Review of Twente Salt Dissolution Studies

Contribution to the evaluation of massive re-injection of fresh water in depleted Twente gas fields; the Netherlands

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Scope of the work :

NAM is currently producing the Schoonebeek Oilfield in the Netherlands and has to manage great amounts of production waters of low salinity. Reinjection into nearby depleted gas fields (a.o.Tubbergen, and Rossum Weerselo) was investigated and operations have started in 2011. The Dutch regulator, SodM, requested further studies complementary to the initial Environmental Impact Assessment to ensure that these reinjection activities are performed in a sustainable and socially responsible manner, the main concern being to assess the risk of degrading cap rock integrity through salt dissolution. These studies are detailed in three reports, namely refered to as [1], [2] and [3], dealing respectively with EP20130201845 “Geology description of Twente gas field”, EP20130203080 on “Halite dissolution modeling”, and EP20130204177 on “Subsidence caused by halite dissolution”. Complementary NAM technical reports have been analysed as background information for the scope of the reviewing process. We had therefore access to NAM documents, EP201502207168 on threat assessment for induced seismicity [4] and EP201410210164, on Technical evaluation of water injection wells, 3 years after start of injection [5]. A first round of complete evaluation of the project is planned for 2016 and multidisciplinary analysis of three NAM reports is underway. The present review of [1], [2] and[3] is a contribution to this evaluation, one major concern being the compatibility of massive fresh water with the evaporitic sequence forming the hosting reservoirs and the risk of loss of confinement that would translate at minima in groundwater quality issues. The three reports were at first separately evaluated.

Notes on report [1] on geology :

The report [1] is to our opinion, very well documented and fully in line with the current understanding of the Zechstein salt series description that can be found elsewhere. Many descriptions of stratigraphic columns at each site and correlation from site to site are given, which are sufficiently informative. Different –sealed- faulted zones inside the former gas traps are exhibited with moderated fault throws with regard to the layer thickness. The fields have been producing from the carbonates strata, mostly from Z2C and Z3C cycles, combining dolomitic and anhydritic banks.
The gas traps are described by cross sections and plan views, and the initial gas water contact GWC level can be observed on the maps, 1450 m below NAP in Rossum-Weerselo, or 1800 m in Tubbergen-Mander field for instance. However external faults most probably do control the spill point of these reservoirs but no comment on the natural hydraulic functioning is given. The possible implication of the open nature of hydraulic boundaries at the down dip base of the reservoir will be rediscussed later. From plan views of the domal structures (e;g. figure 2 to 4 for instance) it can be seen that the reservoirs have a significant dip, from the top of the structure, of about 10 to 20 %. Potential implications from this geometrical constraint are not really introduced for further developments regarding dissolution and subsidence in reports[2] and [3]. Dissolution of the salt in the up-dip direction resulting in surface subsidence has been reported, see reference [9], though this was resulting from a different ground water flow scenario. Additionnal information is given in figure 8, as some Sylvite stratas are mentioned in the Z2H caprock. Sylvite is known to be more soluble in warm waters than Halite. Although temperature ranges are not specified, they should reach 40°C, the geochemical questioning is not conducted further.

The observations of deposit sequences and carbonate/anhydrite cycles in the ZEZ2C and ZEZ3C are detailed enough to discuss probability of contact occurrences along internal-faults segments belonging to the more general Gronau strike-slip fault system. This is properly done in section 5 “faulting and juxtaposition”, figure 16, where offsets are compared to thicknesses of clean carbonates to identify a possible juxtaposition against halite units. This approach is used to derive convincing scenarios, to be tested in the report on dissolution, ref [2].
The report on geology, ref [1], also focuses on the fractured nature of the Dolomites strata within the Z2 and Z3 Carbonate reservoirs, in sections (3) and (4). Open fractures are reported with geometric characteristics (en echelon pattern, abutment on anhydrite sub-layers ...) that result in a strong anisotropy in permeability properties at the reservoir scale. The permeability of core material is given in the order of 0.1 mD. In the Z3C reservoir it is acknowledged that due to their limited thickness, anhydritic layers are expected to constitute baffles for vertical flow rather than seals, with possible vertical fracture communications (page 7, section 3). This is probably the major source of uncertainties in [1] with regard to the final evaluation objective.

The permeability estimate given in section (4) is fully adequate for dynamic reservoir exploitation purposes (gas production, planning of water injection) but long term convective process requires something else as will be rediscussed when reviewing [2]. In report [1], it is accepted that transverse permeability is controlled by anhydrite and lot of faith is put in the statement. The vertical component K_v is therefore set to the (isotropic) permeability value of the massive dolomite. This may alter the reasoning and introduces some weaknesses in the mechanical analysis performed in [3]. It is suggested here that a more appropriate upscaling analysis for heterogeneous stratified media should be done at least for ZEZC3, where injection will be simulated in report on subsidence [3]. The goal of the upscaling would be to derive an equivalent permeability tensor at the formation scale (e.g. with 50 m in thickness), and later characterize an anisotropy factor K_v/K_h of this baffle area. Instead, the use of a power averaging method (equation 11) is suggested in report on dissolution [2] to account for the anisotropy factor, but this is not really an upscaling method appropriate to [1], as the value used for K_v , 0.1 mD, is already considered as an upscaled value of the transverse permeability.

Notes on report [2] on dissolution:

The second report [2] is a quantitative analysis of the Halite dissolution, because it is anticipated that dissolution is the main hazard with regard to cap rock integrity. But the work is motivated by the idea that any dissolution requires a convection loop established throughout the height of Z2C or Z3C in order to have a continuous supply of fresh water to replace dense liquids that tend to migrate to the deepest parts of the carbonate formations.
A conservative option is promoted, assuming a direct contact in between Carbonates and Halite cap rocks, although anhydrite layers are present at any place. A double porous media approach is used to simulate the fractured carbonate reservoir in order to demonstrate that a single porosity approach (with permeability equal to fracture permeability) is sufficient. Two different numeric schemes, explicit in time, are then developed to represent halite dissolution. A number of specific situations are identified, namely wellbore and far-field scenarios, and are investigated using the MoReS in house code. Numerical applications are however performed on geometrical systems made of a combination of adjacent horizontal slabs that do not address the potential role of the dip.

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- Wellbore scenarios are well constrained : cement crack, casing leak, and hydraulic fracture at a well are investigated in a very convincing manner and the risk of significant damages due to undetected leakage is very low.

- Far field situations are of two cases, faulted or un-faulted areas. Characteristic behaviors are discussed according to reference [6], but a more intearesting discussion could have been obtained while going ahead with the new findings exposed in [7] for infinite horizontal and anisotropic slabs, same authors as in [6]. The possibility of a locally more intense dissolution process might have been studied. This could be possible in the scenario 4 or 5 of ref [2], "water flowing past juxtaposed Halite in faulted areas" or "convection loops in down-dip flanks of the reservoir" if the hypothesis of convective cells had not been not discarded, on the sole basis of a K_v/K_h ratio ranging in 10^{-3} to 10^{-4} at the scale of the carbonate formation, leading to a critical time for the onset of convection larger than 7000 years.

- Evaluating the possibility of a local dissolution and corresponding time scales might be of interest in both situation (4) or (5) in report [2], but in sloping stratified formation, using a better combination of box models with anisotropy ration $K_v/K_h = 1$ as done in cross section of faulted scenario (4) and in convection cases 1 and 3 of scenario (5) (Table 5.2, figures 5.14 and 5.15) with no anhydrite intra layers. It is shown in such situations that the diffusion process dominates the mixing at metric scale within a couple of years, as predicted by the set of equations (8)-(10) in ref [2] and [7], and that the amount of dissolved Halite is limited. But authors in [8] have recently examined the slope effects within a stratified medium and shows example of buoyancy driven fluid flow with net transport due to along-slope roll motion. In Z3C formation, dissolution starting in a single sub-layer with $\gamma = 1$, and a cascading convection loop could be considered, allowing brine transfer trough the baffle zone, away from a dissolution area. This would help to confirm or discard the fears of such a localized dissolution process, as it is known that for high lateral permeability, it would be more appropriate to use explicit layering to capture the heterogeneity, since it is the fine-scale heterogeneity that will determine the onset of convection [7]. In turn the use of the scaling laws (equations 8,9,10 in [2]) is somehow unclear, as the text (page 33, ref [2]) states that table 5.3 summerizes results from the analytical equations while the caption given for table 5.3 is dealing with the time to reach an averaged salinity of 150000 ppm all over the reservoir with a domain thickness H. This should be taken with great caution.

    - [Rem: equation (8) in [2] gives the critical time t_c for onset of convection: the numerical value set to 146 of the dimensionless prefactor is not explain: it is usually a function of anisotropy $\gamma = K_v/K_h$. 146 seems to be the lower value considered in [8] for γ=0.01.
    - In the mathematics of eq. (8) t_c scales with $(\varphi\mu)^2$ and not with $\varphi\mu^2$, see ref [7]]. The mathematics of the critical time t_c also show that t_c scales with the inverse of the square of permeability and does not depend on the formation thickness H. In table 5.3, results are puzzling, as a change by a factor 10 in permeability from γ=0.001 to γ=0.0001 should translate into a change by a factor 100 in time t_c, which is not shown.

- On another hand, a localized dissolution would not lead to geomechanical disorders at surface, but more probably to some leakage and possible fluid exchanges with other overlying aquifer formations. Salt extraction, mined out by isolated boreholes and dissolution processes, as in Twente area, usually show cavern collapses at depth, because there is no stiff layer with the mechanical properties that could allow large cavities to remain open in time. But because of bulking effects, a gradual collapse does not necessarily translate into a sinkhole but most often it can generate moderated but long lasting surface deformations of few mm/year due to the soft nature (clay) of some of the overlying rocks [10].

Notes on report [3] on subsidence:

This report is focusing on the potential subsidence due to salt dissolution evaluated in [2] and simulates a water storage in ZC3 formation. Subsidence, when observable at ground surface, is reflecting damages at depth. Therefore the process is highly dependent on the geological context, especially the nature and the mechanical properties of the overburden. Here, there is no clear description of the mechanical properties of rocks on top of Zechstein (formation NS_B, RN, RB, in figures 2.3 to 2.5: Young modulus is however lower at the top, in NS formation, and stiffer beneath, in RB formation, see Annex 2, of [3]). In the common cases, the perturbation is given as the dislocation of the roof of a cavity. Here it is introduced as a spatial distributed strain, at wide scale.

The potential amount of dissolved halite is derived from a calculated water saturation change that is later on turned into a crude estimate of shrinkage strain, according to eq.(3) in [3]. This estimate is based on the premise that fluid previously injected in Tubbergen wells, in Z3C, does not move after 1000 years shutin. Mass transfer by dissolution is driven by density and can then be established in a static column from the salt layer into the volume of fresh water underneath. A total of 4Mm^3 Halite is dissolved, which corresponds to an average dissolved thickness of 0.25m.

- [Rem: this would also correspond to a cavity made of 6 neighboring cells of the "Geomec" grid, 100 x 100 x 65 m in size , 65 m being the thickness of Z3H formation in Tubbergen, according to table 2.1 [3] and Tub-12, figure 8 [1]].
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The resulting strain (eq.(3)) is applied on the ZEZ3C formation (i) all over the gas trap and (ii) in a restricted area nearby injection wells. A very limited subsidence bowl is obtained at surface by the "Geomec" software, in the order of 0.1 m in both cases, and because the equivalent average dissolution is about 0.25 m, it is claimed that the dissolution is of no impact on cap rock integrity. However, Figure A3, shows some vertical displacements in the vicinity of a NW-SE fault (with an horizontal trace at 1450 m, to the west of TUB12), with vertical (up heaves) displacements as large as 0.2 m. This result is not discussed at any place. Stresses in this area should be displayed too.
Under the NAM hypotheses of no lateral fluid motion, resulting from the finding that many thousands years are necessary for generating convection cells, and owing to the magnitude of halite dissolved quantities and to the corresponding surface deformation, we agree that no additional geomechanical model at the global storage scale is necessary. Testing a worse situation could be envisaged: the dissolution of the salt starts for any unknown reason at the base of the formation close to a well or close to a fault (see figure 3.5 in [3], remains focused and progresses upwards. A cavity of great height can be formed in the salt without provoking any major movement at the surface. When all the salt is dissolved (e;g. 65 m in height, about 100 m in radius), this cavity reaches the overlying rocks, which progressively collapse. And this collapse propagates to the surface. Assuming a very conservative bulking coefficient of 1.1, this cavity is not likely to extend more than 650 m upward, and because of the great depth, it might not be able to reach ground surface and cause a sinkhole at the surface.

General comments :

As a general outcome of the review, it is observed that the overall hydrogeologic behavior of the multilayered system does not appear as a priority for NAM, although the feared processes are likely to develop or take place over thousands of years. The final hydraulic situation after the injection of Millions m^3 of fresh water can be evaluated for instance in figures 3.1 or 3.2 in report [3] that shows a possible saturation distribution after 20 years of injection and 1000 years shut in at Tubbergen, with a GWC rising from 1800 to about 1400 m and non zero saturation changes at the down dip east boundaries, suggesting a possible ongoing migration from the injection zone toward this area.

- [Rem: This is unexpected, because the area should have already been with a initial high brine saturation, with little chance to be displaced or replaced by fresh water].

Such a water level change in the trap may imply gas pressurization but also some changes in hydraulic heads and therefore some fluid (brine) migration away from the trap through spill points. The boundary conditions – no flux versus prescribed pressure type?- of the dynamic reservoir model in section 2.4 [3] are not given. Again the characterization of the delay for plumes of such fluids to reach overlying aquifer formations should be of high concern for long term impact studies. A useful indication about the open nature to the far field should first be found in past data bases if some boreholes exhibited changes in water content of the extracted gas, or in the delineation of the GWC surface at the end of the gas extraction phase. Since the fear of a significant mechanical disorder can be ruled out, it would seem wiser to continue the analysis by discussing the case of a localized dissolution leading to a hydraulic disorder. Therefore the hydrogeological context should be accounted for, especially to discard the possibility of having a long term natural fresh water renewal.

Additional questions to NAM :

1) The presence of Sylvite is reported: Is there a potential mechanism for preferential dissolution of such strata that would result in a weakening process of the cap rock ?
2) In Z3C, anhydrite layers are not thick and therefore are thought to act as a baffle zone for vertical flow. Therefore why did you not try to consider the sedimentary sequence as a heterogeneous media in order to apply some upscaling method, and then derive the anisotropy factor at the large scale?
3) The dipping of the flanks of the reservoir is not explicitely used in the discussion for the onset of convection . Why ?
4) It seems that the gas trap is modeled in report [3] as a closed structure, with no flow conditions at down dip flank boundaries. Am I correct? Are there wellbore observations since the date when the field was abandonned (pressure survey away from the former gas trap, GWC changes in wells, gas pressure evolution, ..,) that confim this option.
5) Analytical expressions, section 4.5 report [2] are used to build the table 5.3, where the variable 'H' is ranging in 0.3 to 50 m. How is the variable 'H' considered in the equations (8) to (10)? Is it relevant to consider the case H=0.3 and γ=0.0001, or the case H=50m and γ=1 ? The equation (8) shows that the onset time t_c scales with the

inverse of the permeability, squared. There is a factor 10 in between 8000 years and 75000 years. Are the numbers in table 5.3 correct ?

6) Long term safety of any storage in a geological structure needs some survey. The most common survey consists in monitoring water levels. Are there shallow geological units in the vicinity that may present an interest for water resources management in the near future?

Conclusions :

The long-term disposal of production waters from Schoonebeek oilfield in depleted aquifers is put forward as a solution to continue the exploitation of hydrocarbons. The risk of loss of confinement, consecutive to a phenomenon of cap rock dissolution, has been identified and very detailed studies were performed. In the review conducted above, we concentrate on three studies that evaluate the probability and potential impact of salt dissolution scenarios. Because few points required further explanation, some additional questions were transmitted to the authors.
Answers provided by the company NAM to the 6 questions are given in the Appendix 1. Responses are fully meeting the expectations of the review, and this exchange is revealed very successful as it also showed that we may have misinterpreted some parts of the work done (question n°5). Dealing with the presence of Sylvite, it is recalled that the total quantity of this mineral in evaporates in the Zechstein salt sequences is so small, that our fears cannot be justified. Similarly, it is confirmed that very limited vertical flow within the carbonated formation is expected because of the high anisotropy ratio of the permeability tensor, and we fully agree with the conclusion that the occurrence of convection, dissolution and mixing processes within the trap will be delayed by thousands of years. Furthermore, complementary information has been obtained (responses to points 4 and 6) with regard to the hydraulic functioning of the geological units beneath, around and on top of the trap. The most important is finally given by this overall view of the deep sedimentary system which remains closed and hydraulically static, years after the end of gas depletion. The potential of dissolution is only proportional to the stored volume, and it has been demonstrated, with very conservative assumptions, that the long term impact will be negligible. The good thing is that after filling the storage, with a final reservoir pressure below the virgin reservoir pressure (as stipulated in ref [4]), there is no natural mechanism to renew the brackish water inside the trap, export dense brines away and further extend the dissolution process. Our feeling is that the safety of the long-term storage is not questioned. Very few impacts on shallow water resources and very limited subsidence will be noticeable at ground level. A common survey consisting in water wells monitoring combined with time series of satellite-based measurements of the surface deformation will be sufficient in the early phase to ensure that the storage behaves as expected.

References:

[1] Geology description of Twente gas fields: Tubbergen, Tubbergen-Mander and Rossum-Weerselo. NAM report n° EP20130201845, 35p., 2014

[2] Halite dissolution modeling of water injection into Carbonate gas reservoirs with Halite seals NAM report n° EP20130203080, 36p., 2014

[3] Subsidence caused by halite dissolution due to water injection into depleted Carbonate gas reservoirs encased in Halite. NAM report n°EP20130204177, 25 p., 2014

[4] Threat assessment for induced seismicity in the Twente water disposal fields. NAM report n° EP201502207168, 23 p., 2015

[5] Technical evaluation of Twente water injection wells ROW3, ROW4, ROW7, ROW9, TUB7 and TUB10 3 years after start of injection. NAM report n°201410210164, 45p., 2014

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Annex 1 : responses provided by the company NAM

- 1] The presence of Sylvite is reported: Is there a potential mechanism for preferential dissolution of such strata that would result in a weakening process of the cap rock ?

Some Sylvite is present in the evaporate sequence associated with the Rossum-Weerselo and Tubbergen fields. It occurs in mixed Halite/Sylvite (Sylvinite) layers in the ZEZ-2 and 3 salt sequences. The risk of preferential dissolution of these layers is expected to be very small. The sequences in which these layers occur, are cased off in all injection wells and do not come in direct contact with the injection fluids. Only in areas of fault juxtaposition of the injection reservoir a direct exposure could be possible (see scenarios modelled in report 2). Even if preferential solution were to occur, the total quantity of Sylvinite in the Zechstein salt sequences is so small that cap-rock weakening and destabilization is unlikely.

Data underpinning the above is provided below:

In both fields, Rossum-Weerselo and Tubbergen, presence of some Sylvite has been interpreted on the basis of well log data. Based on the natural radio-activity (Gamma Ray), Sonic velocity and Density (where available) it can be concluded that these layers are not pure Sylvite but a Halite/Sylvite mix (i.e. Sylvinite).

It was observed that these Sylvinite streaks rang in thickness from 1m (in Rossum-Weerselo) to several meters (maximum observed 8m) in Tubbergen. In the Tubbergen Mander field, no hardly any halite is preserved and there is no indication of any Sylvinite.

Other observations:

• In Rossum-Weerselo these streaks are either in the Zechstein 2 salt (in 4 wells) or in the Zechstein 3 Salt (in 3 wells) and there are 3 wells with no Sylvinite streaks, making the distribution of this mixed salt non-correlative (both vertically and laterally). The Zechstein 1 salt does not contain Sylvinite layers.

• In Tubbergen, the Sylvinite streaks are only seen in the Zechstein 2 Salt, and 2 out of 8 wells do not show any Sylvinite. The Zechstein 1 and 3 salt layers do not contain Sylvinite layers. The evaporate sections.

• In Tubbergen Mander field the evaporate sequences consist of almost pure anhydrite (hardly any Halite) and the logs show no evidence for any Sylvinite)

• Based on some rough (conservative) assumptions, an estimate of relative volume of Sylvinite layers in the Zechstein evaporite sequences in the disposal fields are tabulated below:

Relative volume percentage mixed Halite/Sylvite (Sylvinite) layers in evaporate sequences	Rossum Weerselo	Tubbergen	Tubbergen Mander
ZEZ 3	< 0.4%	0%	0%
ZEZ 2	< 0.2%	< 5.5%	0%
ZEZ 1	0%	0%	0%

• In terms of dissolution, it appears that Sylvite and Halite are equal competitors when both are exposed to brine, and, when there is much less Sylvite, this will preferentially dissolve with precipitation of Halite, until ionic equilibrium is reached. Dissolution rates of KCl and NaCl (Sylvite and Halite) are similar (ref: Synthetic fluid inclusions. V. Solubility relations in the system NaCl-KCL-H20 under vapour-saturated conditions, S.Michael Sterner et. al. Geochimica et Cosmochimica Acta, Vol. 52 pp. 989-1005, 1988)

From the observations it is concluded that:

• Of the total salt sequence in the Tubbergen and Rossum Weerselo fields, Sylvinite only makes up a minor quantity, in relation to the total ZEZ2 and ZEZ3 salt volume.

• Where present, the Sylvite appears always in association with Halite, and it is never encountered as pure Sylvite.

• The Sylvinite layers in both the ZEZ2 (ROW & TUB) and ZEZ 3 sequence (ROW) are non-correlative and hence laterally and vertically restricted. The deepest ZEZ 1 salt sequence does not contain Sylvinite layers in any of the fields. The shallowest ZEZ 3 salt sequence is estimated to contain 0% to <0.4% Sylvinite

• The ZEZ-2 and 3 sequences are cased off in all injection wells and not in direct contact with the injection fluids. Only in areas of fault juxtaposition a direct exposure could be possible.

• Dissolution rates of Sylvite and Halite are quite similar, and both minerals dissolve in competition, when exposed to brine. The Sylvite component will dissolve faster until ionic equilibrium is achieved.

In view of the above observations we conclude that the risk of preferential dissolution of the Sylvinite layers (potentially relevant for the Rossum Weerselo and Tubbergen fields only), is very small and even if it were to occur (e.g. near fault juxtapositions) the total quantity of Sylvinite in the Zechstein salt sequences is too small to create a risk for cap-rock destabilization. For this very reason, the Sylvinite layers were not included in the screening models and sensitivity analysis.

- 2] In Z3C, anhydrite layers are not thick and therefore are thought to act as a baffle zone for vertical flow. Therefore why did you not try to consider the sedimentary sequence as a heterogeneous media in order to apply some upscaling method, and then derive the anisotropy factor at the large scale?

  By providing a range in Kv/Kh ratios it was attempted to provide the basis for several vertical flow and convection scenarios. These Kv/Kh ratios were given for the entire Zechstein 3 Carbonate package. As such, these serve as an “upscaled value”. Based on core analysis and results from well test data (Report 1, section 4) it was determined that in unfaulted parts of the reservoir the “upscaled” Kv/Kh ratio is expected to be in the range $5*10^{-3}$ to 10^{-4}. Sensitivity analysis have been conducted with this range in mind.
- 3] The dipping of the flanks of the reservoir is not explicitely used in the discussion for the onset of convection . Why ?

  The intention of the convective models was to do a screening of the characteristic timescales and achieve a better understanding of the main sensitivities. Not all possible sensitivity parameters were included. Dip angle was not considered as a key parameter to study. Although it may have some impact (on timescale to achieve average salinity 150000ppm, but probably not on timescale for onset of convection), the impact is expected to be small compared to that that of layer thickness, Kv/Kh and vertical permeability.
- 4] It seems that the gas trap is modeled in report [3] as a closed structure, with no flow conditions at down dip flank boundaries. Am I correct? Are there wellbore observations since the date when the field was abandonned (pressure survey away from the former gas trap, GWC changes in wells, gas pressure evolution, ..,) that confim this option.

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In this screening study the gas trap is indeed modelled as a closed structure with a no-flow condition at the down-dip flank. This simplification is based on the below rational:

The pressure depletion response during the original gas production history of the fields does not suggest that the fields are underlain by active aquifers. At the start of injection (several years after cessation of production) the depleted reservoir pressure was still on the order of 5-15 bar in the Tubbergen en Rossum Weerselo fields. Given that the top and base of the reservoir units comprise an impermeable anhydrite/salt layer vertical inflow is also restricted. Therefore it is assumed that during the injection phase the rate of water injection into the former gas-bearing reservoir will be much more significant than any lateral aquifer inflow into the gas trap.

There are no observation wells close to the GWC or in the aquifer so direct observations on GWC location and movement are not available.

Based on the above, the planned water injection volumes were assumed to be the only source for a rise of the GWC and hence the change in saturation form gas saturated to water saturated in the donut forming the saturation (GWC) change volumes. The fresh (lower density) water is expected to concentrate more in the central, shallower part of the field. This results in a smaller donut size, hence a slightly more concentrated area of salt dissolution and compaction. This potential effect is tested in the worst case scenario which assumes a locallised injection and dissolution area (in terms of maximum subsidence, not in terms of exact shape and position of the bowl)

- 5] Analytical expressions, section 4.5 report [2] are used to build the table 5.3, where the variable ‘H’ is ranging in 0.3 to 50 m. How is the variable ‘H’ considered in the equations (8) to (10)? Is it relevant to consider the case H=0.3 and γ=0.0001, or the case H=50m and γ=1 ? The equation (8) shows that the onset time tc scales with the inverse of the permeability, squared. There is a factor 10 in between 8000 years and 75000 years. Are the numbers in table 5.3 correct ?

Equations 8-10 only consider the timescale for the onset of convection. This is independent of H (as long as H is larger than the penetration depth at onset of convection (delta_c)). However the time to achieve an average salinity of 150000ppm has a linear dependency with H, because the volume of water involved is linear in H (while the velocity of the convective fingers is independent of H). Therefore, in table 5.3, for a fixed Kv/Kh, the time to reach average salinity 150000ppm is linear in H.

With regard to the scaling with Kv/Kh, also a distinction needs to be made between the time for onset of convection, and the time to reach salinity 150000ppm. The time for onset of convection indeed scales with the inverse of permeability squared (eq. 8). However the time to reach salinity 150000ppm is proportional to (H/(convective velocity)), and the convective velocity is proportional to lambda_c/t_c (with lambda_c and t_c as defined in eqs (9) and (8), respectively), which therefore scales with the inverse of permeability (not inverse of permeability squared).

- 6] Long term safety of any storage in a geological structure needs some survey. The most common survey consists in monitoring water levels. Are there shallow geological units in the vicinity that may present an interest for water resources management in the near future?

There are shallow water resources in the region and groundwater levels/composition at the waterinjection locations is being monitored.

In the area the salt/brackish water boundary is generally located at <25m below sealevel (groundlevel in the area 20-30 m above sealevel). The only water resource in close proximity to one of the injection fields is near the Tubbergen Mander field. The water company operating this Mander water resource area is extracting groundwater down to a maximum depth of 55m below surface from an unconfined aquifer.

The location of the waterinjection wells is more than 1 km outside and in a topographically downdip position from the edge of the water inflow and protection area (the edge of this area is defined as the 100 year inflow margin, implying that water will take 100 years to migrate from this edge to the nearest extraction well).

The presence and risk assessment of this water resource was part of the original Environmental Impact Assessment and we have been in contact with the water company for several years. Future plans of the water company focus on areas further away from the injection fields.

The waterinjection locations are equipped with shallow observation holes where groundwater level and composition is being monitored on a regular basis. In addition the injection well integrity is also checked on a regular basis.