Update Subsidence Analysis & Forecast.final

Based on levelling survey Oct 2003

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Abstract

This document provides technical detail to complement the concept ‘Actualisatie Ontginningsplan Steenzout Concessie Barradeel’ and describes the relation between salt mining and subsidence. This technical document is consistent with FRISIA plans for the future use and abandonment of the BAS 1&2 caverns.

The observed levelling-determined subsidence of 1999 to 2003 is linked to the cavern convergence (salt flow toward the caverns) in these years. The convergence is the difference between salt dissolution volume (calculated from extraction figures) and the remaining open cavern volume, measured by echo-metric surveys, also from 1999 to 2003.

The echo measurements of 2003 confirm the general observation that the total cavern volume of BAS 1 and 2 does not materially change at a given extraction rate. The relation between the maximum subsidence and the convergence due to the BAS 1 and 2 caverns, based on the levelling survey of 2003 is approx. 10 cm per 1 million cubic metres of cavern convergence, although the ratio drops slightly over the years (from 1,10 in 1999 to 0,99 in 2003), suggesting the occurrence of rebound effects.

The subsidence after active leaching is very much dependent on the applied method of abandonment. In the concept ‘Actualisatie Ontginningsplan Steenzout Concessie Barradeel’, FRISIA plans to prepare BAS 1 and 2 after the active leaching phase for shutting in and later abandonment at (near-) lithostatic pressures. A test of several years is planned in BAS 2 in the post-leaching phase to evaluate the high pressure behaviour of a cavern in the ‘FRISIA’ conditions.

The 2002 DIANA modelling of cavern- and surface behaviour, indicates that if the caverns would be shut in at a high pressure directly after active leaching, the subsidence will reduce to a very low rate. An initial post leaching subsidence (na-ijl) effect is expected in the first 2 to 3 years after shutting in the caverns at a high pressure. The latest modelling runs- fitting production data - indicate as well that an uplift (rebound) effect can be expected that will fully compensate the initial ‘naijl’ effects to a – at this stage- not precisely known extent and rate. According to calculations of NITG-TNO this rebound could amount to more than 15 cm of uplift in the BAS 1-2 affected area in the coming decades.

Based on the observed data, FRISIA is convinced that rebound will occur in noticeable sense, since in FRISIA’s opinion no plausible alternative theories are available to explain the full amount of the dropping subsidence-convergence ratio. Quantification of the magnitude and speed of the rebound process can only be given after a period of high-pressure shut-in of at least one well.

If, contrary to FRISIA’s current plans, the remaining cavern volume would be bled down, a volume reduction of 50% per year is considered theoretically possible, but lower values are likely because of the required back flushing and shut-in periods during the bleed down process. A maximum value of cavern volume reduction of ca 2/3 of the available caverns volume would be expected.

Contents

1 Introduction

FRIMA and FRISIA have extracted rock salt from the Barradeel concession since 1995. By injection of fresh water the salt is dissolved in the deep underground, forming saturated brine in the cavern. The resulting brine is lifted to the surface to feed the processing plant in Harlingen. Here vacuum evaporation separates water and salt after purification to remove undesired constituents. The remaining fresh water is supplemented with fresh water from the Harinxma Canal and re-used for the leaching process.
In a cavern that is only slightly affected by cavern convergence (cavern size reduction by salt creep), the cavern volume can be easily calculated from the extraction volume.

The assumption of negligible cavern convergence cannot be maintained in the case of FRISIA's operation. The high temperature of the in situ salt (95 to 105 °C), the high pressure difference between the cavern and the lithostatic rock pressure (as a result of the large depth of the cavern) and the low specific creep resistance, make the salt to flow (creep) towards the local pressure sink (the cavern). FRISIA appears to have reached a more or less dynamic equilibrium: the volume of salt that is dissolved is equal the volume of salt that flows towards the cavern.

The cavern convergence can be calculated by applying an extra parameter: Either sonar (cavern volume) measurements or an injection / extraction mass- balance. The injection volumes are however largely uncertain for a number of reasons, which will be reported separately. The extra information from the echo-metric measurements (sonar readings on the cavern shape) however supply sufficient information to determine convergence. The convergence is the difference between the dissolved volume of salt and the remaining volume, measured by SONAR. The dissolved volume of salt again is the extracted volume of salt plus the salt required to concentrate the brine in the cavern (at 300 kg/m^3).

2 Underground Brine Volume

2.1 SONAR measurements

By installing a SONAR device in the cavern, reflections of the walls can be obtained. The SONAR apparatus records travel-times to the solid walls, which can be related to distances by an in situ determined brine travel speed. Only obstacles with a very different density/ travel time (diesel roof, measurement via corroded tubing) give mismatches.

The only prerequisite for determining the walls of a cavern is that there is a clear transition from brine to salt and that all walls can be probed by the apparatus (i.e. SONAR can not look around the corner).

The October 2001 measurements in caverns BAS-1 and BAS-2 were successful in determining the cavern shape with a high degree of accuracy. Only the sump (loose material) and the cavern neck give small errors in determining the brine volume. The brine filled cavern (excluding sump), as determined by SONAR is expected to have an accuracy of better than 5%, with almost guaranteed accuracy of 10% (DEEP, verbal). The 1999 reading is also expected to have this accuracy. As sonar is likely to detect the innermost particles of a rough wall (small anhydrite lenses) the sonar is likely to underestimate the true volume of the cavern.

In September 2002 the lower part of the BAS-2 cavern could not be observed due to a ledge. The 7" leaching string was lowered and the bottom section of the BAS-2 cavern was successfully surveyed in December 2002. The two surveys were then combined to achieve an estimate of the total volume of the BAS-2 cavern. During the October 2003 measurements, the 7"leaching string was again above the ledge and the bottom part of the BAS-2 cavern could not be seen.

The 1999 to 2003 measurements were performed in approximately the same period as the levelling exercises, by which the results can be combined. A 4th fixed point is of coarse the 0-situation of 1994 before the mining activity started: no cavern volume and zero subsidence.

2.2 Cavern neck volume / oil roof

The cavern volume in the neck, filled with diesel or comparable materials, is not probed by SONAR. However, this volume can never be more than the injected quantities of diesel (minus casing volume). This amounts to several 100's of m^3 only and can be neglected for volume calculations.

2.3 Sump

The cavern bottom contains a sump, a porous structure of fallen down and re-crystallised material of mainly insoluble material (clay, sand, anhydrite, gypsum). The volume of brine in the sump is not exactly known. Both the sump volume and porosity are unknown.

However, it is possible to estimate a maximum volume with conservative assumptions because the height loss in the caverns is known. This sump height due to settling insoluble material is less than this amount, since there will be several metres of floor rise caused by convergence of the sump interval and consequent squeezing up of the settled contents. Assuming zero sump rise due to convergence would be too conservative.

The original cavern dimensions of the sump are known from early SONAR readings. The salt walls will have crept towards the cavern, but salt will never creep away from the cavern. Given the flow restrictions of the sump, fresh water will not reach the salt within the sump, by which it can be safely assumed that dissolution will not take place. Assuming zero inward wall movement is therefore very conservative in determining the maximum sump volume.

If the original diameter of the cavern were 50 metres and the total lost cavern height is 100 metres, the maximum possible sump volume of each cavern is 200.000 m^3, i.e. 400.000 m^3 for two caverns.

The porosity of the sump material is unknown. However in analogy with other slightly compacted materials, it is considered save to assume that the porosity will not exceed 50%. The maximum brine volume in the sump would hence be 50% of the original cavern volume in the sump if no convergence would be applied. A more realistic value is however 15-20%, due to the effect of cavern convergence and compaction in the sump. The expected volume (at 20% of original volume) is some 75.000 m^3 in 2001, 90.000 m^3 in 2002 and 100.000 m^3 in 2003.

DEEP uses another approach, assuming the comparison of the volume of insolubles in the leached salt and assuming that they all fell to the bottom of the caverns. A rough assumption of the original insoluble content (of clay and anhydrite) is 5%. Again assuming a sump porosity of 50% DEEP calculates a sump volume of 170.000 m^3 with a 2001 brine content of 85.000 m^3 (DEEP, dec. 2001).

2.4 Cavern wall

At the SMRI conference in Bad Ischl it was reported (Alkan, 2002) that it would be likely that the salt in the vicinity of the cavern wall has undergone some slight dilation, as a result of locally high differential stresses and low support stresses. A dilatancy induced porosity of 3% could be possible in the first 10 meters of salt. Assuming a 300 m high and 40 meter diameter cavern, a brine volume (per cavern) of 10.000 m^3 can be stored. For two caverns 20.000 m^3 can be stored in theory, constant over the years.

2.5 Volume below the ledge in BAS-2

In Oct 2003 a section of the cavern BAS-2 could not be seen due to a salt ridge below the point of injection (and surveying point), last surveyed in Dec 2002. This 2003 volume below the ridge is estimated to be between 15.000 (Fokker) and 25.000 m^3 (DEEP). The latter is adopted

3 Subsidence versus Convergence

3.1 Levelling

The effects of salt mining at surface are measured by levelling. The best references are again 1999, 2001, 2002 and Oct 2003 (as a result of the simultaneous SONAR measurements). The levelling surveys show / indicate a very neat bowl (Oranjewoud, 1999, 2001,2002, 2003b) which can be described / fitted by a Gaussian curve (Bell shaped in a cross section). See Ch. 3.1. However, in two areas the subsidence bowl cannot be determined accurately.

The subsidence of the Waddenzee cannot be measured and in the south south-eastern part of the bowl there is another source of subsidence: the gas extraction of TOTAL. Along the coastline however the subsidence of gas extraction or other sources can be largely neglected (Oranjewoud, 2002). The measured subsidence can hence be correlated to salt extraction.

The total subsidence bowl by salt mining in the areas mentioned above is then determined by assuming that there exists some axi-symmetry in the bowl, which is a reasonable assumption if one assumes that the overburden-stiffness is equal in all directions (hence a point source of extraction results in circular subsidence lines).
The maximum subsidence has been determined to be 11.4; 20.7, 24.0 and 28.4 cm in respectively July 1999, Sept. 2001, Sept 2002 and Oct 2003, hence approximately 4 cm per year from 1999 on (Oranjewoud 99, 01, 02, 03b)

Note: levelling results with small corrections for 1999 and 2001, due to a change in fixed reference point in 2002

3.2 Subsidence fitting

Both the levelling exercise and Finite Element calculations (see Ch 3.2) show large similarities with a Gauss curve for a cross section. In order to predict subsidence from more than one source (multiple caverns) it is convenient to have a simple equation that predicts the subsidence that is no longer axi-symmetric (because of non-symmetric cavern layout).
The prediction model for subsidence from a single cavern is:

$$w(x,y) = w_{\max}\exp(-\gamma r^{\delta}) = \chi V_{con}\exp(-\gamma r^{\delta})$$

Parameter	Value
γ (-)	$4{,}5 * 10^{-7}$
δ (-)	1,97
χ (m^{-2})	$0{,}99 * 10^{-7}$

Table 1: subsidence parameters from the 2003 survey

Where 'r' is the horizontal distance from the cavern axis and V_{con} is the field-determined convergence (dissolved volume from extraction records minus SONAR-determined open cavern volume). When this subsidence is integrated over the surface, it shows 87% of the convergence volume that serves as input ($V_{bowl} = \psi\, V_{con} = 0{,}87\, V_{con}$). This is roughly in line with predictions from Finite Element calculations, see Ch 3.3.

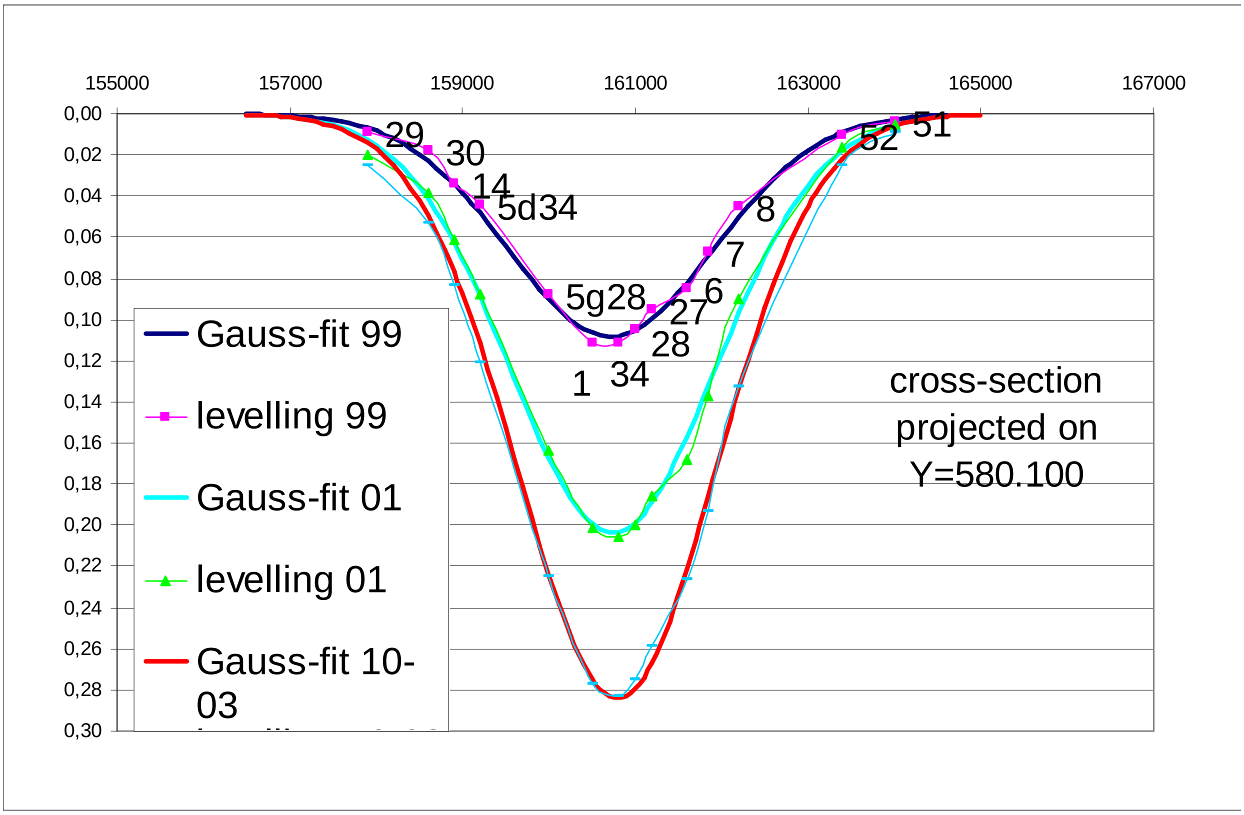

Figure 1: Levelling results from 1999, 2001, 2002 and 2003; fitted with Gauss curve results from BAS-1 and BAS-2.

The shape parameters γ and δ appear to be constant during salt mining so far, whereas the χ value drops in time (from 1,10 in 1999 to 0,99 in 2003). At unaltered shape parameters this is related to a drop in ratio ψ from 97% to 87%.

The convergence is in line with the reported extraction data and cavern volume from SONAR-measurements, as shown in table 2. With these data it can be calculated what volume of salt must have been dissolved to render the extraction tonnes and to fill the existing cavern with saturated brine. The convergence is the total dissolved volume minus the actual open volume, measured by SONAR. Table 3 gives the results of the convergence per cavern.

	extraction (ton NaCl)		extraction	Open Volume m3		Hidden volume m3		Open + hidden Vol		Total vol
	BAS1	BAS2	ton NaCl	BAS1	BAS2	BAS-1	BAS-2	BAS-1	BAS-2	m3
jul-99	1.928.881	1.463.608	3.392.489	300.000	310.000	25.000	20.000	325.000	330.000	655.000
sep-01	3.041.509	2.455.892	5.497.401	386.000	226.400	40.000	35.000	426.000	261.400	687.400
sep-02	3.600.000	2.960.000	6.560.000	415.000	200.000	60.000	95.000	475.000	295.000	770.000
okt-03	4.177.000	3.548.000	7.725.000	443.000	246.000	65.000	80.000	508.000	326.000	834.000

Table 2: reported extraction quantities per cavern and reported cavern volumes

	dissolved m3		dissolved	Convergence m3		converg.	Levelling	subs (cm)
	BAS1	BAS2	m3 NaCl	BAS1	BAS2	m3	subs. cm	per 0,1 Mm
jul-99	938.139	723.430	1.661.569	613.139	393.430	1.006.569	11,1	1,10
sep-01	1.467.273	1.173.293	2.640.565	1.041.273	911.893	1.953.165	20,7	1,06
sep-02	1.732.639	1.411.343	3.143.981	1.257.639	1.116.343	2.373.981	24,0	1,01
okt-03	2.004.352	1.687.870	3.692.222	1.496.352	1.361.870	2.858.222	28,4	0,99

Table 3: calculated dissolved volume and convergence from table 2, assuming a salt (NaCl) density of 2,16 t/m^3 and a brine NaCl concentration of 0,30 t/m^3.

As can be seen from the data above, the total (open) cavern volume has reached equilibrium at the prevailing extraction rate, although the volumes of the individual caverns are different. Differences in operational parameters such as throughput, and cavern pressure are probably the cause of this.

3.3 Finite Element calculations

Finite Element computer programs, such as DIANA, can simulate the cavern convergence process. The cavern behaviour has been calculated by assuming that the cavern is axi-symmetric (more or less cylindrically shaped). The salt layers are modelled according to the in-situ determined stratification / depth. Realistic values for creep parameters and overburden stiffnesses are entered, after which the cavern is loaded with realistic pressures (slightly over brine-hydrostatic). The dominant creep mechanism at operational periods is dislocation creep, which typically displays a powerlaw relation between the creep rate and the applied shear stress, with a power of 3 to 4,5.

Both TNO-NITG (1999, 2003) and GeoDelft (2001; 2002) have performed such calculations. Since creep parameters and overburden stiffnesses are not precisely known, the outcome will differ from the measured subsidence and convergence rates. By matching the creep- and stiffness parameters (within the range of uncertainty) the in situ determined convergence rate and subsidence bowl (shape and depth) can be simulated remarkedly well.

Moreover additional information is gained from the outcome: the salt stresses and strains around the cavern can be calculated to compare them with damage criteria for salt and the casing, the horizontal surface movements can be obtained (displacements and strains) to compare them with damage criteria for buildings.

The calculations based on Finite Element modelling show that the volume of the subsidence bowl is slightly less than the convergence volume. According to the geomechanical model about 85 % of the convergence manifests itself as subsidence. (GeoDelft 2001). The ratio is dependent on the chosen Poissons-ratios in the model for salt and overburden. These have been taken from literature, but are not measured in situ.

The maximum subsidence (for a single cavern) is roughly related to the cavern convergence during the operational period. However, there may be an important time scale effect. If a creep mechanism (called pressure dissolution) with linear stress-creep rate is relatively active in the salt, the subsidence bowl may flatten out in time after ceasing the mining operation. In this case salt flows towards the cavern field from a distance of hundreds to thousands of meters in an attempt to equalise the salt pressure to the original lithostatic pressure level. The overburden will be slightly lifted by the increased pressure, where the far field slowly subsides more. Since the surface area in the uplifting part op the bowl (diameter of approximately 1000 m) is much smaller than the subsiding outer ring (between 1000 and 4000 around the caverns), the net uplift effect is much greater than the subsidence effect, since the effects occur more or less at zero net volume change.

Although the pressure solution creep mechanism is a proven mechanism in science, its activity on macro-scale is -with currently available information- difficult to quantify. It very much depends on the grain (crystal) size of the salt and is only dominant over power-law creep at very small strain rates (typically 1.10^{-10} s^{-1} or 0,3 % per year and slower), which are virtually impossible to simulate under laboratory conditions. However these conditions are very relevant to the salt behaviour after shut in of the caverns. If the creep mechanism is quite active (and some field indications do suggest this), a rebound of tens of centimetres may occur in the decades to come.

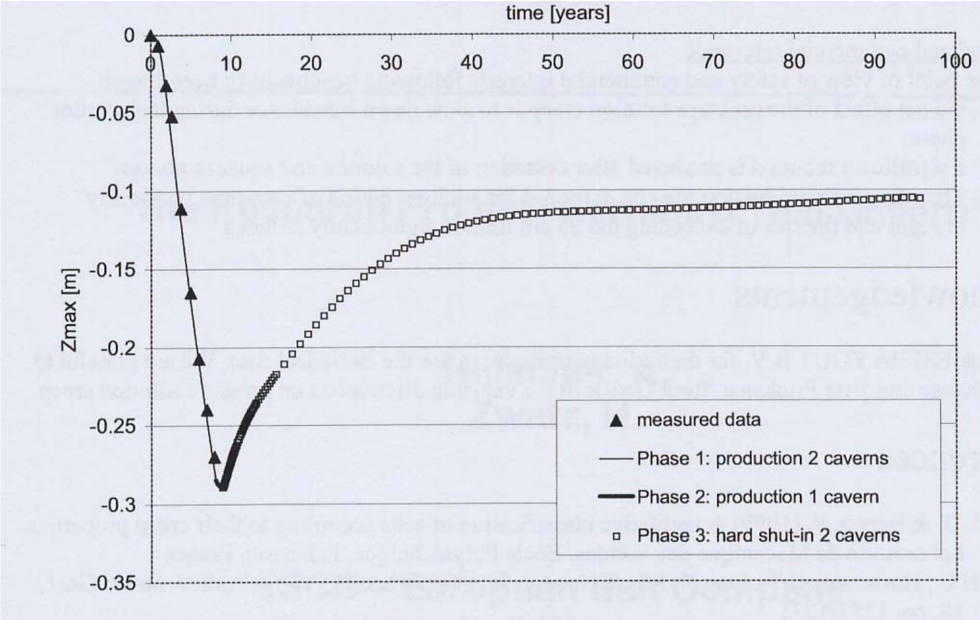

Figure 2: NITG-TNO calculations, displaying a surface uplift (rebound) after shut in of the caverns. These calculations fit the present subsidence- and cavern growth development (1995-2003).

3.4 Sensitivity analysis

Sensitivity to Levelling

Every levelling campaign has two measuring errors which are

- campaign dependent (plus or minus 5 mm with respect to the fixed point)
- systematic (unstable reference point by natural and mining causes; max 2 mm per year; max 1,6 cm in 2003).

The subsidence to convergence ratio χ will hardly be influenced by accidental levelling inaccuracies. In 1999 the maximum error in the subsidence-to-convergence ratio (5 mm over 110 mm) is 5% hence a theoretical ratio of 1,05-1,10. In 2003 (5 mm over 284 mm) this is only 2%, rendering a ratio of 0,97-1,02). Measurements alone can hence not explain the dropping ratio (let alone the very small change of a slight change of overestimation to underestimation between 1999 and 2003.

If the fixed point would subside, this would be at a more or less constant rate (whether or not from mining or natural causes). Given the relatively constant extraction rate from BAS-1 and BAS-2, the subsidence error would be off by a fixed percentage (i.e 1,6 over 28,4 cm = 8% off). Since the error builds up linearly in time, just like the convergence, the ratio χ would be unaffected though.

Sensitivity to cavern and brine volume

The brine volume in a cavern is a parameter that determines the convergence. The brine volume is situated in:

1. The open hole volume (open space, to be probed by Sonar devices)
2. The enclosed volume in the sump (10-40 % of sump volume)

3. The volume in the cavern walls due to dilation
4. The cavern volume behind major ledges or within the oil interface ('invisible' to Sonar)

The first measurement determines the larger part of the brine volume. A small part will be missed however by reflections of minor ledges and other obstacles. The maximum inaccuracy is 10%, plus 60.000 m^3. This amount is however expected to be non dependent on the cavern history and hence slightly fluctuating in time.

The sump-brine volume will increase in time, due to the increasing amounts of anhydrite and gypsum amounts settling at the bottom of the cavern. The brine volume in the sump will be between 60 000 and 200 000 m^3 for two caverns. If this volume is largely underestimated, the convergence is overestimated, by which the subsidence to convergence ratio χ will be underestimated. The error in enclosed volume will be roughly linear with extraction, by which the ratio itself will not be significantly influenced.

The brine volume in any dilatant salt mass is expected to be constant in time, given the more or less constant cavern volumes and stress situation in the cavern wall. If the volume is largely underestimated, the convergence is overestimated. the subsidence to convergence ratio χ will increase in time, contrary to the observed behaviour.

The invisible cavern volume, hidden by major ledges is variable in time and can not systematically influence the ratio χ over time.

The maximum possible error of all undetected brine (sump, wall, ledges), given the incorporated estimated volumes of unseen brine volume, is expected to be 50,000 m^3 in 2003. This would influence the ratio χ by 2% in either direction. This error will probably be systematically positive or negative for all reference years from 1999 to 2003.

Sensitivity to extraction volumes

The extraction volumes are determined by flow- and density meters. On top of these measurements, the extraction volumes can be determined by the produced tonnes of salt (factory output) incremented by a bleed volume of mother liquor (brine disposed at the Harlingen harbour), required to limit the amounts of Bromine (Br) and Potassium (K) in the produced salt. This amount of NaCl discharge via the mother liquor is about 10% of the total feed to the factory.

The measuring errors of flow-meters and density meters are well below 5% and are not systematic in a particular direction. At least the measurements between 2000 and 2003 can hence be relied upon. They can not significantly influence the subsidence-to-convergence ratio over time, although as systematic over- or underestimation of the produced brine can create at a small systematic (but constant!) error.

If it would be assumed for argument sake and to obtain a feel of the sensitivity involved that during the initial mining period (1995-1999) more salt would have been extracted than recorded, the initial convergence volumes will have been underestimated, hence the ratio χ would have been lower than based on the recorded values. It is stressed that there is no documentary or other evidence that there would be substantial unrecorded volumes, however the purpose of this analysis is to demonstrate the sensitivity.

If, to illustrate the sensitivity, during the period 1995-1999 an extra (off- record) amount of 200 000 tons of salt would have been extracted from the Barradeel field area influenced by BAS 1 and 2, and such an amount is added to the recorded production figures, the ratio χ varies less strongly than calculated on the basis of the recorded values. Ratio χ based on the inflated extraction volume drops from 1,01 to 0,96, as illustrated by the tables below:

	extraction BAS1 ton	extraction BAS2 ton	extraction total ton NaC	Volume BAS1 m3	Volume BAS2 m3	Hidden volume BAS-1	BAS-2	Vol +sump BAS-1	Vol +sump BAS-2	Total vol
jul-99	2028881	1563608	3.592.489	300.000	310.000	25.000	20.000	325.000	330.000	655.000
sep-01	3141509	2555892	5.697.401	386.000	226.400	40.000	35.000	426.000	261.400	687.400
sep-02	3700000	3060000	6.760.000	415.000	200.000	60.000	95.000	475.000	295.000	770.000
okt-03	4277000	3648000	7.925.000	443.000	246.000	65.000	80.000	508.000	326.000	834.000

Table 4: reported extraction quantities per cavern plus 200 000 tons in total and reported cavern volumes

	dissolved BAS1 m3	dissolved BAS2 m3	dissolved total m3 NaC	Convergen BAS1 m3	Convergen BAS2 m3	Total conv m3	Levelling subs. cm	subs (cm) per 0,1 Mm
jul-99	984.436	769.726	1.754.162	659.436	439.726	1.099.162	11,1	1,01
sep-01	1.513.569	1.219.589	2.733.158	1.087.569	958.189	2.045.758	20,7	1,01
sep-02	1.778.935	1.457.639	3.236.574	1.303.935	1.162.639	2.466.574	24,0	0,97
okt-03	2.050.648	1.734.167	3.784.815	1.542.648	1.408.167	2.950.815	28,4	0,96

Table 5: calculated dissolved volume and convergence from table 2, assuming a salt (NaCl) density of 2,16 t/m^3 and a brine NaCl concentration of 0,30 t/m^3.

In this case the rebound effect would be less pronounced than before, but still very significant at ca 50% of the currently estimated values.

Sensitivity conclusions

The drop in subsidence-convergence ratio χ from 1,10 to 0,99 between 1999 and 2003 seems to be systematic. Measurement errors (subsidence, volume sonar detection, extraction) may influence this ratio and the relative drop. However, the drop can not be explained in full by a single measurement error. If it is assumed for arguments sake that the ratio is constant over time in reality and the drop is purely driven by data-errors it would require a very unlikely combination of errors all pointing in the same direction.

Frisia is convinced that the observed drop is at least partially the result of rebound effects (far field salt flow by pressure solution creep).

4 Subsidence predictions

4.1 Operational period

During the BAS-2 post-saturation phase of BAS-3 brine, convergence will continue while dissolution is at a much slower rate. A volume reduction of 20.000 m^3 is anticipated during 4 months of post-leaching (35.000 m^3 convergence and 15.000 m^3 dissolution). In November 2003, BAS 2 has been upgraded to lithostatic shut-in capability by sealing the 13 $^3/_8$" x 10 ¾" annulus with cement. After February 2004, BAS-2 will be used for testing and monitoring the behaviour of a cavern over several years at high shut in pressures, measuring pressures and cavern volume. After a testing/monitoring period of several years, BAS 2 will be permanently abandoned.

The monthly extraction from BAS 1 is planned to decrease from 55.000 ton (25.000 m^3) in 2003 per month to 26.000 ton (12000 m^3) until end Oct 2004, when BAS-4 is planned to be ready for stand-alone brine production.

A post-leaching phase via BAS-1 is anticipated (using an auxiliary injection pump to inject the weak BAS-4 brine). Extraction from BAS 1 will then be reduced to ca 26.000 ton per month until cavern BAS-4 is fully operational. After completion and several months of leaching in BAS-4, BAS-1 be upgraded to lithostatic shut in capability by sealing the 13 $^3/_8$" x 10 ¾" annulus with cement. It will then be possible to pressurise BAS 1 as desired to minimise convergence during extraction standstill. BAS-1 is then planned as a standby cavern until BAS 5 is established, being leached only when one of the new caverns has to be shut down. The use of BAS 1 as a standby cavern is currently foreseen at ca 22.000 ton per year, but would be determined on the basis of the best information available at the time having an increasingly accurate determination of the actual subsidence and rebound effects. The actual use of BAS 1 as stand by cavern would continue to be based on the subsidence limit dictated by the ministry of EZ.

4.2 Short-term post-abandonment subsidence (0-5 years)

After closing in a cavern and allowing the cavern pressure to build up to lithostatic, some continuing subsidence ('naijl') may occur. In the worst case scenario an additional 1,5 cm per cavern might surface, according to GeoDelft calculations within 1-3 years after shutting in a cavern. The subsidence is probably much less and may be fully compensated by the rebound effect.

Recent (2003) TNO-NITG calculations suggest a strong rebound that exceeds all post-abandonment-subsidence effects. This effect is demonstrated in Figure 2. Even if this predicted effect is only 25% in reality it still is important for the possible use of cavern BAS-1. In order to establish an early quantification of the subsidence effects following the reduction of the rate of extraction in the BAS 1 and 2 affected area, it is being considered by FRISIA to set up several stationary GPS based monitoring stations.

Although there exists no absolute certainty that the rebound effects are stronger than other effects on the short (0-5) or medium time scale (5-20 years), it is considered very likely that post-abandonment subsidence can a least be crossed out against medium time-scale rebound.

Frisia is planning to monitor the shut-in effects of BAS-2 closely by GPS-stations at the well location (deepest point of bowl). In this way an accurate trend is obtained on monthly basis of the maximum subsidence. The accuracy of post-installation subsidence is expected to be within 1-2 mm applying historical trending and statistical analysis.

- If the TNO-NITG predictions are fully accurate, the rebound effect will cause a standstill in subsidence after 2-3 months of BAS-2 shut in, although the extraction of BAS-1 continues.

- If the the rebound effect is only 25% - 50% of the amount as above, and the “na-ijl” effect of BAS-2 is not very dominant, the subsidence rate will drop by roughly 50%

- If the rebound effect is absent and the “na-ijl” effect is strong (up to 1,5 cm for BAS-2 in 6 months), the subsidence rate will still be 80-90% of the present rate of subsidence, even after 3-5 months of shut-in of BAS-2.

In a time frame of 6 to 9 months after shut in BAS-2 (Oct-Dec 2004) some first conclusions can be made on which of the above scenarios is closest to reality. In case the first scenario is close to reality, the exists a pronlonged production lifetime of BAS-1 in the coming decade, without exceeding the 35 cm subsidence level.

If the third (unlikely) scenario is close to reality, the subsidence will be about 34 cm in Dec 2004. The well BAS-1 must be shut in to maintain the 35 cm subsidence limit. The na-ijl subsidence of BAS-1 will then lead to a continuing subsidence of about 1,5 cm. The 35 cm limit might then be slightly exceded in the post-abandonment years by 0,5 cm.
Frisia expects the government bodies to accept a small chance of exceeding the subsidence limit by less than 1 cm, given that there will be no direct implications for third parties.

In the subsidence predictions Frisia assumes a somewhat conservative assumption of no rebound effects and a constant subsidence-convergence ratio of 0,99. It is very likely however, that the actual ratio will drop further in the years to come.

On the other hand however, the na-ijl subsidence is neglected as well. In this case the subsidence directly linked to the convergence.

In 2007 the subsidence is only 32,4 cm, still applying BAS-1 as stand-by well for workover periods of wells BAS-3 and BAS-4. For details, see appendix I.

4.3 Long-term post-abandonment subsidence (5-100 years)

The long-term post-abandonment subsidence effects are difficult to predict with accuracy. The creep rates in the salt are 1 to 2 orders of magnitude lower than at present rate. However the range of inaccuracy can be estimated.

The largest inaccuracy is the importance of a second creep mechanism with linear stress- strain rate dependence. It has been argued by Spiers et al (1990) that water assisted pressure solution may speed up deformation at low creep rates. The mechanism is proven in laboratory circumstances for compacted crushed salt samples with small grain size. For normal in situ grain sizes (2-50 mm) the mechanism is almost impossible to test in the laboratory as a result of the required testing period of many years, given the power-3 relation of the creep rate to the average grain diameter.

Also the rate limiting grain diameter is unknown for the FRISIA case. In a multiple layered bedded salt (alternating anhydrite and halite layers) diameters of 2 mm to 50 mm can be expected, the smaller ones being rate dominating (as a result of the power 3 relation). For FRISIA a 5 (and 2,5) mm rate limiting diameter has been assumed as realistic lower limit and a (far field) temperature of 105 °C (378 K).

$$\frac{d\varepsilon}{dt}(s^{-1}) = 4*10^{-4}*\exp(-{Q}/{RT})*\frac{\sigma}{T*d^3} = 4*10^{-4}*\exp(-{25000}/{8.314*378})*\frac{\sigma}{378*5^3} = 3*10^{-12}\sigma$$

$$\frac{d\varepsilon}{dt}(s^{-1}) = 4*10^{-4}*\exp(-{25000}/{8.314*378})*\frac{\sigma}{378*2.5^3} = 2{,}4*10^{-11}\sigma \text{ (in MPa)}$$

(d = grain diameter in mm; Q= activation energy; T= temperature in K; σ = differential stress in MPa).

This mechanism has a strong stress levelling effect and allows salt transport from large distances. According to the creep formula of Spiers and assuming an average grain-size of 5 mm for the FRISIA salt the total effect of this likely but in-situ unproven creep mechanism can be demonstrated. It can be seen that a rebound occurs after some 4 years of shut in, becoming important after some 6 years of cavern shut in. Some 4 cm of rebound per cavern may occur in a timeframe of some 80 years.

TNO-NITG calculations, based on present day subsidence effects, indicate an even larger rebound effect of some 20 cm in total, hence assuming a smaller (dominating) crystal size or a higher creep constant.

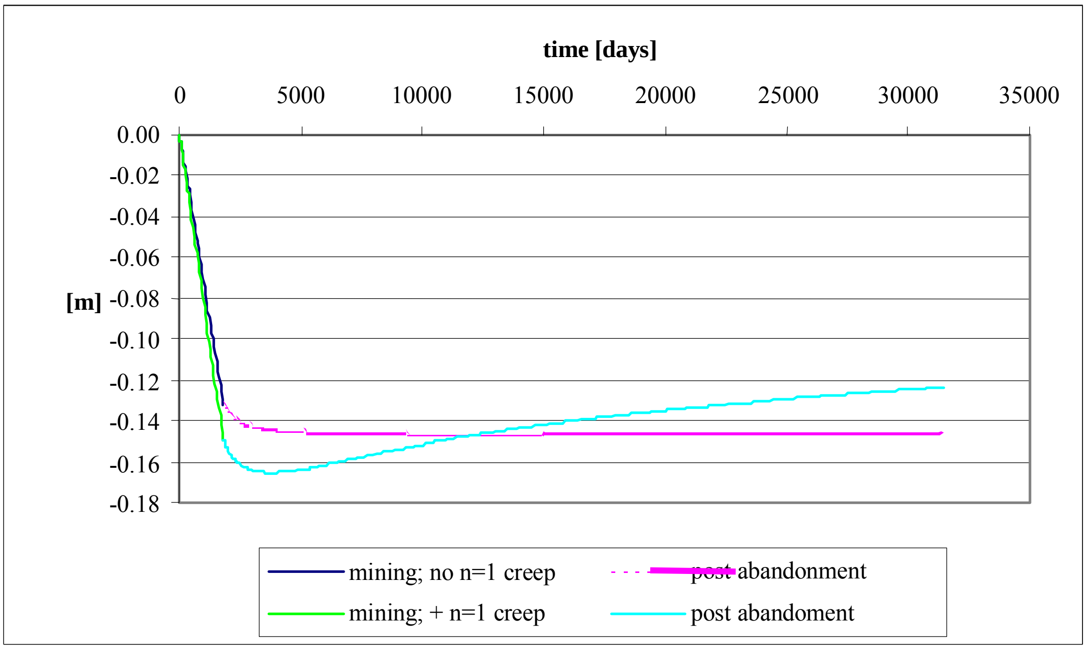

Fig. 2 Lagging subsidence and rebound effects for both the situation that power 1 creep occurs (with large rebound) and without power 1 creep (negligible rebound): Source: GeoDelft (2001)

In the Finite Element Calculations it is assumed that the brine pressures at the cavern roof will never exceed the lithostatic pressure. As soon as a salt cavern is at full lithostatic pressure as a result of cavern convergence, the cavern will start to leak (Fokker, 1995). As a result of the density difference between brine and salt (about 1 bar/10 m or 20 bar/200 m) the lower part of the cavern has a tendency to shrink, while the upper part has the tendency to expand.

The brine pressure at the roof exceeds the tensile strength of salt (at 1-2 MPa tensile stress). A system of small fractures will open up (as long as the brine pressure exceeds the minimum salt stress) and brine may escape from the cavern. Since fractures will close when the brine pressure drops, the roof pressure will stay at near lithostatic. The driving sub-lithostatic pressure at 200 meters below the cavern roof will be 20 bars. Presently the sub-lithostatic pressure is some 250 bars. The pressure deficit from lithostatic will drop from 250 to 20 bars after abandonment. A reduction to 8% of the original deficit.

According to French literature [for instance Brouard, 1998] the relation between convergence pressure deficit is a power 3 (to 5) relation. The convergence rate is proportional to the volume:

$$\frac{dV}{dt} = B * V * \Delta p^3$$

If the deficits drops to 8%, the third power is 0,5 ‰. At an initial (present) convergence rate of 0,25 M m^3 per cavern per year, a reduction to 0,5 ‰ will cause a convergence of 250 m^3 per year for both caverns. Assuming the present relation between convergence and subsidence (about 1 cm per 100.000 m^3) a subsidence rate of 0,025 mm per year (2,5 mm per century) may be expected. The Finite Element calculations do not indicate the additional subsidence, but a 0,1 to 4 cm uplift (per cavern) instead as a result of far field salt flow towards the local pressure sink (the caverns). These effects have not been taken into account in the subsidence prediction.

Closed-in caverns will not develop fractures of large aperture that remain open at sub-lithostatic pressures. Experience at Nedmag Industries has not shown lowering pressures in caverns that have been fully shut in for many years (such as VE-1). The pressure just levels off at lithostatic. Tests at the

Etzel caverns in Germany where caverns were pressurised (just) above lithostatic showed leakage at injection but no drop in pressure to sub-lithostatic pressures.

4.4 Subsidence effects at concession Barradeel

In determining subsidence over a number of years to come, a number of data should be available

1. The most recent levelling results and the shape parameters from it.
2. The corresponding salt production per cavern at the moment of levelling.
3. The most recent Sonar measurements and volume determination.
4. The best estimates of the brine volume in the sump and cavern wall.
5. The best relation between convergence and maximum subsidence.
6. The extraction plan for the caverns BAS-1 and BAS-2 (partly derived from the drilling and extraction plan of caverns BAS-3 and BAS-4 and the production plan of vacuum salt plant.
7. The best assumptions concerning the growth or reduction of open volume in the caverns before final abandonment.
8. The best theory about post-shut in / post abandonment subsidence.
9. The best theory about post-shut in / post abandonment rebound.
10. The best theory about post-abandonment cavern convergence by super-lithostatic pressure conditions at the cavern roof and the subsidence caused by it.

The assumptions were taken here as

1. A maximum subsidence of 28,4 cm by Oct. 2003 and a subsidence bowl with parameters $\gamma = 4{,}5 * 10^{-7}$; $\delta = 1{,}97$ (fitting the 1999 to 2003 bowls)
2. The production figures of Table 2
3. The Sonar volumes of Table 2
4. The estimate of brine volume in sump and wall (for calculations assumed at 20% of the open volume)
5. A value of 0,99 cm per 100.000 m^3 of convergence has been applied for the time being, until quantification of the magnitude and speed of rebound has been established.
6. An extraction of 1,35 million tons per year
7. The lagging subsidence (na-ijl) and the rebound. Conservative assumption: no influence of total effect on the medium and long time scale (10-100 years).
8. The migration rate from abandoned caverns is in the order of 125 m^3 per year per cavern or less. This is about 1.3 mm per cavern per century, applying the present relation between subsidence and convergence and is about the same magnitude as the rebound effect (zero effect). The effective uplift (rebound) has not been taken into account.

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