Main questions from The Centre de Géosciences- MINES Paris-Tech to NAM about the Twente water injection studies (compiled by Dr. D. Bruel, Hydrologic Systems and Reservoirs group)

- 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 explicitly 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.

  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. Therefor 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.

Schematic map and section through Tubbergen-Mander gasfield and water resource area Mander