of gas injection/production string	9 $^5/_8$	inch
OD of water injection/brine production string	-	
Gas injection (per cavern)	110,000	Nm^3/h
Gas withdrawal (per cavern)	190,000	Nm^3/h
Duration of gas withdrawal (between 250 and 90 bar using the big caverns only)	17	days
Duration of gas injection (between 250 and 90 bar using the big caverns only)	29	days

Enclosure 12-1: Overview of estimated basic design parameter for 5 conventional and 3 strategic caverns

PN 2905
080915_Encl._12_1_Basic_parameters_Hybrid_3-5.doc

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(b) Project basics for strategic caverns

STRATEGIC CAVERNS		
Number of caverns / wells	3 / 6	
Geometrical volume per cavern (initial – final)	300,000 - 480,000 (x 3 = 900,000 – 1,440,000)	m^3
Working gas volume per cavern (total of 3, initial)	48 (x 3 = 144)	x 10^6 Nm³
Cushion gas volume per cavern (total of 3, initial)	27 (x 3 = 81)	x 10^6 Nm³
DRILLING AND CASING		
OD of last cemented casing	9 ⅝	inch
LEACHING		
OD outer leaching string	7	inch
OD inner leaching string	4 ½	inch
Leaching time per cavern	15	months
CONVENTIONAL GAS OPERATION		
OD of gas injection/production string	5 $^1/_2$	inch
OD of water injection/brine production string	7	inch
Between 250 and 120 bar		
Average Gas injection (per cavern)	100,000	Nm^3/h
Gas withdrawal (per cavern)	85,000	Nm^3/h
Duration of gas withdrawal	19	days
Duration of gas injection	16	days
Between 120 and 90 bar		
Gas injection (per cavern)	110,000	Nm^3/h
Gas withdrawal (per cavern)	45,000	Nm^3/h
Duration of gas withdrawal	8	days
Duration of gas injection	4	days
COMPENSATION		
SEAWATER FILL		
Volume of gas (@ 170 bar, per cavern)	51 (x 3 = 153)	x 10^6 Nm³
Sea water injection rate	900	m^3/h
Possible gas withdrawal (@ 170 bar, per cavern)	51000	Nm^3/h
Duration of gas withdrawal	42	days
GAS FILL		
Cushion gas (initial, after 1st, 2nd, 3rd turnover of 1 strategic cavern)	27, 32.4, 37.3, 43.2	x 10^6 Nm³

Enclosure 12-1: Overview of estimated basic design parameter for 5 conventional and 3 strategic caverns

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080915_Encl._12_1_Basic_parameters_Hybrid_3-5.doc

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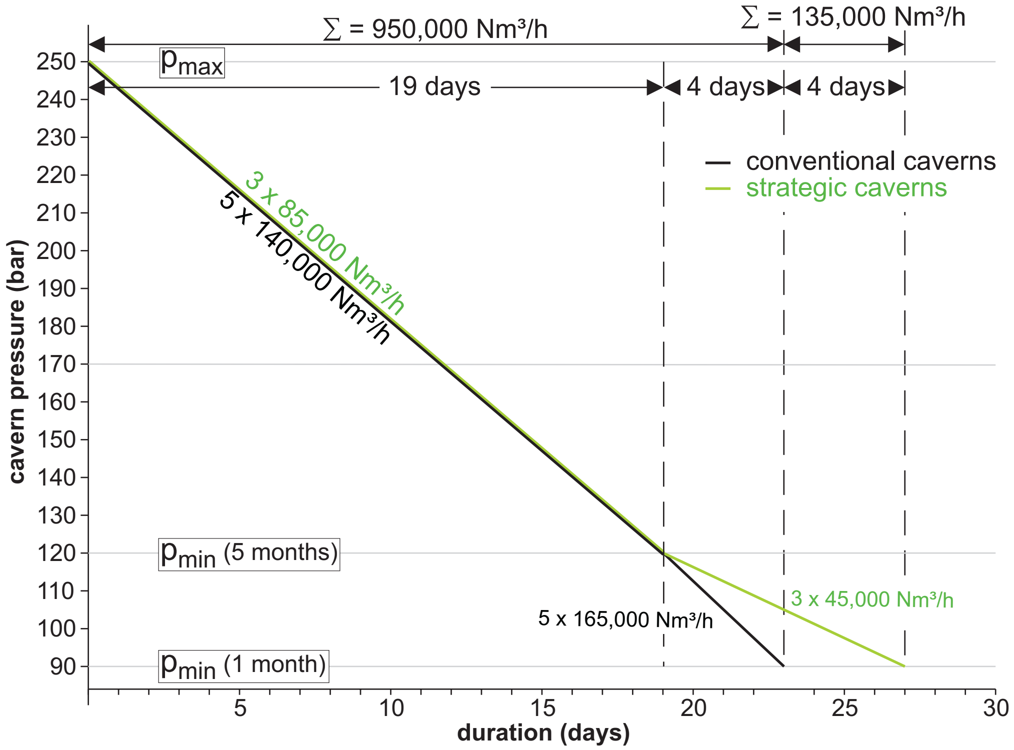
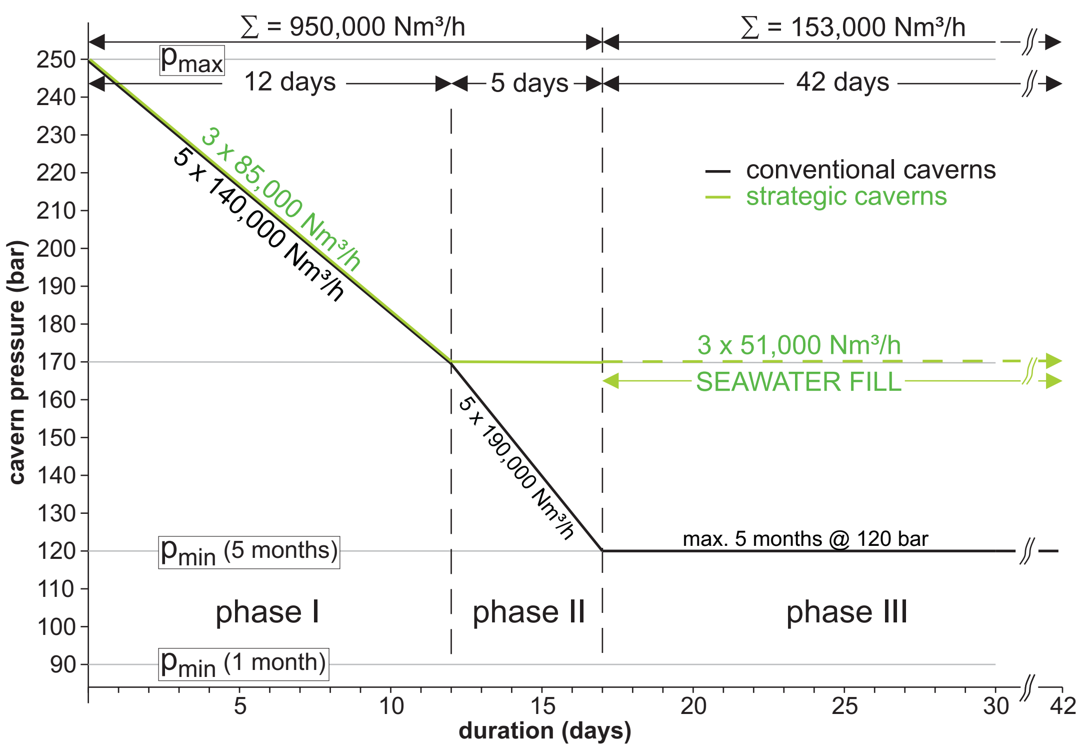
a) conventional gas withdrawal



b) gas withdrawal with subsequent seawater compensation



Enclosure 12-2: Possible modes of gas withdrawal for 5 conventional and 3 strategic caverns, Larne Lough Gas Storage Project; a) conventional gas withdrawal, b) gas withdrawal with subsequent seawater compensation.

PN 2905
080920_Basic_design_withdrawal.des/SW

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Underground Engineering

APPENDIX 4.2 SUPPLEMENTARY TECHNICAL REPORT

Islandmagee
Storage

Supplement to the
Outline Technical Report
on the Proposed Gas Storage Project
at Islandmagee, Northern Ireland

for:

Islandmagee Storage Limited

80 Hill Rise

Richmond, Surrey

TW10 6UB

UNITED KINGDOM

Date: October 28th, 2009

Table of Contents

List of Tables

1 Introduction

An ‘Outline Technical Report on the Proposed Gas Storage Project at Islandmagee, Northern Ireland’ was provided by DEEP. Underground Engineering GmbH dated 22nd June 2009. The report is to be appended to the Islandmagee Planning Application. With further clarification of the scheme for the planning application, this Supplement to the Outline Technical Report has been prepared. Following the public exhibition at the end of June 2009 and other stakeholder consultations, the alternative cavern field layout, as stated in the ‘Outline Technical Report’ has now been selected by Islandmagee Storage Limited (Enclosure 1-1) [1].

2 Surface Subsidence

Following the final selection of the location of the wellpad, as a result of the public exhibition and stakeholder meetings at the end of June 2009, a model for the surface subsidence has been developed. As a result of the solution mining process and subsequent gas operations, surface subsidence can extend over areas beyond the margins of the cavern field. In order to assess the possible impact of the storage operation on the topography at the surface, the Institut für Gebirgsmechanik GmbH, Leipzig, Germany (IfG, Institute for Rockmechanics) was entrusted to prepare a prognosis based on their comprehensive experiences from various cavern projects. The following descriptions and calculations are the results of this work [2]. The memorandum ‘Subsidence prognosis for Islandmagee Storage’ of IfG is also attached to this supplement (Appendix).

The rock-mechanical behaviour of the rock salt, in which the caverns are planned to be constructed underneath Larne Lough, is incomplete. This is due to the lack of sample material from the Permian salt. This will be acquired by drilling a borehole to take cores of the salt as part of the Front End Engineering design. Thus, data on the parameters involved has to be inferred from experience with rock salt behaviour from comparable locations/projects. The resulting assumptions necessary for the assessment of subsidence represent the closest approach to real conditions within the area of interest possible at this stage of the project.

2.1 Subsidence Prognosis

The convergence of salt caverns and the resulting surface subsidence depend on the creep behaviour of the rock salt. Reasonable assumptions on the stress conditions and the temperature have to be made. For estimating of stress conditions, a common approach is to assume a mean cavern pressure equivalent to a pressure induced by a brine column. Correspondingly, at the reference depth (lower third of the cavern height) at 1,620 m, the brine pressure equals to 191.2 bar (without wellhead pressure) while the overburden pressure from the overlaying rocks is assumed to be 37,3 MPa on the basis of an assumed gradient γ of 23 kPa/m.

Estimates for the prevailing formation temperature are required for the subsidence assessment. For the Islandmagee gas storage project, the initial mean formation temperature of 65°C can be calculated from T = 18°C + 0.035 K/m.

As evident from many creep tests carried out on the Permian rock salt “Zechstein 2” from many different locations in Germany, the ratio between the constant creep rate at room temperature and the constant creep rate at 65°C may vary in the range of one order of magnitude.

This dependency of creep rate on temperature is also reflected in the widely used rock salt creep law BGR-a (incorporating an activation energy Q for thermo-dynamics), in which

$e^{-Q/RT}$ (Q/R = 5600 K) changes from

$e^{-5600\,K/295\,K}$ (at 22°C) to

$e^{-5600K/338K}$ (at 65°C).

From the IfG data base, a creep rate of

$\dot{\varepsilon}_{cr} = 5.1 \cdot 10^{-7} \cdot \sigma^{4,44}$

is to be assumed for the Permian rock salt underneath Larne Lough.

Following the approach suggested by Berest & Brouard (2003) [3], the analytical calculations lead to rates of cavern convergence as a function of depth and estimated formation temperature illustrated in Enclosure 2-1.

From the intersection of the green line (creep rate at 65°C) in Enclosure 2-1 with the reference depth of 1,620 m, a rate of convergence of 0.5 %/a can be deduced. Such a rate of convergence seems to be a realistic assumption [2]. This value is used for further subsidence calculations.

The cavern convergence rate depends on several other geo-mechanical and mining operational parameters, such as depth, shape and dimensions of the caverns and the pillars.

In the Islandmagee Storage Project, seven caverns with a usable volume of 480 Tm^3 per cavern are planned to be constructed below Larne Lough within a period of approximately two years.

Further preliminary parameters for the calculations are the distance between cavern wells of 300 m, a reference depth of 1,620 m and a period of 30 years of cavern operation.

In most cases, a critical angle of 55° is viable to describe the geo-mechanical influence from the place of convergence, the cavern, to the surface.

By application of the program code 'SENK', calculations were carried out to depict surface subsidence (Enclosure 2-2) as well as subsidence slopes (Enclosure 2-3) and the maximum strain (Enclosure 2-4) in the region of the subsidence bowl.

The prediction of cavern convergence is based on the assumption of an annual storage cycle. The subsidence is predicted to be negligible over the lifetime of the project. The subsidence is predicted to be a maximum of 0.28 m (28 cm) along the shores of Larne Lough by the well pad area, reducing to zero within a distance of 1,000 m. The slope of subsidence does not exceed 0.4 mm/m; well below the

10 mm/m maximum recommended for mining operations in UK by the National Coal Board in 1975.

From the assumptions and calculations outlined above, the IfG concludes:

‘From the rock-mechanical point of view, the values predicted for subsidence in the vicinity for the planned Islandmagee gas storage are uncritical. The cavern operation is safe as far as the surface infrastructure is concerned.’

3 Pipeline Design

The design of the water intake as well as brine disposal pipelines across Islandmagee, the water and brine lines between brine facilities and header area on the well site and the gas pipe between wellheads and gas facilities are represented in Table 3-1, Table 3-2 and Table 3-3, respectively.

Table 3-1: Water and brine pipelines between water intake station/sea and brine facilities

flow	1,000	m³/h
mean velocity	2.6	m/s
outer diameter	450	mm
inner diameter	368.2	mm
wall thickness	40.9	mm
material	HDPE	-
max. pressure	10	bar
design pressure	PN 16	-

Table 3-2: Water and brine lines between brine facilities and header area on the well site

flow	1,000	m³/h
mean velocity	2.6	m/s
outer diameter	406.4	mm
inner diameter	366.4	mm
wall thickness	20	mm
material	Steel L 360MB	-
corrosion allowance	5	mm
max. pressure	115	bar
design pressure	PN 150 (ANSI 900)	-

Table 3-3: Gas pipe between wellheads and gas facilities

max. flow	950,000	Nm³/h
max. pressure	230	bar
min. pressure	100	bar
mean velocity	25.7	m/s
outer diameter	406.4	mm
inner diameter	361.4	mm
wall thickness	22.5	mm
material	Steel L 360MB	-
corrosion allowance	0	mm
design pressure	PN 250 (ANSI 1500)	-

4 Decommissioning of Caverns

When a gas storage cavern reaches the end of its life, it must be decommissioned in a way that does not allow for any later hazard or environmental degradation. Some effects influencing the long-term abandonment of caverns (increase / decrease in pressure) are:

- Initial undersaturation of the brine fill,
- thermal expansion of the brine fill,
- convergence of the cavern (due to salt creep),
- long-term permeation into the salt,
- fluid permeation through the sealing plug/casing cement, and
- chemical processes (e. g. re-crystallisation).

A basic cavern sealing and abandonment concept (CSA) is required for the Islandmagee Gas Storage Project. Technical procedures have been set out on how to realise the post operational (abandonment) phase (Chapter 4.4).

Up to now, worldwide, there are only a few gas storage caverns that have been abandoned or are currently in the preparation for abandonment. However, during recent years, extensive research has been undertaken to study the various aspects of cavern abandonment. A substantial portion of this work has been done under the aegis of the Solution Mining Research Institute (SMRI) in a special 'Cavern Sealing and Abandonment (CS&A) Project' worked out by an international board of experts from the salt industry and relevant authorities [4]. In 2006, a 'Cavern Well Abandonment Techniques Guidelines Manual' was prepared by KBB Underground Technologies (KBB UT) for SMRI [5]. To summarize the results of these studies, it can be stated, that reliable and internationally accepted procedures for cavern abandonment have been developed, which have to be adapted to the specific situation of every single cavern.

4.1 Requirements

A CSA concept (Cavern Sealing and Abandonment) needs to meet the following requirements:

- Long-term protection from contamination of drinking water aquifers and the escape of brine and/or flammable and/or environmentally hazardous storage product residues at the surface,
- long-term stability of rock mass surrounding the cavern,
- free of (or low in) maintenance,

- application of tried-and-tested methods and materials as far as possible,
- affordability, and
- acceptable by the authorities.

After a successful plugging, the field lines, the well head as well as other installations on the cavern pad have to be dismantled and the cavern pad and the access roads restored.

4.2 Preparations for Cavern Sealing

First of all, the gas cavern to be abandoned needs to be depressurised down to permissible minimum pressure, at which the stability of the cavern still can be guaranteed. To replace the remaining cushion gas with (sea-) water, the subsurface safety valve is to be removed or sleeved before a (sea-) water injection string can be snubbed in under gas pressure. As soon as the cavern is filled with (sea-) water, the injection string and gas completion can be removed. Before the plugging, a waiting period will be given to allow for the thermal equilibrium between the brine fill and formation. After this waiting time, the installation of the plug can commence.

4.3 Cavern Sealing

The objective for the abandonment of a cavern is to guarantee the long-term stability of the formation around the cavern and the integrity of the cavern seal. In a plugged and fluid-filled cavern, the internal cavern pressure will increase over time due to salt creep resulting in cavern convergence and thermal expansion of the enclosed brine approaching the formation temperature once prevailing prior to leaching and gas operations. The increase of internal cavern pressure is counteracted by further salt dissolution (inducing a decrease of the brine temperature) and brine slowly permeating into the salt matrix. Theoretically, the pressure increase will stop as soon as the internal cavern pressure is equal to the formation pressure of the surrounding rock salt.

Since the thermal expansion of the brine has a major effect, it is recommended, that prior to cavern sealing, all caverns should be kept open as long as possible and practical (i. e. in shut-in and bleed-off periods) to minimise the temperature difference between the salt formation and the brine [4].

Following the end of operations and a period of time to reach thermal equilibrium, the work on the plugging can be conducted. There are basically three possible alternatives for plugging cavern boreholes prior to abandonment:

- plug within cemented casing,
- plug within cavern neck (open hole) below cemented casing, and

- plug within milled casing section.

The option of plugging depends on the local cavern conditions (e. g. geometry of the cavern neck) as well as on the cavern history.

4.4 Investigations and Monitoring

A long-term equilibrium will be reached, if thoroughly prepared abandonment schemes are adhered to. In a preparation phase prior to cavern abandonment, some site-specific investigations will have to be carried out and the following features will have to be monitored or tested:

- cavern compressibility,
- in-situ creep behaviour of the surrounding rock mass, and
- temperature development with time during the brine fill (temperature logs in the brine-filled cavern).

These tests and observations together with the geology, cavern as well as well data, rock mechanics, salt permeability and operational history of the cavern will provide specific data for numerical simulations of the pressure development in the cavern during abandonment. This data will provide indications, whether critical values may be reached in the future of the abandoned cavern.

A pressure control may be necessary in case of insufficient data and parameters listed above. In homogenous salt formations, in which long-term stability and integrity of the cavern and seal is proven and a complete data set is available, the monitoring in the post-abandonment phase can be reduced to periodic measurements of the subsidence [5].

References

[1] DEEP. Underground Engineering GmbH (2009): Outline Technical Report on the Proposed Gas Storage Project at Islandmagee, Northern Ireland. -77 pp.

[2] Institut für Gebirgsmechanik (2009): Memorandum: Subsidence prognosis for Islandmagee Gas Storage. – 5 pp.

[3] Bérest, P.; Brouard, B. (2003): Safety of Salt Caverns Used for Underground Storage. - Oil & Gas Science and Technology – Rev. IFP, Vol. 58 (2003), No. 3, pp. 361-384.

[4] Ratigan (2003): Cavern Sealing and Abandonment Program, 1996 through 2002, SMRI Research Project Report No. 2002-3.

[5] Crotogino & Kepplinger (2006): Cavern Well Abandonment Techniques Guideline Manual, SMRI Research Project Report No. 2003-3.

List of Enclosures

Appendix

Memorandum - Subsidence prognosis for Islandmagee Gas Storage, Institut für Gebirgsmechanik (September 2009).