Development of a New Brine Cavern Field for the Hengelo Salt Plant:

Basic Leaching Concepts and Production Planning of the Haaksbergen Site

for:

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1 Introduction

To ensure the long-term brine supply for the salt evaporation plant in Hengelo, AkzoNobel plans to develop a new cavern field north of the town of Haaksbergen approx. 10 km southwest of Hengelo. The new brine field is designed to produce 2.6 million tons of salt per year for at least 50 years. However, as the salt production from the Hengelo brine field will gradually decrease from 2017 onwards (Figure 1), the development of the new field has to compensate successively for this difference. To allow for sufficient preparation time the Haaksbergen leaching operation is planned to be initiated beginning of 2014.

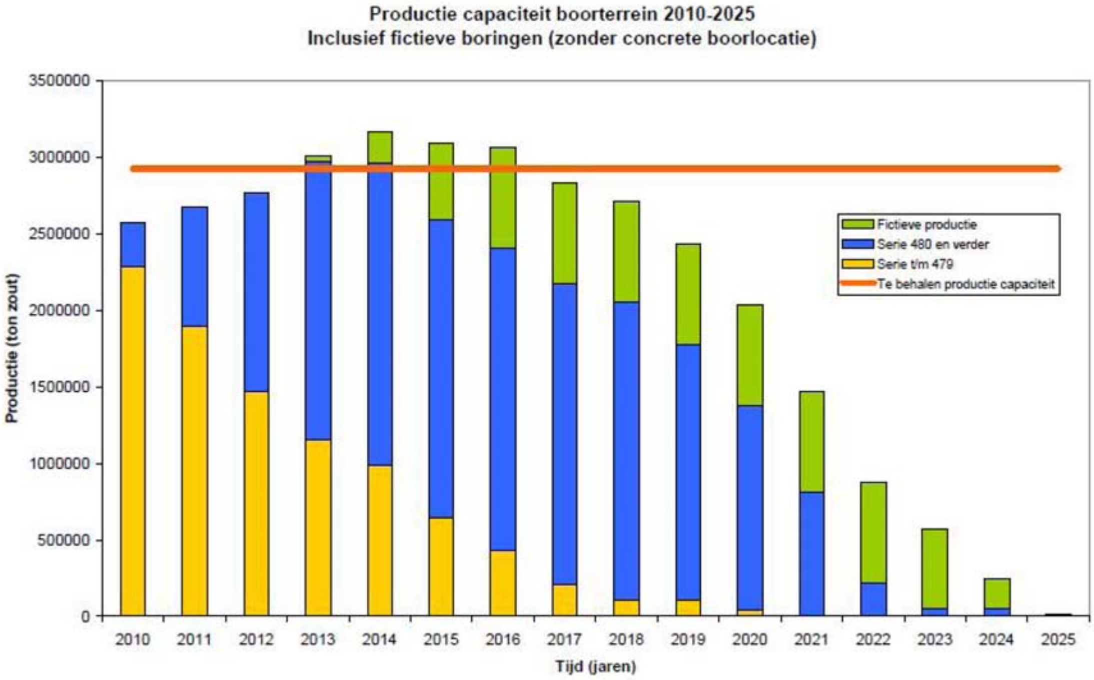


Figure 1: Brine production capacity of the Hengelo brine field (2010 – 2025)

The Haaksbergen salt structure is a bedded, slightly up-domed (pillow shaped) deposit of the Zechstein Group. The Werra Formation (Zechstein 1) reaches up to 400 m thickness in the centre of the salt body and thins out towards the edges of the deposit.

To allow for an optimal exploitation and a constant brine production, the leaching and production scenario considers the development of 36 caverns to be operated in three phases. All 36 caverns are arranged in a hexagonal grid (Enclosure 1). In the entire cavern grid is room for additional 28 caverns, i.e. for a total of 64 caverns.

After commencement of leaching in 2014 with 12 caverns of the 1st phase, the 2nd phase needs to be started around 2020 to allow for a smooth transition after the caverns of the 1st phase are almost completely exploited. During the 3rd phase another 12 caverns will be constructed starting after 2030. The potential remaining 28 caverns will be planned not earlier than 2045.

Four types of caverns with different heights and volumes were defined to reflect the varying thickness of the salt deposit (Chapter 6).The present study provides an update of the basic leaching concepts [1] for the four different cavern types. The production planning for the 1st and 2nd phase and the preliminary plan for the 3rd phase and the potential remaining caverns has been updated accordingly.

The update presented herein includes the following aspects and further information:

- results of the seismic campaign and the subsequent review of the geological 3D model and the consequences on the arrangement of caverns of different height throughout the field,
- drilling sequence, i.e. starting in the eastern cavern field (close to the leaching station) and westward development,
- leaching test results,
- leaching completion and respective hydraulic calculations,
- selection of four different type caverns,
- number and sequence of leaching activities (work-over, sonar measurements and blanket level measurements),
- simultaneous leaching start-up of four caverns and successive start-up of the following caverns at intervals of 1 ½ months during the 1st phase, and
- total salt production of 217,000 tons of salt per month.

The planning does not consider any secondary use of the caverns. After brine production, the caverns will be abandoned.

2 Project Requirements

The basic parameters for the development of the new brine field and thus, for the update of the leaching concepts, result from technical and commercial requirements of the Hengelo salt evaporation plant as well as from geological and rock-mechanical boundary conditions evaluated after drilling of the exploration well ISH-01 [5,6].

To develop a reliable leaching strategy and field development, several pre-conditions and requirements have to be considered. In this project, the major boundary conditions are:

- the guaranteed production of 2.6 million tons of salt per year,
- the production of salt for a minimum of 50 years,
- a total brine flow of 1,050 m³/h,
- the reduction of number of work-over,
- a reduced number of caverns in leaching operation with a saturated brine flow of 150 m³/h to limit the subsidence above the cavern field to the lowest possible magnitude, and
- the successive usage of brine from the new cavern field, beginning in 2014 prior to the gradual reduction of the brine production from the Hengelo brine field.

3 Geological Framework

In the subsurface of the Haaksbergen area, Z1 (Werra) evaporite deposits of Zechstein age occur as an elongated, roughly E-W trending salt pillow, some 6 km long and 2 km wide. In the target area, the thickness of the Z1 Salt varies from approx. 115 m to 400 m while the top of the unit is found at approx. 515 m to 990 m below NAP (Enclosures 1-3). The revision of the geological model [3] is based mainly on two new seismic lines running roughly across the centre of the salt pillow. The results of the exploration well ISH-01 [6] were also used to adapted to the previous seismic model [2]. Compared to the previous model, the revision revealed one elongated salt ridge with no indication of two individual summits. The new geological model shows that the base of the Z1 (Werra) salt sequence in the target area is at greater depth of approx. 845 m to 1,140 m NAP than previously assumed [2].

The Z1 Salt sequence is sandwiched between two massive anhydrite beds (Z1 Upper and Lower Anhydrite). In well ISH-01 the Z1 Salt (335.4 m thick) consists of rock salt (halite) with a low content of approx. 4 % anhydrite for more than 80 % of the salt interval. At the top of the Z1 Salt and in the basal part anhydrite intercalations occur that are a characteristic sedimentary feature for the bedded salt deposit. As proven by the drilling results of the well ISH-01, the Haaksbergen salt deposit has retained more or less the original horizontal bedding without a complex internal structure, although, slump features occur locally in well ISH-01.

The lenticular shape of the deposit with varying thicknesses of the salt sequence will be considered in the definition of the four cavern types (Chapter 6) and their corresponding leaching concepts (Chapter 7).

4 Rock-mechanical Layout

Starting point of the cavern design and prime constraint for cavern development is the rock-mechanical envelope, i.e. the maximum theoretical boundary that guarantees the long-term stability of the cavern contour. The rock-mechanical envelope should not be exceeded at any time during the leaching process and the cavern lifetime.

The rock-mechanical cavern layout established for the project phase I-II simplifies the salt deposit as well as the operational assumptions [1].

The proposed design parameters of the rock-mechanical envelope (Table 1) are selected based on the review of the geology, the information gained by the exploration well ISH-01 and the results of the additional seismic survey [3, 6]. The rock-mechanical layout represents the boundary conditions of a cavern created in a salt thickness of approx. 375 m (cavern no. 04) and is located in a depth range from 712 m to 1,007 m. It has an elliptical shape of the bottom part, a cylindrical section with a diameter of 125 m and a spherical roof (Table 1). The overall shape, diameter and thickness of the bottom and roof pillar is applied to all locations in the field. The safety pillar of the cavern roof to the top of the salt is 70 m. The bottom pillar is 10 m. Consequently, the height of the cylindrical part varies. Therefore, four caverns types are defined for simplification (Chapter 6).

Table 1: Proposed rock-mechanical layout according to information gained from exploration well ISH-01

top of salt [m]	642
depth of last cemented casing shoe [m]	682
depth of cavern roof [m]	712
depth of top - cylindrical cavern part [m]	774
depth of bottom - cylindrical cavern part [m]	972
depth of cavern sump [m]	1,007
base of salt [m]	1,017
max. diameter [m]	125

5 Cavern Hydraulics

The selection of the tubing combination for the leaching completion has to consider the permissible pressure at the last cemented casing shoe and the energy costs. The leaching rates, the leaching mode, the depth of the last cemented casing shoe and the hydraulic friction loss inside the leaching tubings are the input parameters for hydraulic calculations. The input data for hydraulic calculations with the most conservative assumptions (deepest Z1 Salt occurrence and max. setting depth of the inner leaching tubing) are summarized in Table 2.

Table 2: Basic data for hydraulic calculations for the leaching process

depth of last cemented casing [m TVD]	785.5
setting depth CS; inner leaching tubing [m TVD]	1,103
setting depth CS; outer leaching tubing [m TVD]	1,096
pipe roughness [m]	0.00001
density of injection water [kg/m³]	1,000
density of produced brine [kg/m³]	1,200
density of blanket medium [kg/m³]	820
blanket type	oil
depth of blanket level [m TVD]	1,095
max. leaching rate (direct/reverse leaching mode) [m³/h]	150
well deviation	negligible

The blanket pressure at the last cemented casing shoe increases with increasing depth of the brine-blanket interface. At every stage of the leaching process, the pressure at the last cemented casing shoe has to be below the maximum operational pressure. The most critical blanket pressure will be reached when the blanket level is at its deepest position and the brine density is close to saturation at 1.200 kg/m³. Thus, for the hydraulic calculation the most conservative situation has to be checked:

- deepest pipe settings,
- deepest blanket depth, and
- direct leaching mode.

The results of the hydraulic calculations during the sump leaching phase with a 10 ¾” x 7” and a 9 ⅝” x 6 ⅝” tubing combination are shown in Enclosure 4. The pressure at the last cemented casing shoe will reach approx. 110 bar (10 ¾” x 7”) at a flow rate of 150 m³/h during the sump leaching phase (direct mode). Even an increase of the flow rate to 200 m³/h will result in a pressure of 113 bar and thus the permitted pressure at the last cemented casing shoe of 141 bar will not be exceeded. The results of the hydraulic calculation for the leaching process with a 10 ¾” x 7” and a 9 ⅝” x 6 ⅝” tubing combination are shown in Table 3.

In the subsequent phases of the leaching process, the blanket level will be raised stepwise and the leaching mode will be switched to reverse mode. Therefore, the hydraulic conditions will be less critical.

Table 3: Results of hydraulic calculation for the leaching process with 10 ¾” x 7” and 9 ⅝” x 6 ⅝” tubing combination

	10 ¾” x 7”	**9 ⅝” x 6 ⅝”**
max. flow rate [m³/h]	150	150
max. injection pressure at the well head [bar]	30	41
max. pressure at the last cemented casing shoe [bar]	110	120
max. allowable pressure at the last cemented casing shoe [bar]	141	141
max. blanket pressure at well head [bar]	47	57

Table 4 displays the required energy of the pumps for the solution mining process in direct and reverse leaching mode with different tubing combinations.

Table 4: Required energy of pumps with different tubing combinations

	required pump energy @ 150 m³/h [kWh/day]	
tubing combination	**direct mode**	**reverse mode**
10 ¾" x 7"	4,222	4,153
9 ⅝" x 6 ⅝"	5,914	5,656
8 ⅝" x 5 ½"	6,195	6,183
7" x 4 ½"	12,810	12,708

As shown in Table 3 to 4 and Enclosure 4, the most efficient tubing combination is a 10 ¾” outer leaching tubing and 7” inner leaching tubing.

6 Conceptual Cavern Design

After the update of the geological model of the Haaksbergen salt deposit (Chapter 3, Enclosures 1-3) the cavern design was adjusted to the revised salt thickness. Due to simplification purposes, four cavern types were defined. The four cavern types are characterised by the same bottom and roof pillar thickness, i.e. the vertical distance to the underlying and overlying non-salt beds. The same cavern types are used by IfG for their numerical modelling to predict the cavern convergence.

The classification of the cavern types 1 to 4 is summarized in Table 5 and Enclosure 5 according to the revised thicknesses of the Z1 Salt. The cavern types 1 to 4 are defined by a fixed total height of the cavern and depend on the position in the cavern field (Enclosures 6).

Table 5: Dimensions of cavern types 1 to 4

type	quantity	height [m]				radius [m]
		sump	cylindrical part	roof	total cavern	
1	11	35	190	62.5	287.5	62.5
2	17	35	140	62.5	237.5	62.5
3	18	35	90	62.5	187.5	62.5
4	18	35	40	62.5	137.5	62.5

Each cavern type comprises a group of caverns with a specified range of cavern heights. Type 1 is representative of caverns with a height between 270 to 320 m. The height of type 2 caverns is between 220 to 270 m, of type 3 caverns between 170 to 220 m and of type 4 caverns between 120 to 170 m. The number of caverns of the different types 1 to 4 and respectively cavern heights is illustrated in Figure 2 and Table 5 for all 64 potential caverns. Up to now, it is planned to realize 36 caverns.

Furthermore, the number of caverns in Figure 2 is grouped regarding the three phases (1st phase-caverns no. 1-12, 2nd phase-cavern no. 13-24, 3rd phase-caverns no. 25-36). The distribution of cavern types 1 to 4 of the 1st to 3rd phase caverns throughout the cavern field is shown in Enclosure 6.

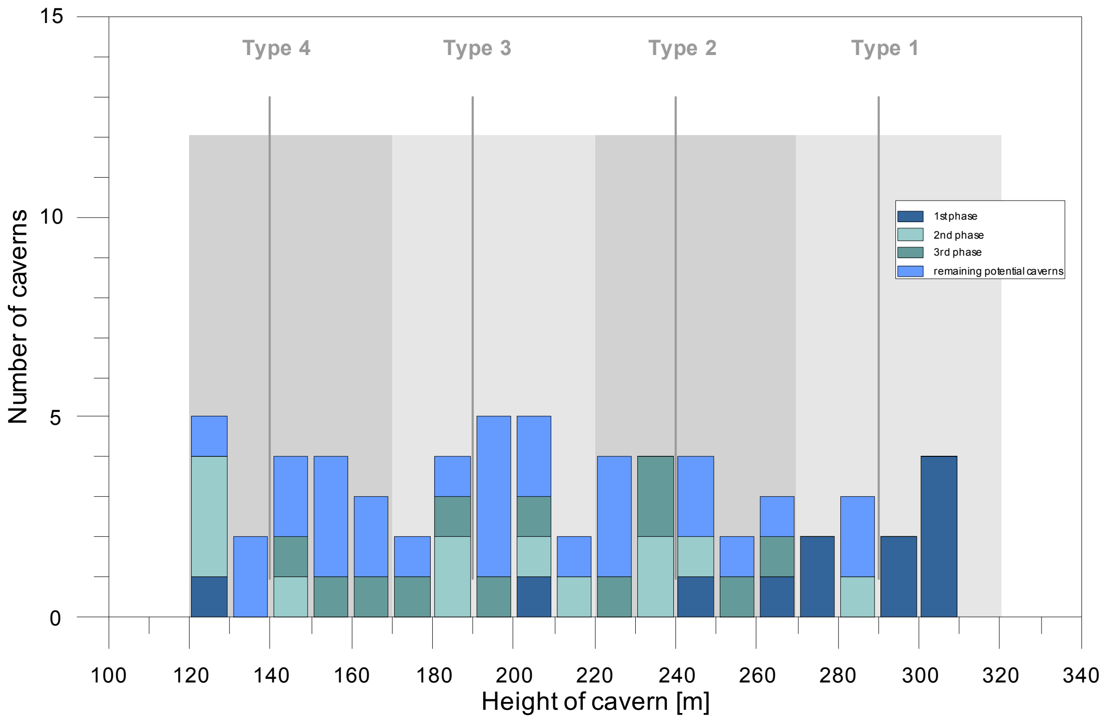


Figure 2: Classification of cavern types 1 to 4

It was calculated that the potential 64 “type 1 to 4 caverns” with a diameter of 125 m (Table 5) and an utilization factor of 0.8 of the cross-sectional area of the rock-mechanical envelope are sufficient to cover a production period of approx. 60 years with a total salt production of approx. 174 million tons (at a constant rate of approx. 1,050 m³/h). The utilization factor accounts for a safety margin that compensates for effects as asymmetrical cavern development, preferred up-dip leaching or preferential leaching of particular beds. The maximum cross-sectional area used for the leaching simulation is 9,800 m², which equals to a diameter of 112 m in the case of axi-symmetric development. An axi-symmetric cavern model was applied for leaching simulation, because there are no indications in the field for expected elliptic or otherwise preferred directional development of the cavern shape.

7 Leaching Concepts

Based on the previously described conditions and assumptions, the 3D leaching simulation software *UbroAsym for Windows* was used to model the cavern development. The software tool has the capability to produce rotational symmetrical models with a vertical resolution of 500 slices. In many years of experience, the results of the simulation have always proven to be very reliable when later being compared to the actual leaching process.

The leaching simulation was performed for each cavern type (type 1 to 4). The basic input parameters are described in Chapter 7.1. Once the cavern model is established, the leaching simulation is performed by iterative optimization of the solution mining variables, i.e. the injection rate, leaching tubing settings and blanket level depth and the time allotted to each leaching step.

The output of the leaching simulation is a conceptual leaching programme that lists the operating parameters and the number as well as the chronology of actions (work-overs, sonar surveys, etc.). Moreover, the leaching model yields:

- the concentration of the brine produced,
- the dissolved and produced amount of salt,
- the net cavern volume,
- the volume of insolubles in the cavern sump,
- the level of the sump, and
- the axi-symmetrical development of the cavern shape.

7.1 Input Parameters

The leaching simulation had to be updated with regard to the cavern dimensions, formation properties and operational parameters in order to optimize the leaching concepts. Tables 6 to 8 show the input parameters of the first leaching concept (project phase I-II) [1] compared to the updated concept (project phase III).

7.1.1 Cavern Dimensions

The rock-mechanical cavern dimensions as used for the leaching simulation are summarized in Table 6. Four different cavern types with different heights of the cylindrical part were considered according to the conceptual cavern design described in Chapter 6. The utilization factor of 0.8 is applied for the cross-sectional area to represent a most probable exploitation of salt reserves within the rock-mechanical envelope.

Table 6: Rock-mechanical cavern dimensions applied to the leaching simulation

	project phase I-II	project phase III
height of roof [m]	65	62.5
height of cylindrical part [m] (cavern types 1 to 4)	140 / 120 / 70 / 20	190 / 140 / 90 / 40
height of sump [m]	35	35
max. diameter [m]	125	125
diameter for simulation [m] (with utilization factor of 0.8)	112	112
cross-sectional area [m^2]	12,300	12,300
cross-sectional area [m^2] (with utilization factor of 0.8)	9,800	9,800

7.1.2 Formation Properties

The leaching behaviour of the cavern depends on the leaching properties of the surrounding rock salt formation. The properties of the salt rock were experimentally acquired by laboratory tests on core samples from well ISH-01 under standardised conditions. The main leaching properties are the horizontal and vertical leaching velocities as well as the total amount and the distribution of the insoluble components and the loosening (bulking) factor of the insolubles in the sump. Table 7 summarizes the input data used for the leaching simulation.

Table 7: Formation properties as applied in the leaching simulation

	project phase I-II	project phase III
insolubles content [%]	10.0	0.25 – 17.20; average 4.6
bulking factor (sump porosity)	1.6	1.50 – 2.00; average 1.9
average leaching velocities, vertical [mm/h]	18.0	16.9
average leaching velocities, horizontal [mm/h]	12.0	8.8
density of rock salt [kg/m³]	2.155	2.165
undisturbed rock salt temperature [°C]	30	25

The percentage and distribution of the insoluble components in the cavern interval as determined from well ISH-01 were considered for the leaching concept. The insoluble content of ± 10 vol.% in the depth interval of the first leaching step between 920 m and 956 m TVD (Enclosure 7) implies a rapid increase of the sump level during the initial sump leaching phase. This was taken into account in the planning of the sump cavern (Chapter 7.2.1). The occurrence of insoluble-rich beds in the depth interval between 720 m and 780 m TVD is also considered in the leaching simulation for the main/roof leaching phase.

7.1.3 Operational Parameters

Maximum injection rates of 150 m³/h were considered for both, sump and main leaching phases. (Table 8). The leaching rate will be temporary reduced to keep the brine concentration above 312 g NaCl/l. The demand of the salt plant is brine at a rate of 1,050 m³/h to cover a monthly salt production of 217,000 tons (Chapter 2). The maximum brine demand of AkzoNobel in Hengelo is 1,200 m³/h.

Table 8: Operational parameters as realized in the leaching simulation

	project phase I-II	project phase III
minimum brine concentration [g NaCl/l]	312	312
leaching rate [m³/h per cavern]	80 - 150	max. 150
brine production rate [m³/h]	1,200	1,050
temperature of injection water [°C]	30	25

The leaching medium is a mixture of condensate from the Hengelo salt plant (60%) and water from the Twentekanaal (40%). The temperature of the canal water is 4°C in winter and 24°C in summer and the condensate temperature is approx. 60-70°C. Thus, the average temperature of the injection water will be approx. 25°C.

The minimum concentration of the delivered brine to the salt plant has to be 312 g NaCl/l. Therefore, the weak brine from the sump leaching process has to be re-saturated in other caverns of the Haaksbergen field (Chapter 7.2.3 and Chapter 8).

7.2 Leaching Programme

Altogether, the cavern construction comprises the sump phase and the main leaching phase including the roof leaching phase. These phases are briefly described below. Tabular leaching programmes for every cavern type (1 to 4) are presented in Enclosures 8b, 9b, 10b, 11b and 11d. Enclosures 8c, 9c, 10c, 11c and 11e show the brine flow, the brine concentration and the development of cavern volume over time, while Enclosures 8a, 9a, 10a and 11a display the development of the cavern shapes as modelled by the *UbroAsym for Windows* simulation software tool.

The cavern is shaped within the boundaries of the rock-mechanical envelope by switching between the leaching modes and variation of the leaching rates. Essential activities such as changes in the setting depths of the leaching strings and continuous adjustment of the blanket level will require several activities (work-overs, sonar surveys).

Operational downtime assumed for work-overs is 30 days, because one month is the smallest time increment that was applied in the modelling of the overall field development at this stage of the project. In reality, the time span required for work-overs will be significantly less (approx. 3-10 days).

Sonar measurements for volume and shape control should be performed with every 150,000 m³ of created cavern volume of the leaching process. Ideally, the sonar surveys are combined with work-overs according to the planning in the leaching concepts (Enclosure 8b, 9b, 10b, 11b, 11d). If this cannot be realized, the inner leaching tubing has to be lifted to execute a sonar survey through the outer leaching tubing (partial measurement). From experience, it is known that the number of sonar measurements can be reduced with the progress in field development as a better knowledge of the leaching behaviour of the formation is successively achieved.

Table 9 summarizes the number of interventions (work-overs, sonar surveys, blanket adjustments) and key production data during the sump and main leaching phase considered for cavern type 1 to 4.

Table 9: Key production data and number of interventions per cavern type

		type 1	**type 2**	**type 3**	**type 4,** fresh water	**type 4,** weak brine
sump leaching phase	no. of work-overs	1	1	1	1	1
	no. of blanket steps	2	2	2	2	2
	max. leaching rate [m³/h]	150	150	150	150	150
	duration [d]	634	616	653	653	653
	average concentration [g NaCl/l]	222	220	222	222	222
	volume [million m³]	0.229	0.224	0.242	0.245	0.245
	extracted salt [million tons]	0.458	0.440	0.473	0.474	0.474
	no. of sonar measurements	2	2	2	2	2
main leaching phase	no. of work-overs	3	3	2	2	2
	no. of blanket steps	2	2	2	2	2
	max. leaching rate [m³/h]	150	150	150	150	150
	duration [d]	3,630	2,880	2,040	1,320	3,803
	average concentration [g NaCl/l]	313	313	313	312	314
	total volume [million m³]	2.242	1.809	1.371	0.962	0.978
	extracted salt [million tons]	3.844	3.026	2.149	1.363	1.363
	no. sonar measurements	13	10	7	5	5

7.2.1 Sump Leaching Phase

The sump leaching phase is defined as the initial stage of cavern development during which the cavern delivers weak brine. The leaching process in this phase is the same for all four cavern types. The final volume and the amount of extracted salt reached at the end of the sump leaching phase vary slightly according to the different heights of the cylindrical part of the different caverns.

The insoluble content in the depth of the first leaching step is higher than in the remaining cavern interval (Enclosure 7) [7]. When leaching the sump in a single step as proposed in the earlier leaching concepts [1], it is most likely that the insoluble material will prevent the sump from developing to a sufficient diameter. The slope angle of the sump and the volume loss would be significant. Thus, it is recommended to start solution mining with a sump height of 8 - 10 m (1st leaching step) in a section between 948 m and 956 m TVD (according to the geological section of well ISH-01) with a minor amount of insolubles of approx. 4 % (Enclosure 7). This 1st leaching step will take approx. ½ year to create a flat and broad initial cavity. The inner and outer leaching tubings are installed approx. 10 m apart and the initial blanket level is set just above the shoe of the outer tubing. After a work-over the leaching process will continue with a sump height of 35 m for approx. 2 years.

A second work-over serves to adjust the position of the leaching tubings, which are both lifted by some 10 m. Solution mining will then continue in reverse mode (top injection).

After some 780 days of gross leaching time (including work-overs and other measures) with a leaching rate of 150 m^3/h, the cavern has achieved a volume of approx. 230,000 m^3 and a diameter of 100 m to 105 m at the end of the sump leaching phase. Up to this point in time, the brine concentration has steadily increased, yielding an average concentration of approx. 222 g NaCl/l. When four caverns will be leached simultaneously in the sump leaching phase, the brine plant will be provided with 600 m^3/h of weak brine for the first two years (Chapter 8.1).

Brine of full concentration (312 g NaCl/l) can already be produced after approx. 8 months during the sump leaching phase. For this purpose, the injection rate needs to be reduced to 25-30 m^3/h during the second step of the sump development. The total brine volume forwarded to the Hengelo salt plant will then be 120 m^3/h due to the reduced leaching rate. Consequently, the duration of the entire sump leaching phase would extent to approx. 6 years.

7.2.2 Main Leaching Phase

The main leaching phase comprises the creation of the cylindrical part and the cavern roof. Throughout this phase the cavern is exclusively operated with reverse circulation (top injection). Constantly saturated brine of >312 g NaCl/l is produced at a rate of 150 m^3/h.

As the height of the cylindrical part varies from 40 to 190 m depending on the thickness of the formation (Chapter 6), the number of interventions (blanket movements, work-overs), the timing and the sequence of actions are slightly different for the four cavern types (Enclosures 8b, 9b, 10b, 11b, 11d). The main leaching phase includes three work-overs for type 1 to 2, two work-overs for type 3 to 4 and two blanket steps for each cavern type. For all cavern types, the main leaching phase starts with a work-over.

Subsequent blanket steps and adjustments of leaching tubings already serve to develop the cavern roof. In order to utilize the reserves enclosed in the spherical roof shape, the cavern roof is leached stepwise to form a terraced cupola. While shaping the roof, considerable volume is still added to the cylindrical part.

To keep the number of blanket measurements as low as possible, the leaching concepts consider two blanket changes at the end of the leaching process. This results in a cavern roof shape that only roughly fits into the rock-mechanically ideal, domal contour. Here, potential for improvement and optimization is still given by planning for one or two more blanket steps to adjust the cavern roof to an optimum shape and to produce an additional volume of salt from the roof (approx. 150,000 m^3).

In the type 4 caverns the main leaching phase is shortest in comparison to the other types. The main leaching phases for the different cavern types will last:

- 3.5 years for type 4,
- 5.5 years for type 3,
- 7.5 years for type 2, and
- 9.5 years for type 1.

7.2.3 Fresh Water versus Weak Brine Injection

During the sump leaching phase, weak brine with an average concentration of 222 g NaCl/l is produced. To guarantee a constant flow of saturated brine (>312 g NaCl/l), this weak brine needs to be saturated bypassing it through other caverns before being delivered to the salt plant. The concept of further saturation is described in more detail in Chapter 8. It is considered that the weak brine will be saturated within the Haaksbergen field as soon as it has been sufficiently developed.

While the cavern volume is created relatively fast when injecting fresh water at a rate of 150 m^3/h (averaged volume increase of 560 m^3/d), the cavern lifetime is significantly increased by weak brine injection at the same rate (averaged volume increase of 192 m^3/d). It was recommended in the first leaching concept [1] that the small-sized type 4 caverns should be chosen for further saturation. Keeping the smaller cavern volume open for a longer time span has a much lesser effect on the overall subsidence than using larger caverns with increased lifetime for re-saturation. Due to the given drilling sequence, all cavern types 1 to 4 have to receive weak brine from the sump leaching process of other caverns for further saturation during the 2nd and 3rd phase (Chapter 8). The first four caverns of the 1st phase will be used as long as possible for re-saturation; in consequence of infrastructural conditions (e.g. piping).

The leaching programme for the “saturator caverns” operated with weak brine is basically the same as for those that receive fresh water (Chapter 8.1). As shown in Table 9, the duration of the main leaching phase is increased by a factor of roughly 3 for the “saturator caverns”.

8 Field Development

For a maximum utilization of the Z1 Salt reserves of the Haaksbergen structure, the caverns are arranged in an almost hexagonal grid with 300 m distance between the cavern wells and a safety pillar width of minimum 175 m (Enclosures 1-3). A few cavern positions were skipped or shifted due to surface infrastructure constraints. These are mainly parts of the village Sint Isidorushoeve and the northern outskirts of Haaksbergen. In addition, some areas in the eastern part of the field, close to the planned leaching station, were excluded.

In the current planning phase of the project, the entire field layout comprises a number of 36 caverns with a potential for expansion to 64 caverns. Each cavern has a maximum allowable diameter of 125 m, while the cavern height varies according to the different cavern types (Chapter 6). Due to the assumed lenticular geometry of the Haaksbergen salt pillow, the largest caverns (type 1) are situated in the centre of the field and the smallest caverns (type 4) are arranged at marginal positions.

Designed as such, the potential 64 Haaksbergen caverns will provide brine at a constant rate of approx. 1,050 m³/h for a period of approx. 60 years. This figure corresponds to an annual production of 2.84 million tons of salt per year and a total salt extraction of 174 million tons. To guarantee the annular salt production of 2.6 million tons of salt, a safety margin of 9 % is considered in the calculation to allow for e.g. additional shutdowns or a decreased rate.

8.1 Hengelo - Haaksbergen Transition

The field development model assumes that only two pipelines are installed from the Haaksbergen brine field to the Hengelo plant. One pipeline is used for leaching water and the other is used alternatively for the transport of the weak brine to the Hengelo brine field or for fully saturated brine to the salt plant.

To realize the transition from the Hengelo brine field to the new Haaksbergen field, the basic production concept includes two steps prior to independent, fully saturated brine production from Haaksbergen (Figure 3, Enclosures 13 and 14). The leaching operation in the Haaksbergen field starts with four caverns (no. 01, 02, 03, 04) in parallel. These caverns produce weak brine during the sump leaching phase for two years after start-up. This weak brine (a total of 600 m³/h) is delivered to the Hengelo field and injected into the production caverns for further saturation. After two years of leaching operation at Haaksbergen, the first four caverns (no. 01 to 04) are capable of producing fully saturated brine at a total rate of 600 m^3/h.

During the second step from year 3 to year 4, four new cavern wells (no. 05, 06, 07, 08) are drilled and leaching operation may start with all caverns at the same time, or at intervals of approx. 1 ½ months. Cavern no. 08 will be a spare cavern. The weak brine from the sump leaching process of these new caverns (no. 05, 06, 07, 08) is further saturated by passing it through the first four caverns (no. 01, 02, 03, 04) in the Haaksbergen field, which are then already in the main leaching phase. This is different to the approach in [1], where only the small-sized type 1 caverns are used for re-saturation. The envisaged drilling sequence requires also other cavern types to be selected for re-saturation. However, the remaining brine demand of the salt plant during the 3rd and 4th year has still to be delivered from the Hengelo field.

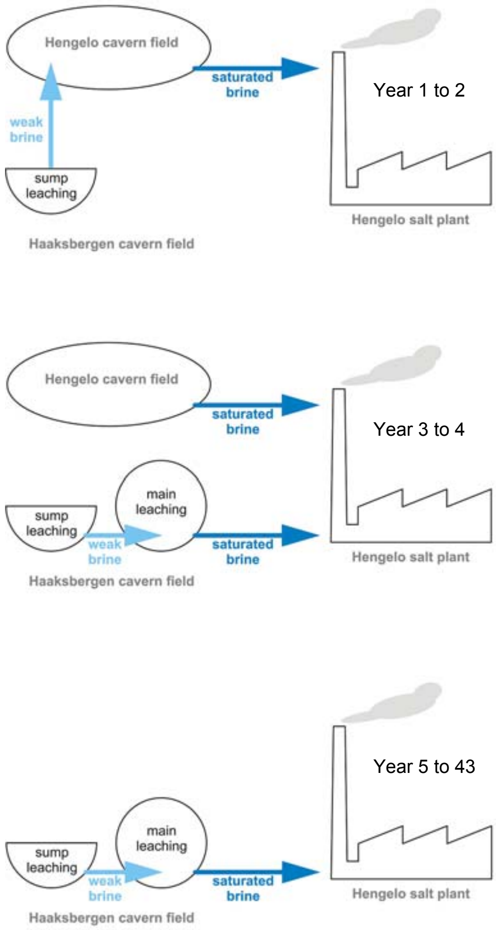


Figure 3: Operation scheme for the transition from Hengelo to the Haaksbergen field

8.2 Independent Haaksbergen Production

According to the operational scheme developed herein, the transition of the brine production from the Hengelo field to the new Haaksbergen cavern field takes approx. 4 years. From year 5 onwards, the first eight caverns (no. 01 to 08) are capable of delivering fully saturated brine with the required total rate of 1,050 m³/h (Enclosure 13 and 14). Cavern no. 08 will be used as spare (in times of e.g. work-overs, maintenance) and will be in continuous operation (main leaching phase) at the end of year 9.

From year 6 onwards it will be necessary to develop new caverns to compensate for fully exploited caverns, which are to be prepared for abandonment. The proposed operation scheme considers cavern no. 01 as a “saturator cavern”, taking the brine with a rate of 150 m³/h from the sump leaching phase of at least 6 other caverns during years 3 to 13.

As indicated in Enclosure 13, the sump leaching phase of cavern no. 08 is finished in year 5 and will be used as spare. The lag time between the sump and the main leaching phase of cavern no. 08 is due to the full deliverability of saturated brine of the first seven caverns in the main leaching phase. Nevertheless, it is proposed to have at least one cavern available as back-up to compensate for e.g. maintenance, work-overs or short-term increased demand of brine. This also means that, when the leaching operation of cavern no. 02 will be terminated in year 9 an additional cavern (in this case cavern no. 09) has to be available in main leaching status.

In the further course of field development a sufficient number of caverns has to be prepared at any time during saturated brine production from Haaksbergen to ensure an overall flow rate of 1,050 m³/h and to completely compensate for exploited caverns. It is recommended to have a minimum of 8 caverns available for production of saturated brine. Depending on the operational philosophy (one or two back-up caverns) and the fluctuation in brine demand, the total number of caverns capable of full production may be increased to 9 or 10. Enclosure 12 demonstrates that an average of 300 m^3/h of weak brine is produced from caverns in the sump leaching phase. These caverns have to be operated in parallel to the above mentioned 8 (or 9 to 10, respectively) caverns which are in full production.

The criteria for the selection of caverns for re-saturation of weak brine from the sump development of new caverns are:

- minimization of the number of “saturator caverns” due to infrastructural constraints (e. g. reduction of the number of additional pipelines from sump leaching caverns to “saturator caverns”),
- prevention of simultaneous termination of several caverns to avoid a bottleneck with regard to the disposal of weak brine,
- prevention of long time gaps between sump and main leaching phase, thus reducing subsidence effects, and
- selection of preferably small caverns (cavern types 3 and 4) for re-saturation to minimize the subsidence; additionally constrained by the pre-defined drilling sequence.

With the 24 caverns of the 1st phase and the 2nd phase approx. 65 million tons of salt (at a constant flow rate of 1,050 m³/h) will be produced within a period of approx. 23 years. Together with the hypothetical 3rd phase (additional 12 caverns), approx. 102 million tons of salt with a constant rate of 1,050 m³/h will be produced within approx. 36 years. Furthermore, the field layout allows for additional 28 caverns. With these 64 caverns approx. 174 million tons of salt will be produced within a period of approx. 60 years.

Table 10 provides an overview of the cavern volumes and the salt produced in relation to the anticipated height of the caverns.

Table 10: Total salt production and final volumes for each cavern

	cavern no.	cavern height [m]	cavern volume [m³]	produced salt [t]
1st phase	1	124	838,000	1,605,000
	2	205	1,535,000	2,940,000
	3	248	1,904,000	3,647,000
	4	295	2,305,000	4,415,000
	5	276	2,139,000	4,097,000
	6	275	2,135,000	4,089,000
	7	261	2,009,000	3,848,000
	8	309	2,422,000	4,639,000
	9	306	2,396,000	4,589,000
	10	293	2,281,000	4,369,000
	11	300	2,347,000	4,495,000
	12	301	2,351,000	4,503,000
2nd phase	13	141	987.000	1,890,000
	14	213	1,596,000	3,057,000
	15	242	1,848,000	3,539,000
	16	231	1,753,000	3,357,000
	17	207	1,548,000	2,965,000
	18	128	874,000	1,674,000
	19	232	1,760,000	3,371,000
	20	121	809,000	1,549,000
	21	121	811,000	1,553,000
	22	182	1,331,000	2,549,000
	23	185	1,362,000	2,609,000
	24	282	2,188,000	4,191,000
3rd phase	25	269	2,081,000	3,986,000
	26	259	1,994,000	3,819,000
	27	232	1,763,000	3,377,000
	28	237	1,806,000	3,459,000
	29	205	1,536,000	2,942,000
	30	220	1,663,000	3,185,000
	31	182	1,338,000	2,563,000
	32	190	1,406,000	2,693,000
	33	164	1,184,000	2,268,000
	34	171	1,238,000	2,371,000
	35	143	1,004,000	1,923,000
	36	154	1,091,000	2,090,000
potential remaining caverns	37 - 64	197*	1,463,000*	2,802,000*

* average values for caverns 37 to 64

Following the operational scheme for 36 caverns (Enclosure 14) after the start-up period of more than 10 years every year approx. 1 new cavern needs to be drilled and developed. Also the average salt production from all 36 initial caverns of approx. 2.84 million tons (at a constant flow rate of 1,050 m^3/h) in comparison to the yearly production of approx. 2.6 million tons confirms the average number of 1 new cavern per year.

References

[1] DEEP. Underground Engineering GmbH (2010): Development of a New Brine Cavern Field for the Hengelo salt Plant: Basic Leaching concepts and Development of the Haaksbergen Site, report, 22 pp, enclosures.

[2] MWH B.V. (2008): Study of the Salt Mining Possibilities in the Haaksbergen Area, the Netherlands, report, 82 pp, enclosures.

[3] MWH B.V. (2011): Seismic survey and geological model update of the Haaksbergen area of interest, draft report – version 1.0, 98 pp, enclosures

[4] Institut für Gebirgsmechanik (2009): Rock Mechanical Investigations and Dimensioning for the new AkzoNobel NaCl-Brine Production Field Haaksbergen, report, 18 pp., enclosures.

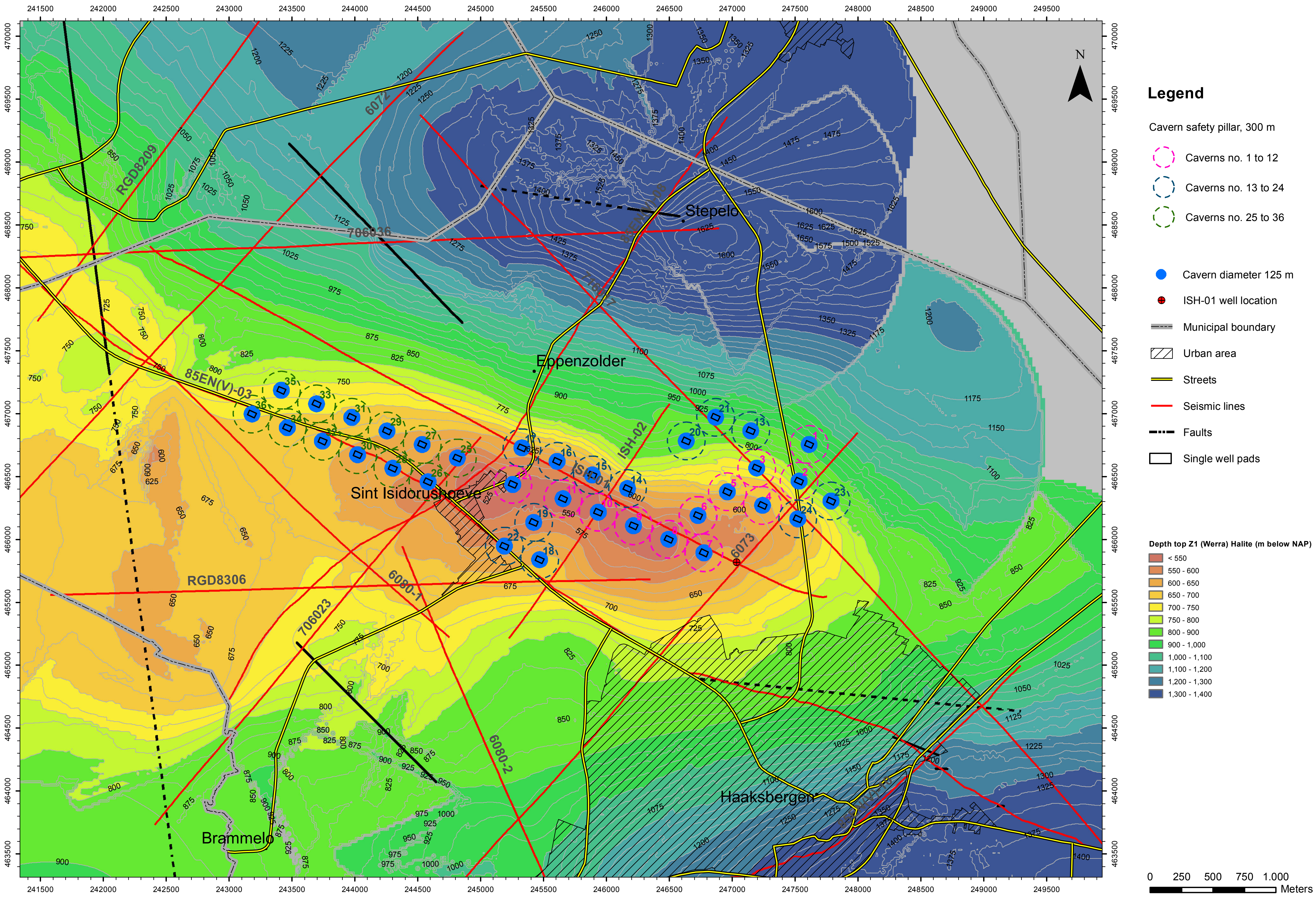
[5] KBB UT (2010): Development of a new Brine Cavern Field for the Hengelo Salt Plant: Basic subsidence Prediction, report, 15 pp., enclosures.

[6] DEEP. Underground Engineering GmbH (2011): Development of a new Brine Cavern Field for the Hengelo Salt Plant: Geological End-of-well Report for Exploration Well Isiodorushoeve-01 (ISH-01), report, 14 pp., enclosures.

[7] DEEP. Underground Engineering GmbH (2011): Leaching Test Report for Well ISH-01, report, 12 pp., enclosures.

[8] KBB UT (2011): Development of a new Brine Cavern Field for the Hengelo Salt Plant: Extension of the Phase I Subsidence Prediction Model, report, 21 pp., enclosures.

List of Enclosures



Enclosure 1: Depth top Zechstein Z1 Halite (m) [3] with planned brine production field lay-out (23-02-2012)

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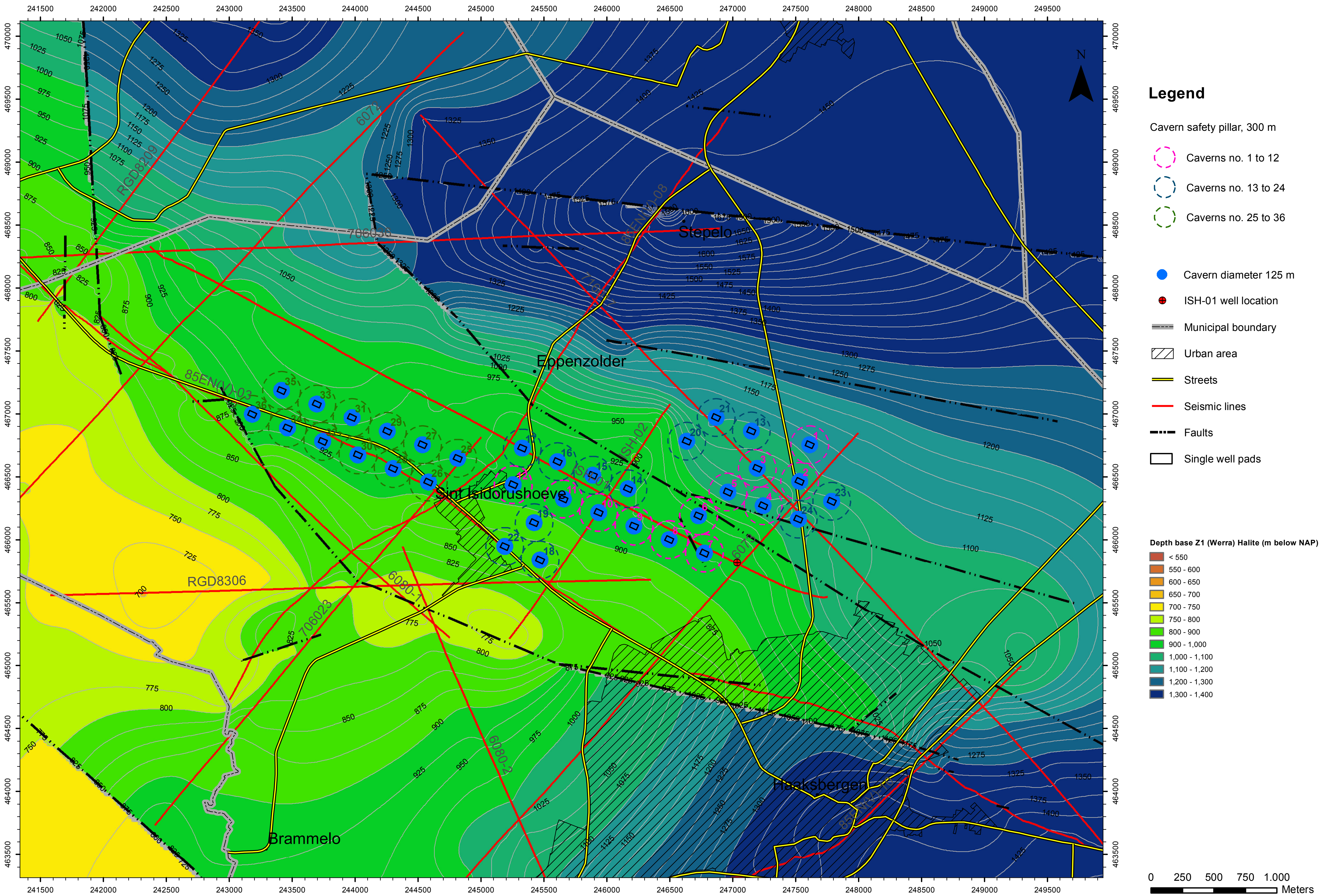

Enclosure 2: Depth base Zechstein Z1 Halite (m) [3] with planned brine production field lay-out (23-02-2012)

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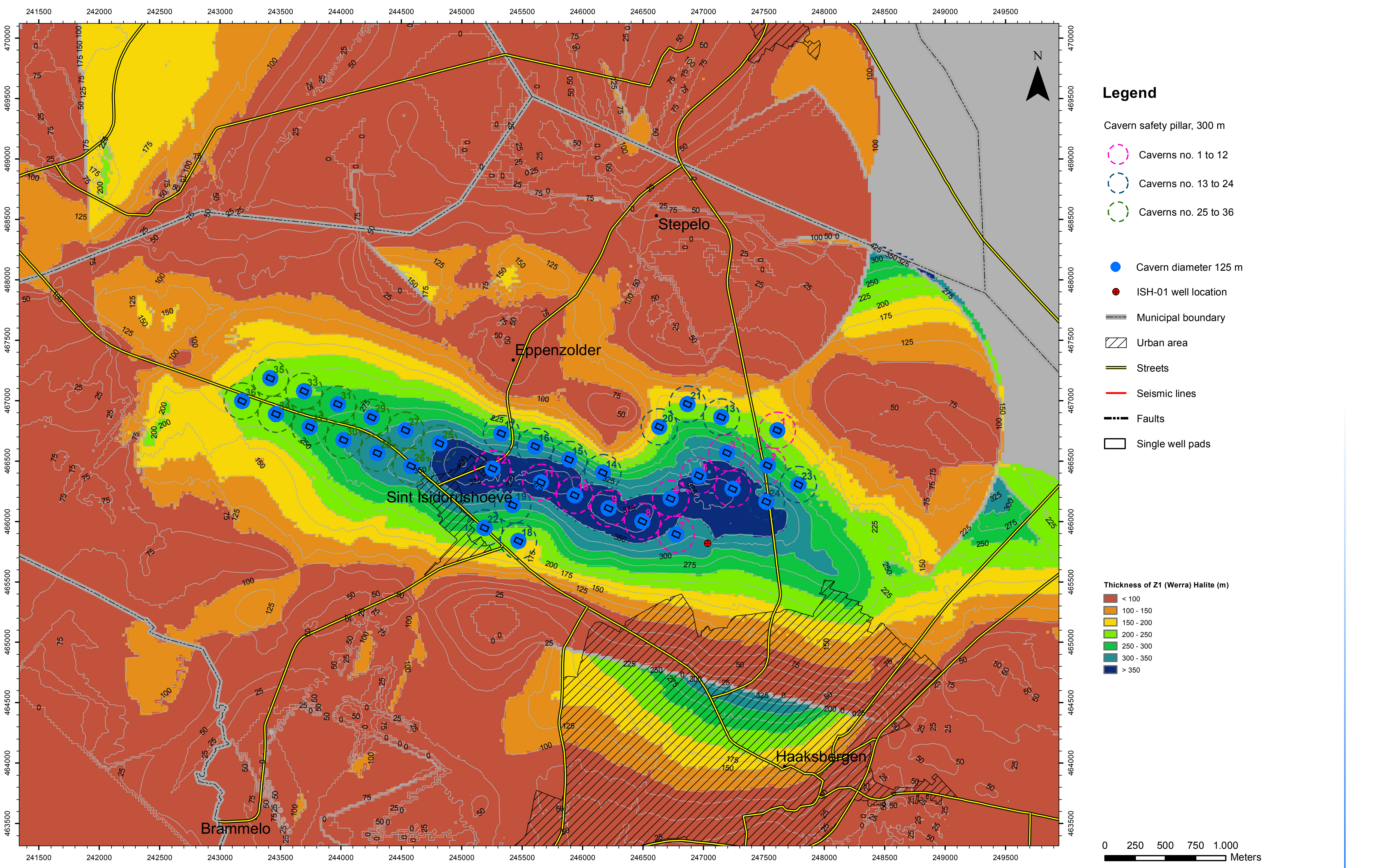

Enclosure 3: Thickness Zechstein Z1 Halite (m) [3] with planned brine production field lay-out (23-02-2012)

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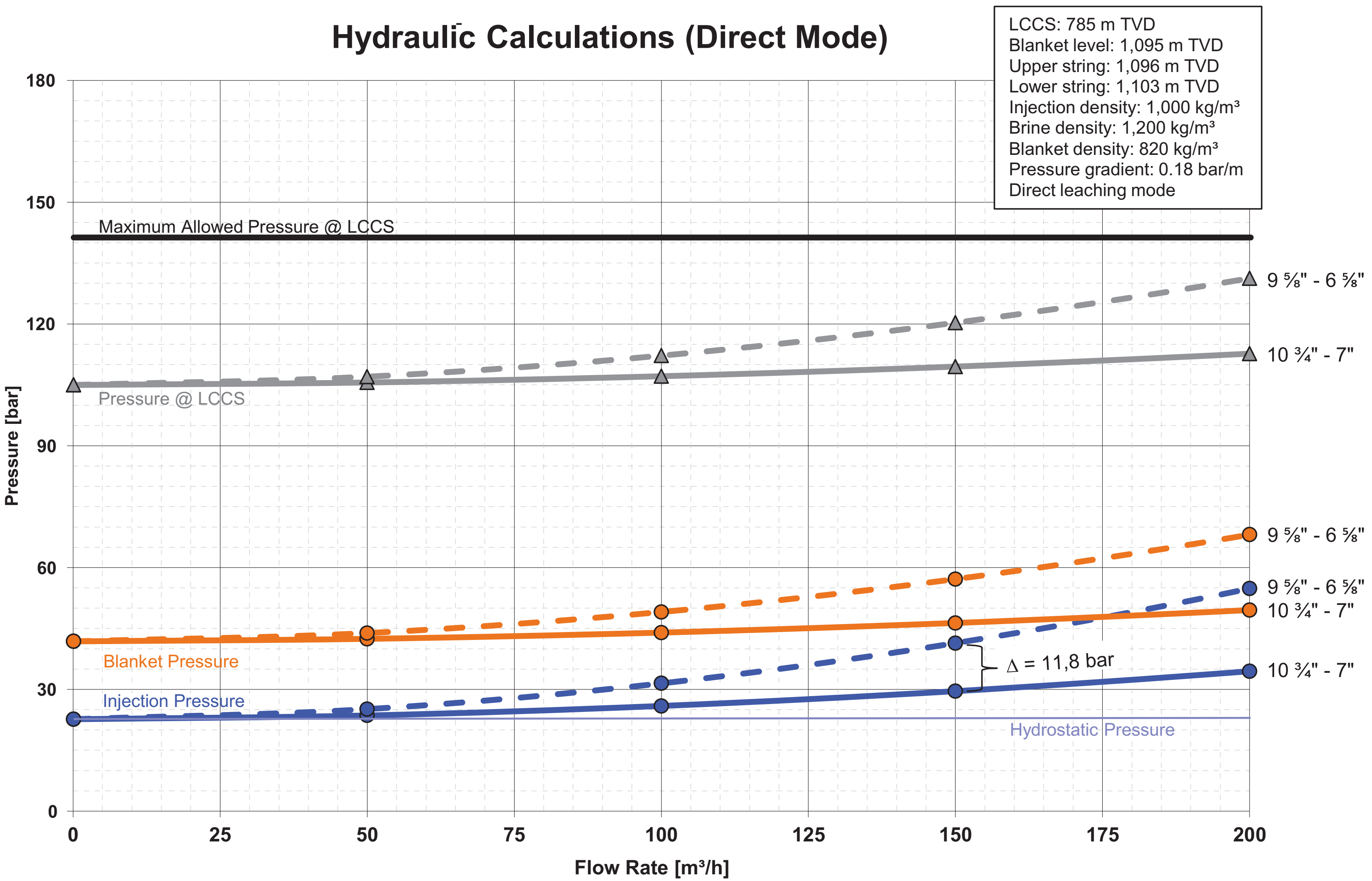
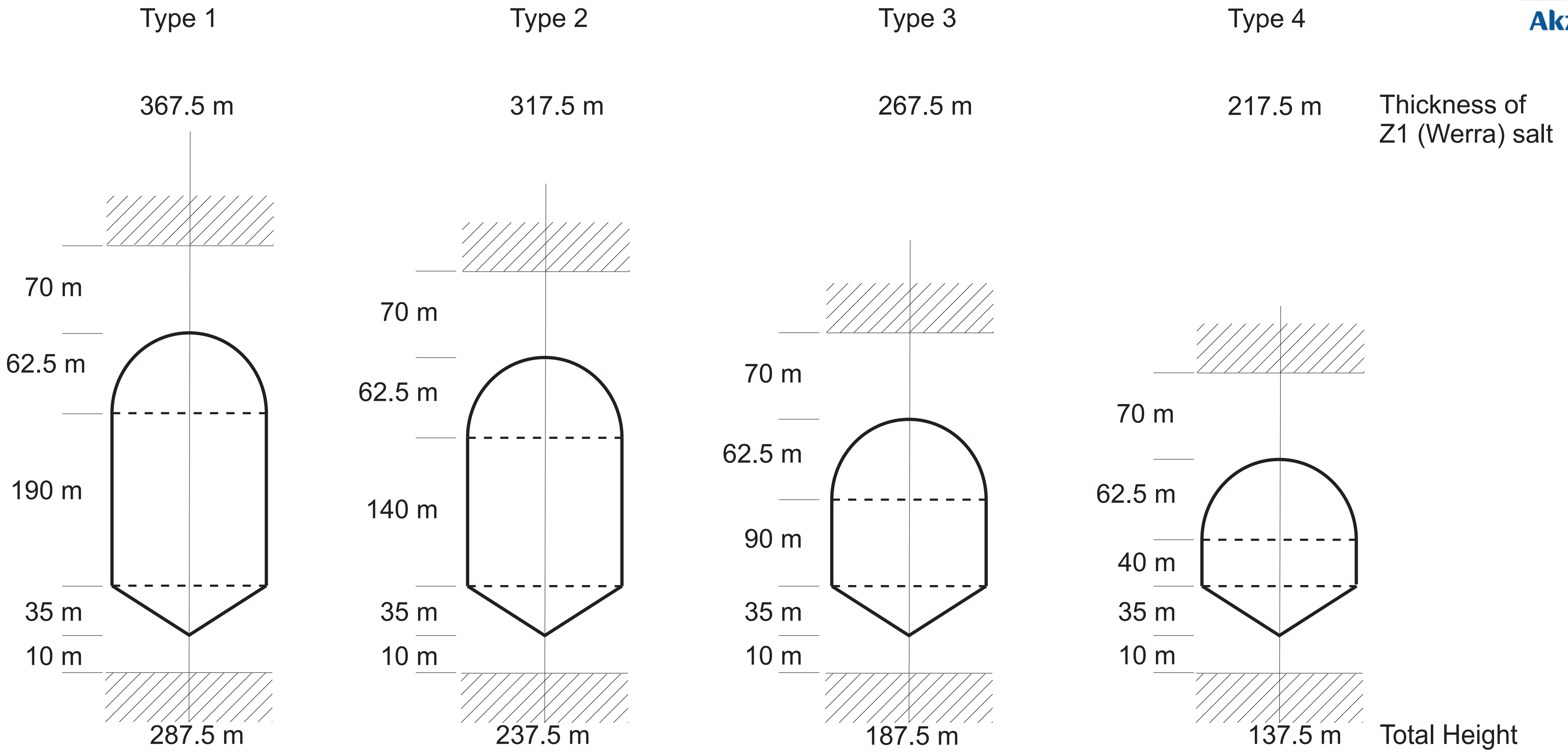
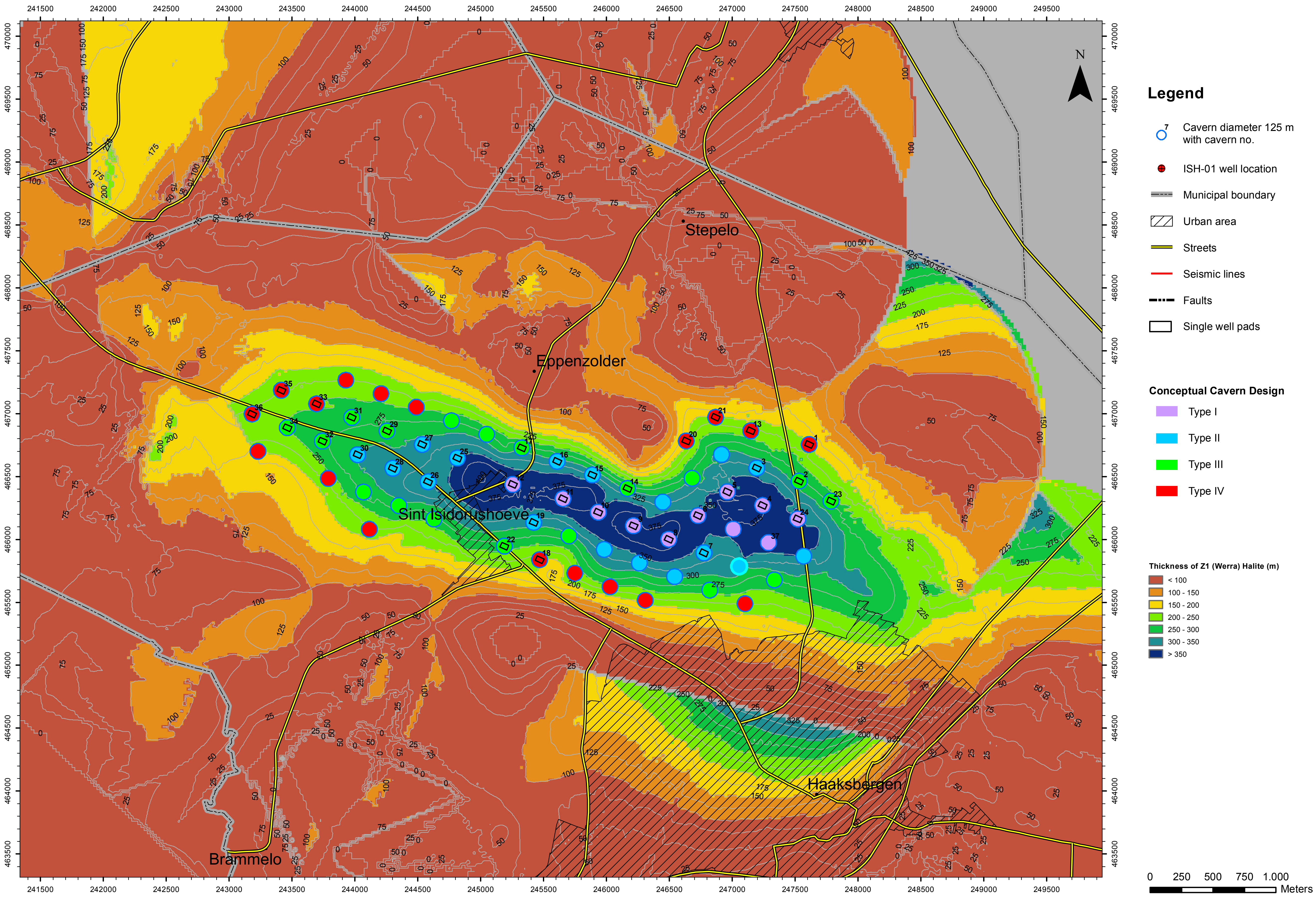


Enclosure 4: Hydraulic calculation for sump leaching phase (direct mode) for 10 $^3/_4$" x 7" and 9 $^5/_8$" x 6 $^5/_8$" leaching combination



Enclosure 5: Dimensions of type 1 to type 4 caverns



Enclosure 6: Thickness Zechstein Z1 Halite (m) [3] with potential brine production field lay-out and location of cavern types 1 to 4 (23-02-2012)

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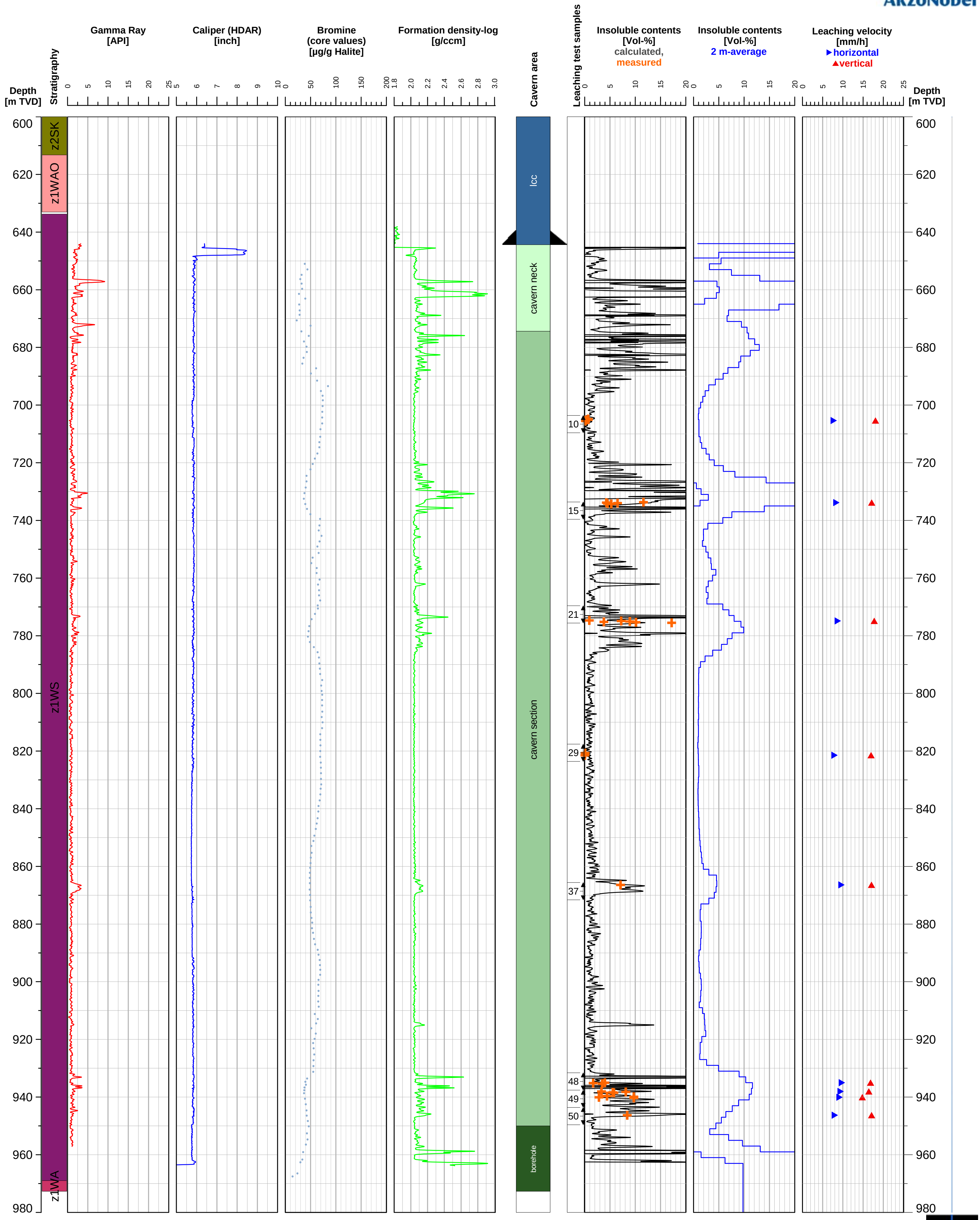
Well ISH-01



Enclosure 7: Leaching test data with stratigraphy, bromine and log data

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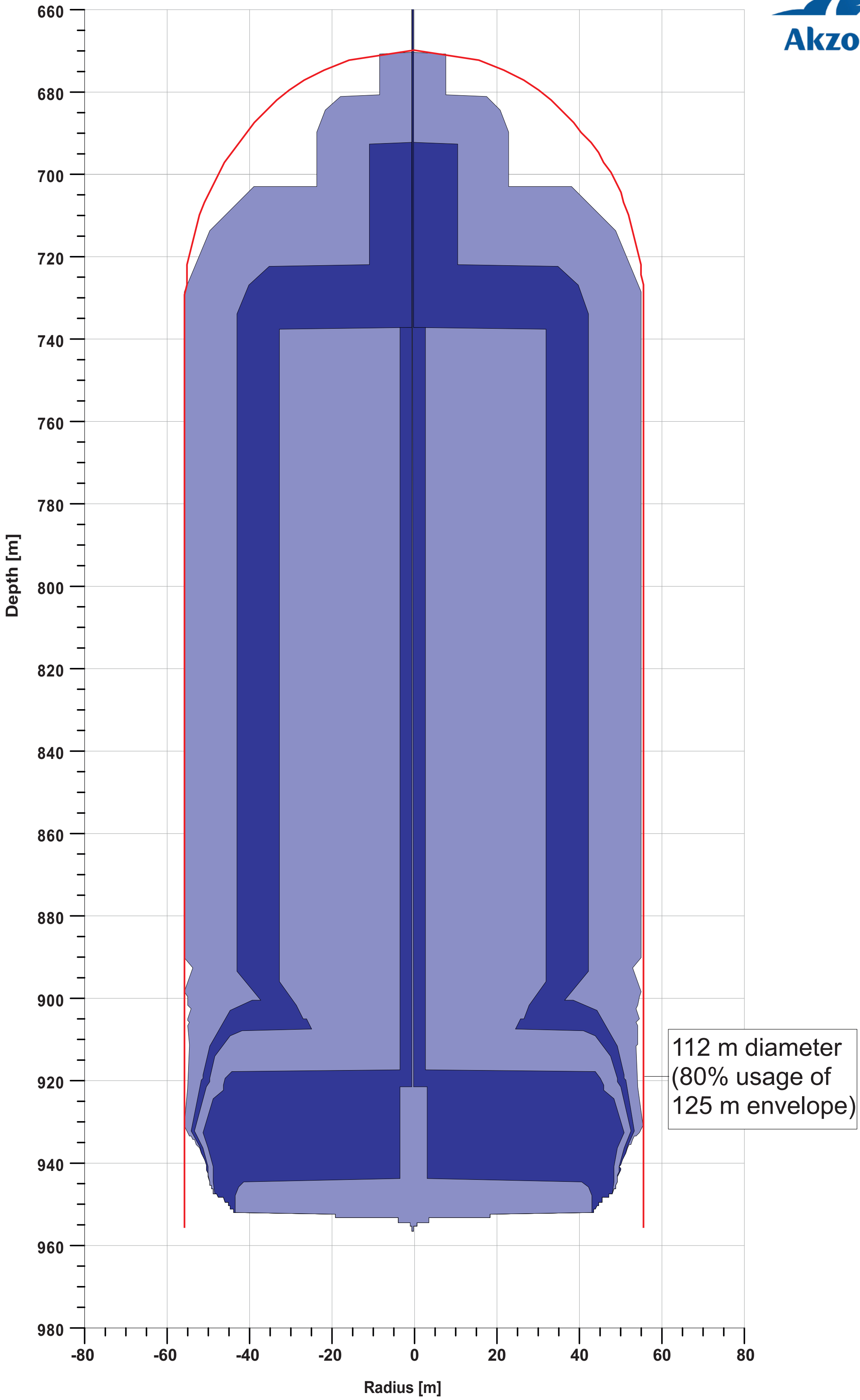

Enclosure 8a: Type 1, cavern shape development, 287.5 m height of cavern

AkzoNobel

Leaching concept type 1 cavern

Settings						Leaching			Results				
Start [d]	Activities	Duration [d]	Inner string [m]	Outer string [m]	Blanket depth [m]	Duration [d]	Mode	Injection rate [m³/h]	Duration total [d]	NaCl average [kg/m³]	Sump level [m]	Volume [m³]	Total mined salt [t]
1			956	949	948	169	bottom	150	169	62	953	18,000	37,000
169	Blanket				921	62	bottom	150	231	233	953	46,000	88,000
231	W/O, Sonar	30	951	934		291	top	150	552	287	948	184,000	378,000
552	Blanket				736	82	top	150	634	283	948	229,000	458,000
634	W/O, Sonar	30	945	898		1,080	top	150	1,744	314	944	844,000	1,632,000
1,744	W/O, Blanket	30	940	898	691	1,440	top	150	3,214	314	939	1,665,000	3,198,000
3,214	W/O, Blanket	30	935	898	669	1,020	top	150	4,264	313	935	2,242,000	4,304,000

Enclosure 8b: Type 1, leaching concept with freshwater injection (tabular)

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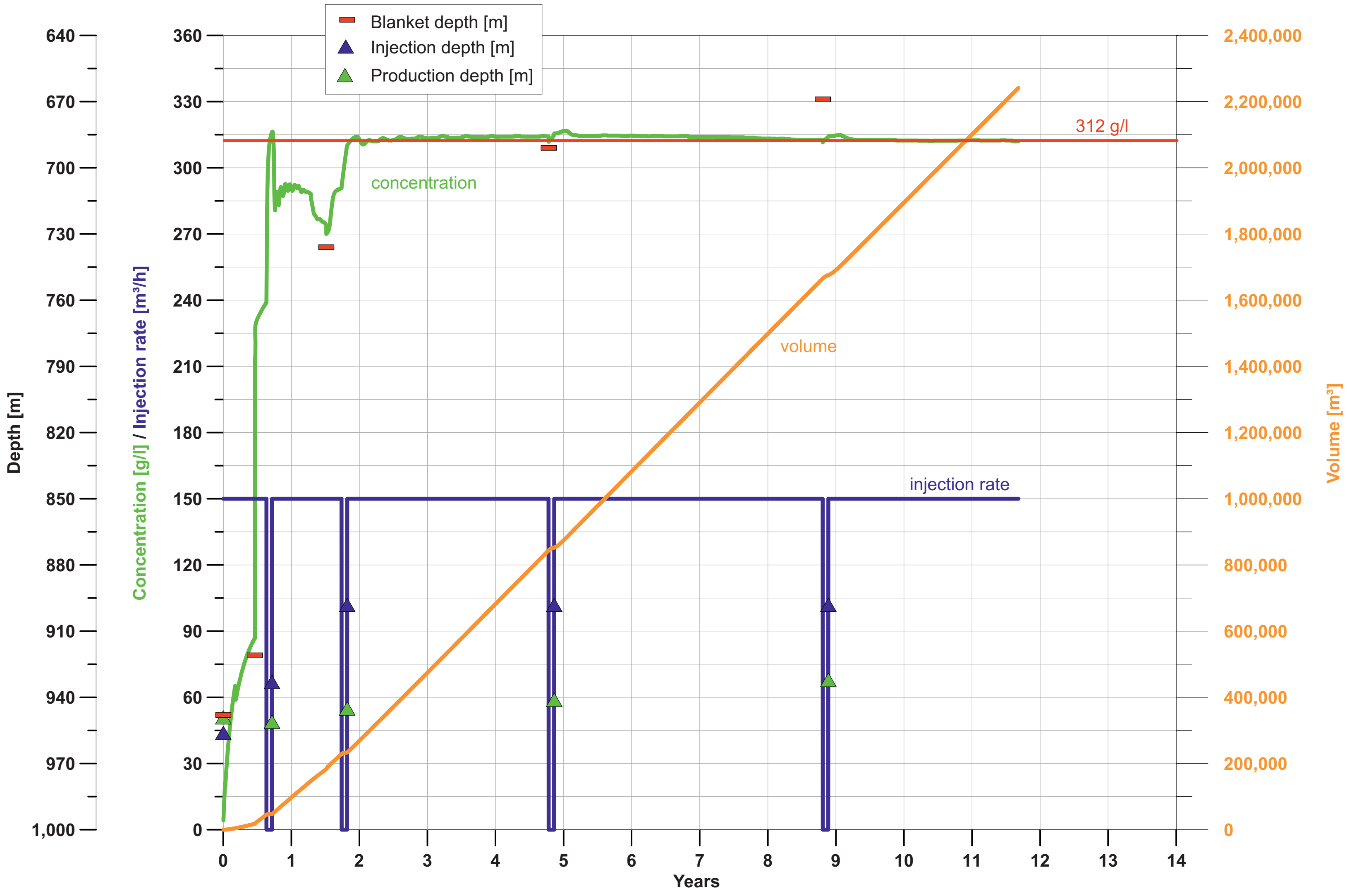
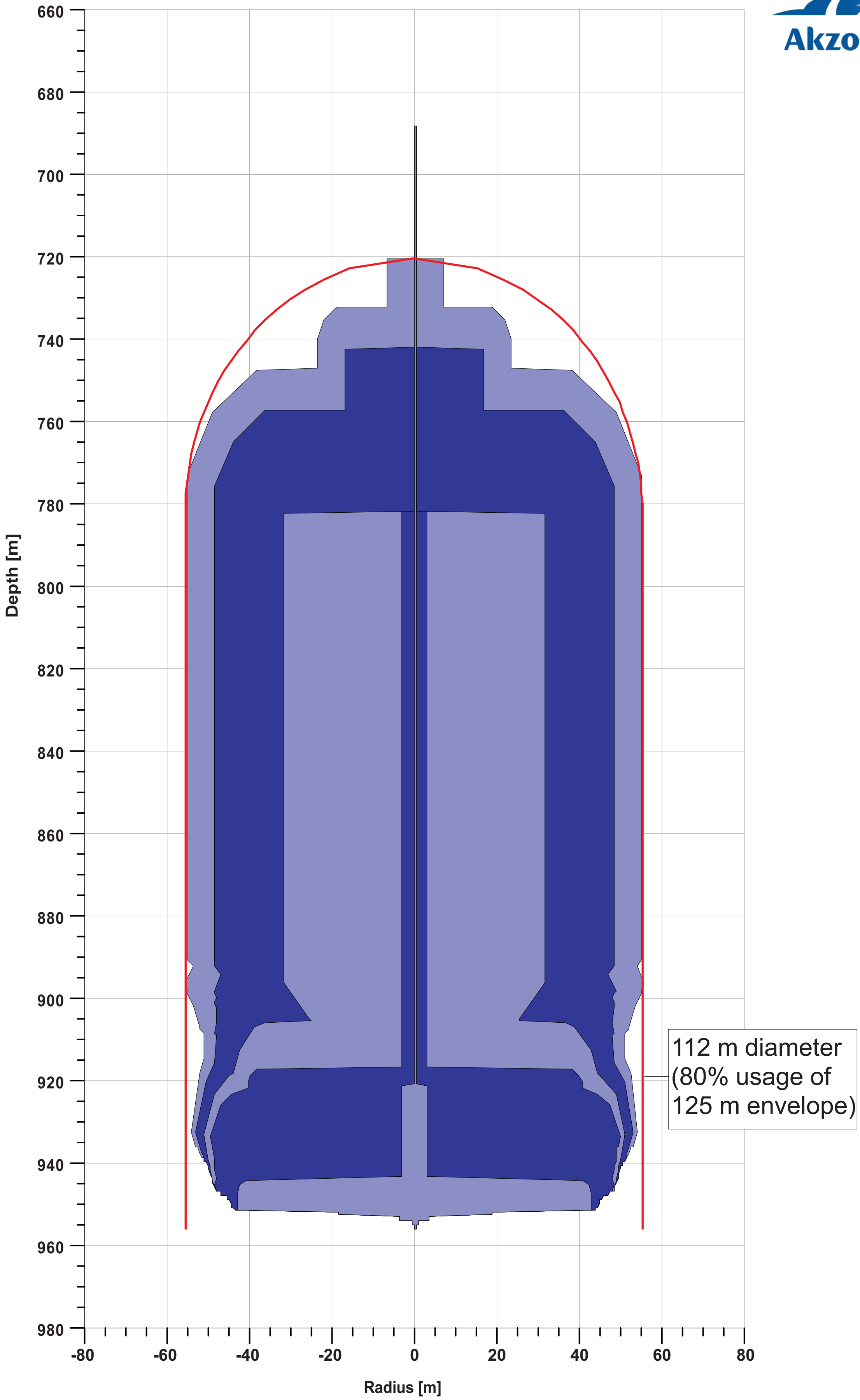
Underground Engineering



Enclosure 8c: Type 1, leaching concept with freshwater injection (graphical)

AkzoNobel



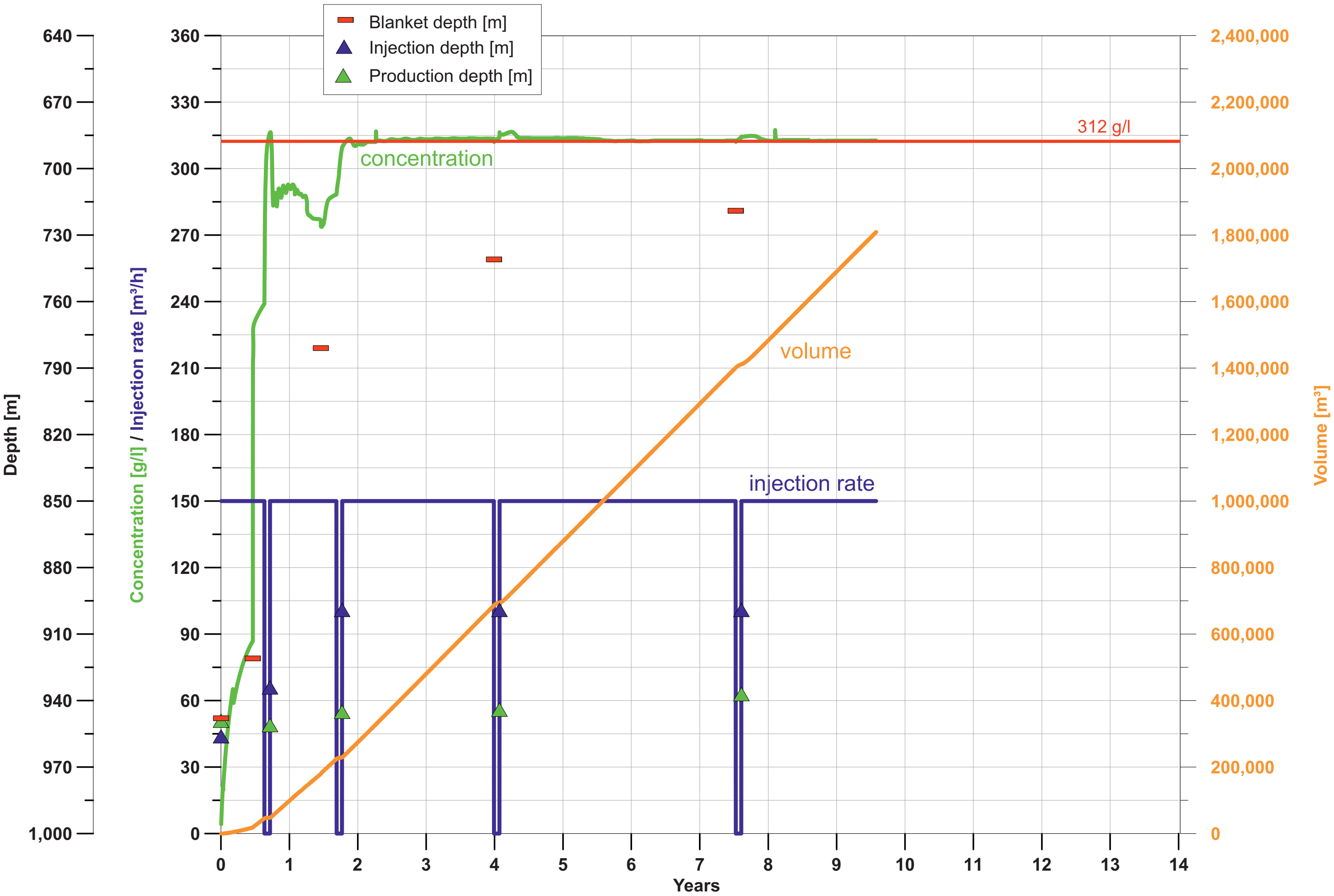
Enclosure 9a: Type 2, cavern shape development, 237.5 m height of cavern

DEEP. Underground Engineering

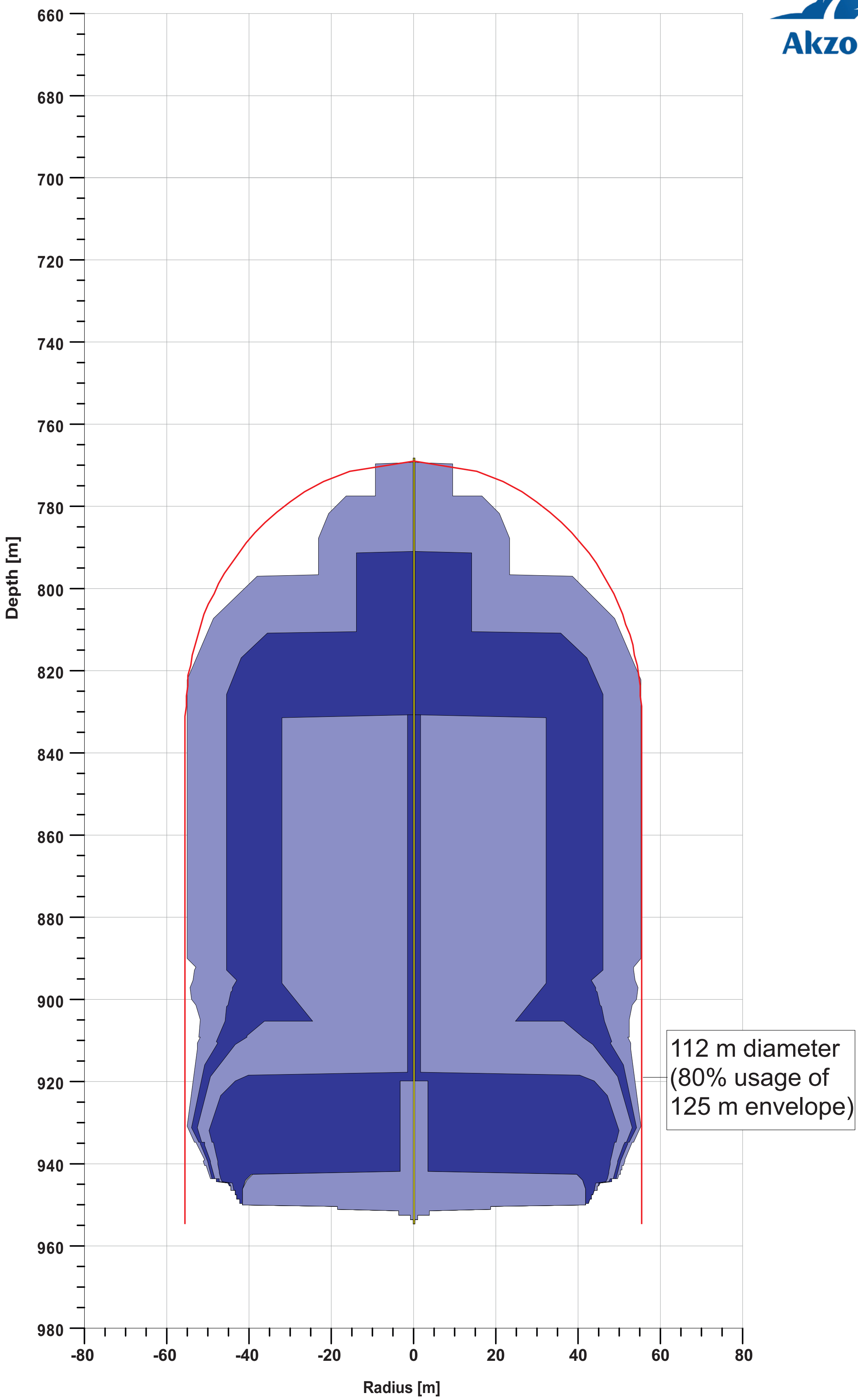
Leaching concept type 2 cavern

Settings						Leaching			Results				
Start [d]	Activities	Duration [d]	Inner string [m]	Outer string [m]	Blanket depth [m]	Duration [d]	Mode	Injection rate [m³/h]	Duration total [d]	NaCl average [kg/m³]	Sump level [m]	Volume [m³]	Total mined salt [t]
1			956	949	948	169	bottom	150	169	62	953	18,000	37,000
169	Blanket				921	62	bottom	150	231	233	953	46,000	88,000
231	W/O, Sonar	30	951	934		271	top	150	532	287	950	179,000	358,000
532	Blanket				781	84	top	150	616	283	949	224,000	440,000
616	W/O, Sonar	30	945	899		810	top	150	1,456	313	947	686,000	1,318,000
1,456	W/O, Blanket	30	942	899	741	1,260	top	150	2,746	313	942	1,401,000	2,687,000
2,746	W/O, Blanket	30	939	899	719	720	top	150	3,496	313	939	1,809,000	3,467,000

Enclosure 9b: Type 2, leaching concept with freshwater injection (tabular)



Enclosure 9c: Type 2, leaching concept with freshwater injection (graphical)



Enclosure 10a: Type 3, cavern shape development, 187.5 m height of cavern

Leaching concept type 3 cavern

Settings						Leaching			Results				
Start [d]	Activities	Duration [d]	Inner string [m]	Outer string [m]	Blanket depth [m]	Duration [d]	Mode	Injection rate [m³/h]	Duration total [d]	NaCl average [kg/m³]	Sump level [m]	Volume [m³]	Total mined salt [t]
1			956	949	948	162	bottom	150	162	61	953	17,000	35,000
162	Blanket				921	64	bottom	150	226	229	953	45,000	86,000
226	W/O, Sonar	30	950	934		304	top	150	560	281	950	193,000	384,000
560	Blanket				831	93	top	150	653	280	949	242,000	473,000
653	W/O, Sonar	30	947	900		540	top	150	1,223	313	948	550,000	1,058,000
1,223	Blanket				791	720	top	150	1,943	314	946	963,000	1,842,000
1,943	W/O, Blanket	30	943	900	769	720	top	150	2,693	313	943	1,371,000	2,623,000

Enclosure 10b: Type 3, leaching concept with freshwater injection (tabular)

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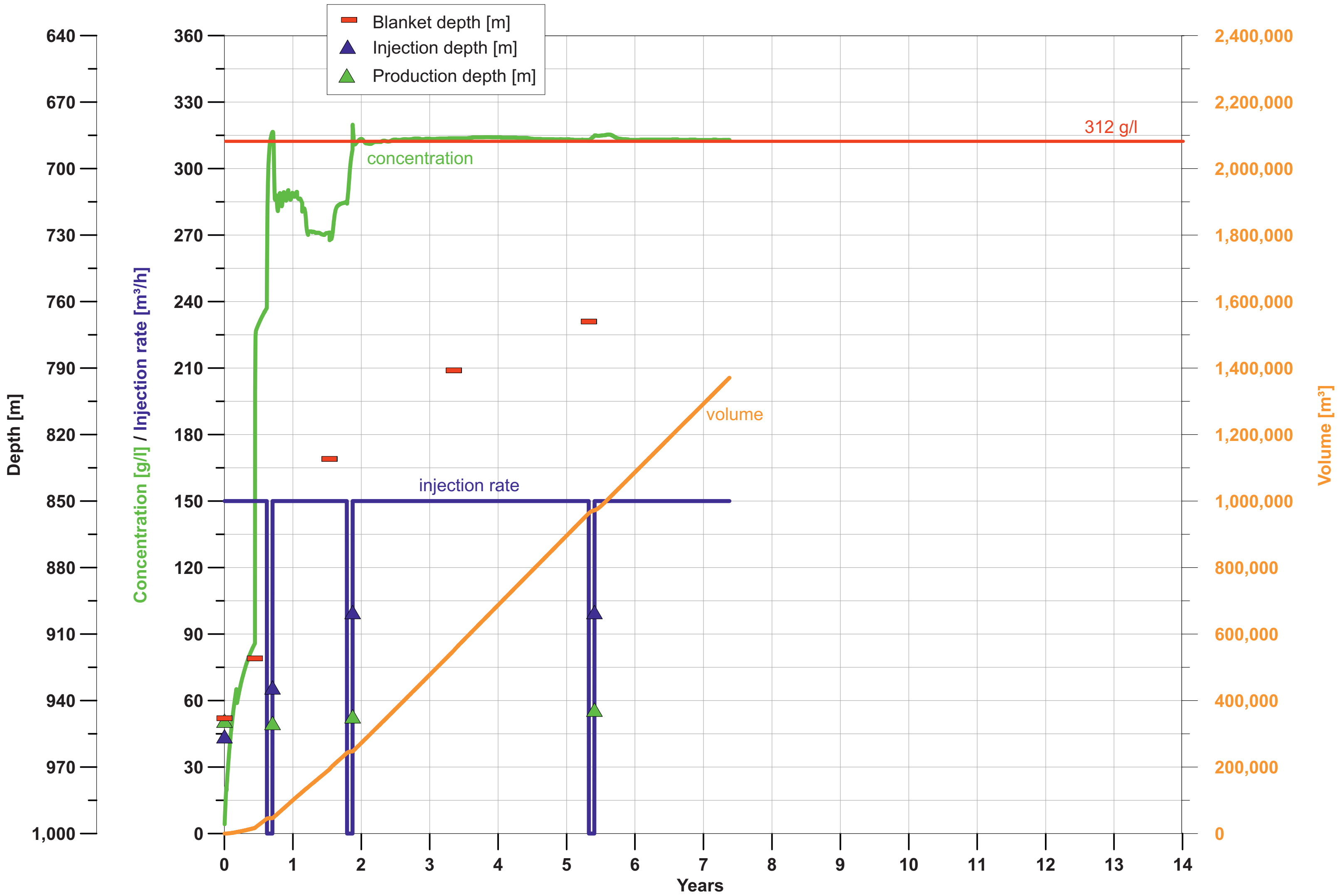
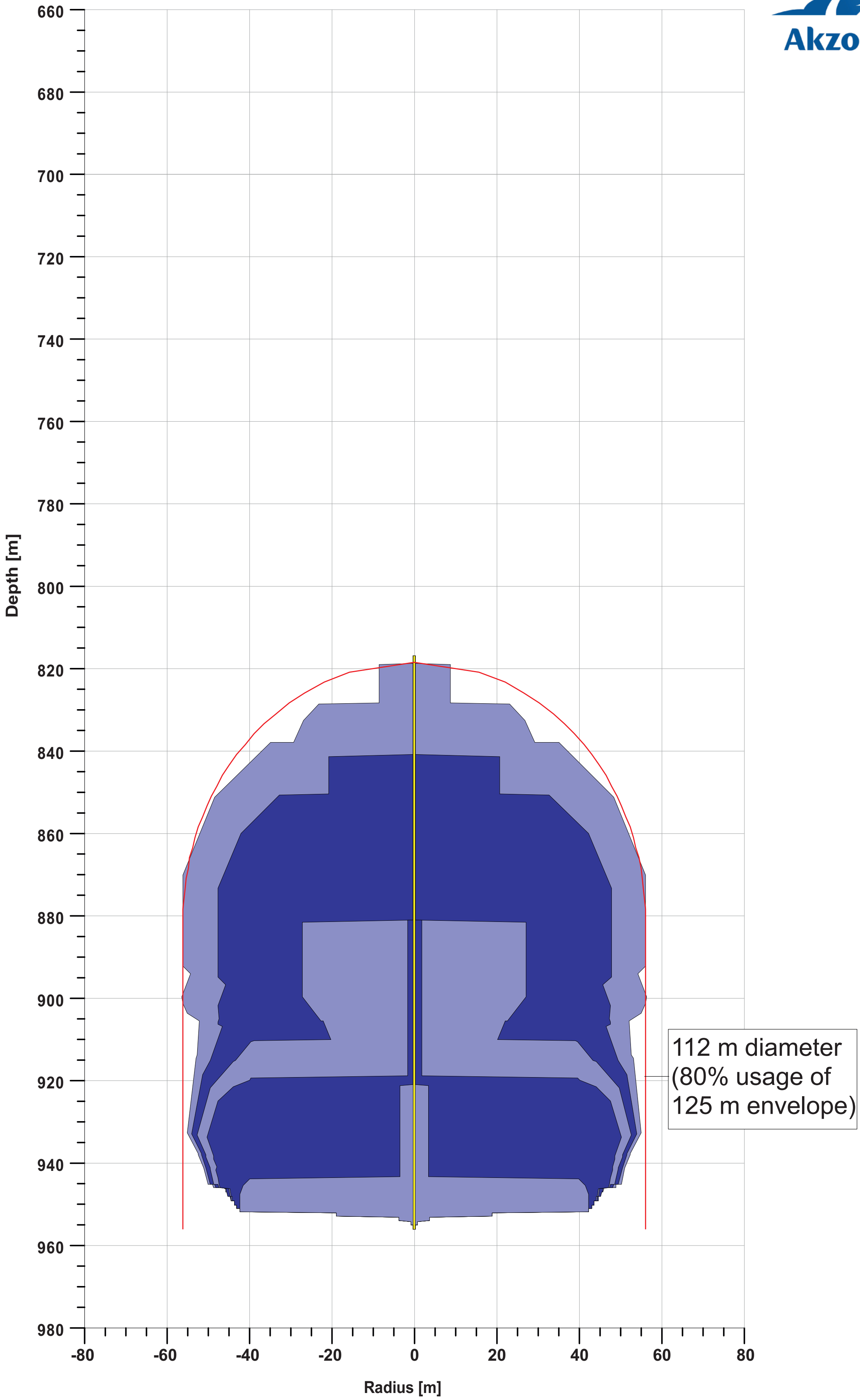


Enclosure 10c: Type 3, leaching concept with freshwater injection (graphical)



Enclosure 11a: Type 4, cavern shape development, 137.5 m height of cavern

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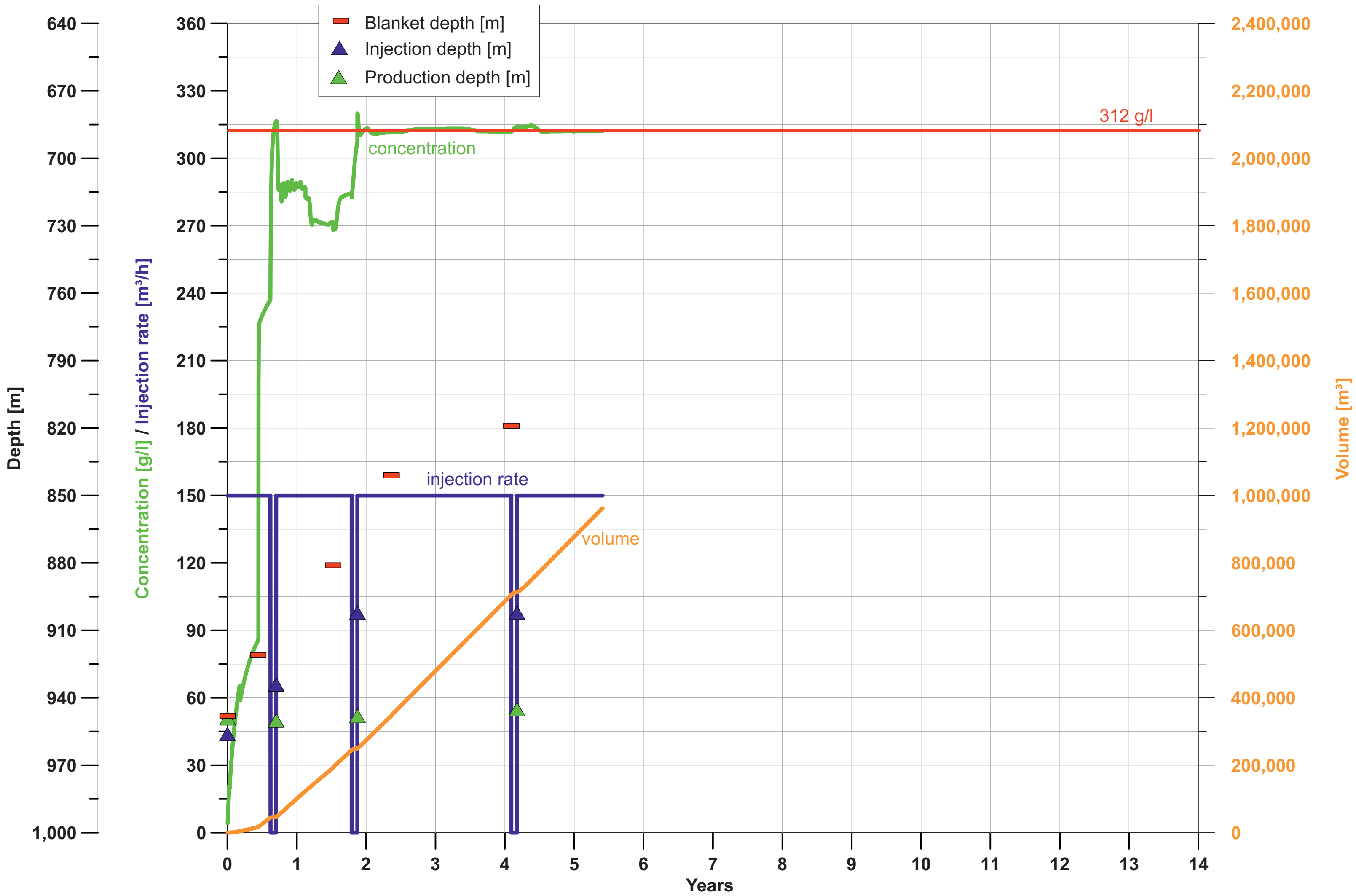
Underground Engineering

Leaching concept type 4 cavern (fresh water injection)

Settings						Leaching			Results				
Start [d]	Activities	Duration [d]	Inner string [m]	Outer string [m]	Blanket depth [m]	Duration [d]	Mode	Injection rate [m³/h]	Duration total [d]	NaCl average [kg/m³]	Sump level [m]	Volume [m³]	Total mined salt [t]
1			956	949	948	162	bottom	150	162	61	953	17,000	35,000
162	Blanket				921	64	bottom	150	226	229	953	45,000	86,000
226	W/O, Sonar	30	950	934		300	top	150	556	281	950	193,000	380,000
556	Blanket				881	97	top	150	653	280	950	245,000	474,000
653	W/O, Sonar	30	948	902		180	top	150	863	312	949	348,000	668,000
863	Blanket				841	630	top	150	1,493	313	948	705,000	1,351,000
1,493	W/O, Blanket	30	946	902	918	450	top	150	1,973	313	946	962,000	1,839,000

Enclosure 11b: Type 4, leaching concept with freshwater injection (tabular)

DEEP.
Underground Engineering



Enclosure 11c: Type 4, leaching concept with freshwater injection (graphical)

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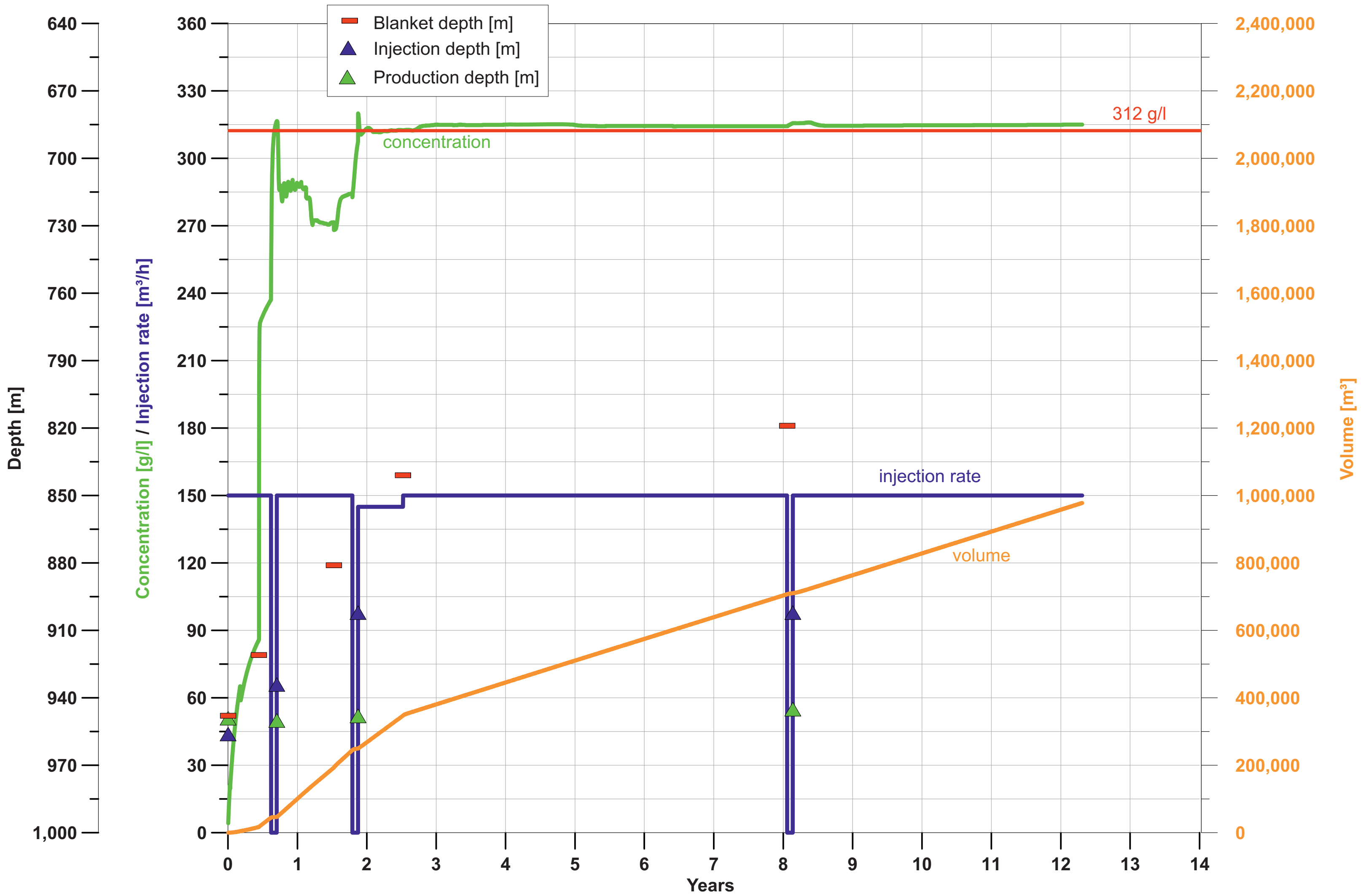
Leaching concept type 4 cavern (weak brine injection)

Settings						Leaching			Results				
Start [d]	Activities	Duration [d]	Inner string [m]	Outer string [m]	Blanket depth [m]	Duration [d]	Mode	Injection rate [m³/h]	Duration total [d]	NaCl average [kg/m³]	Sump level [m]	Volume [m³]	Total mined salt [t]
1			956	949	948	162	bottom	150	162	61	953	17,000	35,000
162	Blanket				921	64	bottom	150	226	229	953	45,000	86,000
226	W/O, Sonar	30	950	934		300	top	150	556	281	950	193,000	380,000
556	Blanket				881	97	top	150	653	280	950	245,000	474,000
653	W/O, Sonar	30	948	902		237	top	150	920	312	949	347,000	665,000
920	Blanket				841	2,020	top	150	2,940	315	948	707,000	1,339,000
2,940	W/O, Blanket	30	946	902	918	1,521	top	150	4,491	315	946	978,000	1,851,000

Enclosure 11d: Type 4, leaching concept with with weak brine (220 g/l) injection (tabular)



Enclosure 11e: Type 4, leaching concept with with weak brine (220 g/l) injection (graphical)

PN 5304
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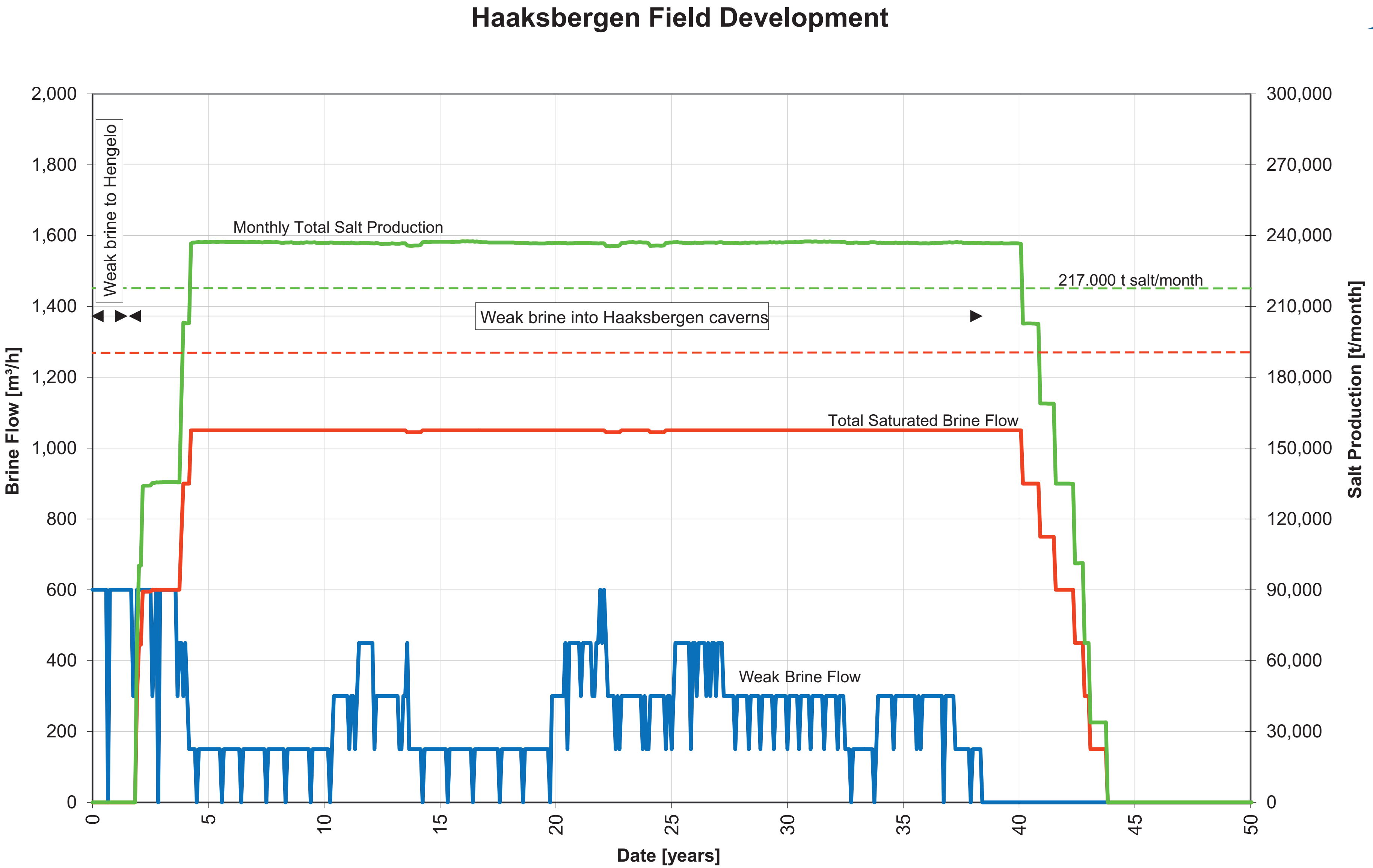
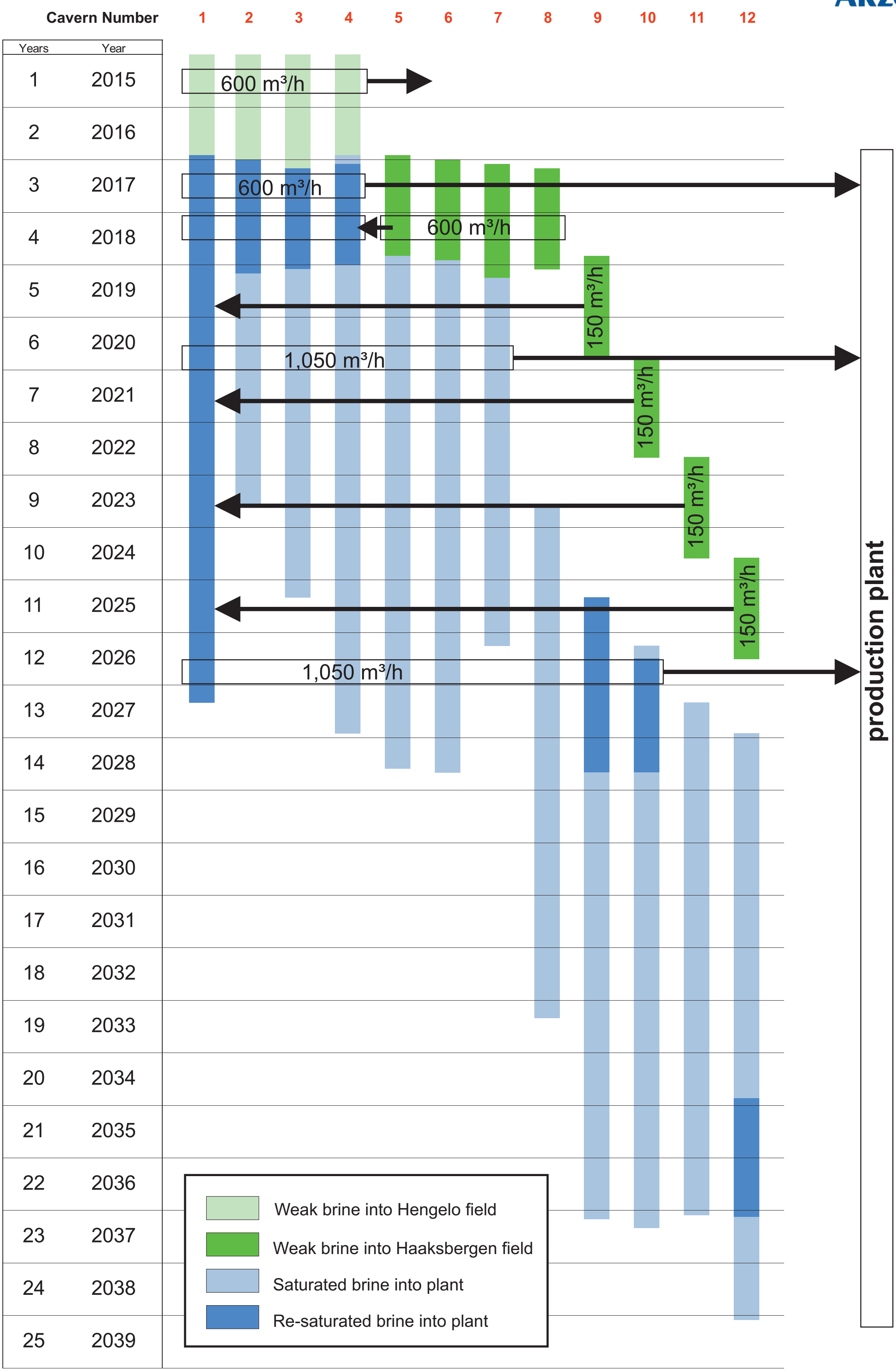


Enclosure 12: Saturated, weak brine brine flow and monthly salt production, cavern field Haaksbergen

PN 5304
120126_Haaksbergen_Update_Detailed_Planning.des/MP



Enclosure 13: Production outline during Hengelo - Haaksbergen transition until full production capacity of 1,050 m³/h

AkzoNobel

Enclosure 14: Haaksbergen field development

Enclosure 14: Haaksbergen field development

PN 5304
120126_Haaksbergen_Update_Detailed_Planning.des/MP

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