Hydraulic connections between Nedmag caverns

Underlying mechanism, chance of new connections and possible consequences

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1. INTRODUCTION

In their 2018 extraction [1)] plan Nedmag describes the pathway to secure their brine production at 315 ktpa $MgCl_2$. In Period 1 of the extraction plan brine will be produced by bleed-off of the big TR-1..8/VE-4 cluster by continuing pressure reduction supported by injection and production from caverns TR-9 and VE-3. Because the readily squeezable brine of the big cluster will potentially deplete within 2 years Nedmag will also drill and develop four new caverns from Well Head Centre 1 situated in Borgercompagnie in order to keep brine production at a sufficient level. With the drilling of VE-5..8 Bischofite containing layers of the ZE-III 1b deposit will be targeted. Initially the new VE caverns will be developed at near lithostatic pressures followed by squeeze operation at sub-lithostatic pressures. It is expected that the new wells VE-5 & 6 and VE-7 & 8 will pairwise hydraulically connect within the duration of Period 1 of the 2018 extraction plan. When 1.7 million tons $MgCl_2$ has been produced injection will be minimized and Period 2 starts.

In Period 2 brine will be solely produced by bleeding off the free brine from the big cluster as well as from wells TR-9, VE-3 and VE-5..8.

In Period 1 with active leaching new hydraulic connections can arise that may impact cavern operation. This study starts off with an historic analysis of existing connections followed by a prediction of chance of new formed connections between existing and new wells and possible effects for cavern operation.

2 HISTORY AND NATURE OF HYDRAULIC CONNECTIONS

2.1 **Connection history**

The status of hydraulic connection is determined by the observation of permanent synchronization of cavern pressure variations of neighboring caverns. The first connection was observed in October 1989 between caverns TR-1 en TR-2 then operated under light sub-lithostatic pressures. The connection was observed during leaching in the upper ZE-III 2b/3b Carnallitic caverns pointing at a possible connection at upper cavern level.

Later on during the sub-lithostatic squeeze operation, that was applied from 1995 onwards, cavern TR-5 connected to the TR-1/2 sub-cluster in November 1996. During testing of the squeeze production concept with cavern TR-4 in 1993 – 1995 an initially pressure difference dependent on-off connection was noticed with TR-6 which became permanent in January 1998. In the further course of production cavern TR-7 became connected to the TR-1/2/5 sub-cluster in July 1999 and a few months later TR-3 connected as well. In later stages cavern TR-8 and the TR-4/6 sub-cluster connected as well to the cluster. The latter two connections most likely by contact with the nearest TR-5 cavern. This resulted in a full connectivity of all TR caverns present at October 2002. An additional connection with cavern VE-4 via cavern TR-7 in November 2009 resulted in full connection of caverns TR-1..8/VE-4 forming the big cluster.

Cavern VE-1, which in contrast to the other caverns is developed in the 2b/3b section only, is still separate.

Although a connection between VE-2 and VE-3 was previously reported [2)], the VE-3 cavern compressibility of 180 m^3/bar as well as its low squeeze potential indicate that suspended cavern VE-2 and cavern VE-3 are still separate.

Currently brine is produced from the big cluster and separate wells TR-9 and VE-3 .

2.2 The nature of hydraulic connection paths

According to production reports a permanent hydraulic connection had established between caverns TR-1 and TR-5 in November 1996 after a period of 7.8 years of Bischofite dissolution. The salt-logs of the drilling holes show that Bischofite is present in a number of discrete layers summing up to columns of 10.6 and 20.6 m respectively for TR-1 and TR-5. For connection a distance of 331 m has to be bridged at an overall upward inclination of 9 degrees from cavern TR-5 towards cavern TR-1. According to mass balance calculations [2)], at the moment of connection some 260,000 m^3 Bischofite had been dissolved from TR-1 and 370,000 m^3 from TR-5.

By elementary geometry it can be calculated that in case of concentric dissolution of Bischofite around the injection point only a ¼ of the total Bischofite column had been contacted by solvent. Calculated radii are 179 m for TR-1 and 152 m for TR-5, giving overall dissolution rates of 23 m/year for TR-1 and 19 m/year for TR-5.

However given the inclination of the dissolving layers an upward distorted dissolution shape is much more likely than a perfect circular shape. An up-dip dissolution shape can be approximated by an ellipse with long axis a and short axis b with the injection point positioned at its focal point. The height of the dissolved body of volume V can then be calculated through: $H = V / (\pi ab)$.

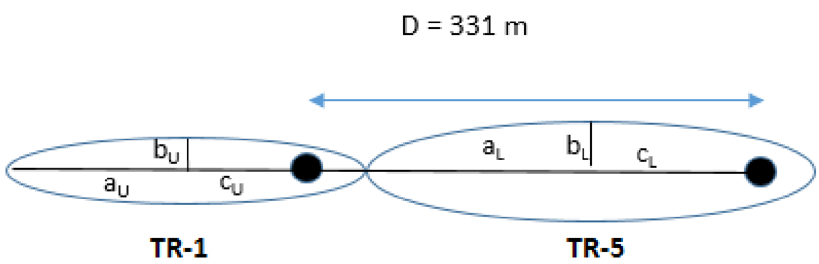

Figure 1: Top view of touching elliptical dissolution shapes of caverns TR-1 and TR-5

In the extreme situation of an up-dip dissolution rate four times faster than the horizontal rate (a/b = 4) , it can be calculated that then a 0.84 fraction of the Bischofite column had been contacted by solvent.

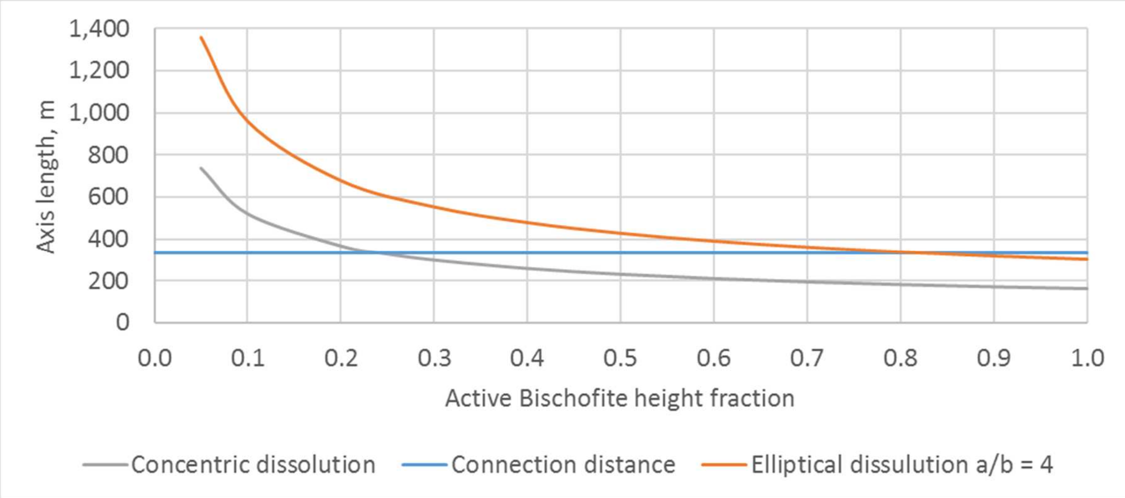

Figure 2: Distance between TR-1 and TR-5 dissolution fronts for concentric and elliptical up-dip dissolution

This results in a distance of 325 m in TR-5 ($a_L + c_L$) giving an upward dissolution rate of 42 m/year, and a downward distance in TR-1 of 6 m ($a_U - c_U$) giving a downward dissolution rate of less than 1 m for TR-1. Please note that in the elliptical approximation the 331 m connection would be tunnel shaped with a width (b) of about 80 m.

The main mass transport mechanism in the more quiescent zones far away from the turbulent injection area is natural convection due to density differences. After turbulent plume mixing of injection water and cavern brine in the cavern a mildly diluted brine migrates upwards through channels towards a Bischofite face which dissolves and forms a saturated brine. The heavier saturated brine gravitates towards the main cavern as depicted in Figure 3.

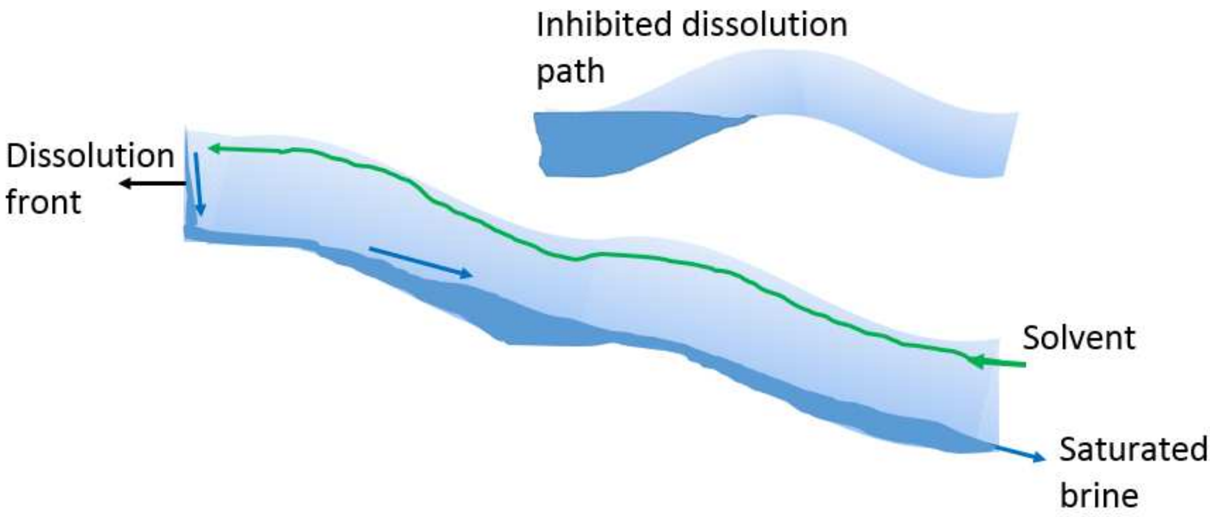

Figure 3: Schematic up-dip dissolution paths

Whether a connection between caverns arises depends on the structure and continuity of the intermediate Bischofite. A connection between a deeper and a more shallow cavern is favored by a continuously rising Bischofite layer. In the case of a downward deformation whereby the Bischofite surface is covered by saturated brine, further up dip dissolution stops.

2.3 History of hydraulic connections between existing caverns

In figure 4 connection history is depicted by arrows following the overall upward direction of the Bischofite layers between injection positions.

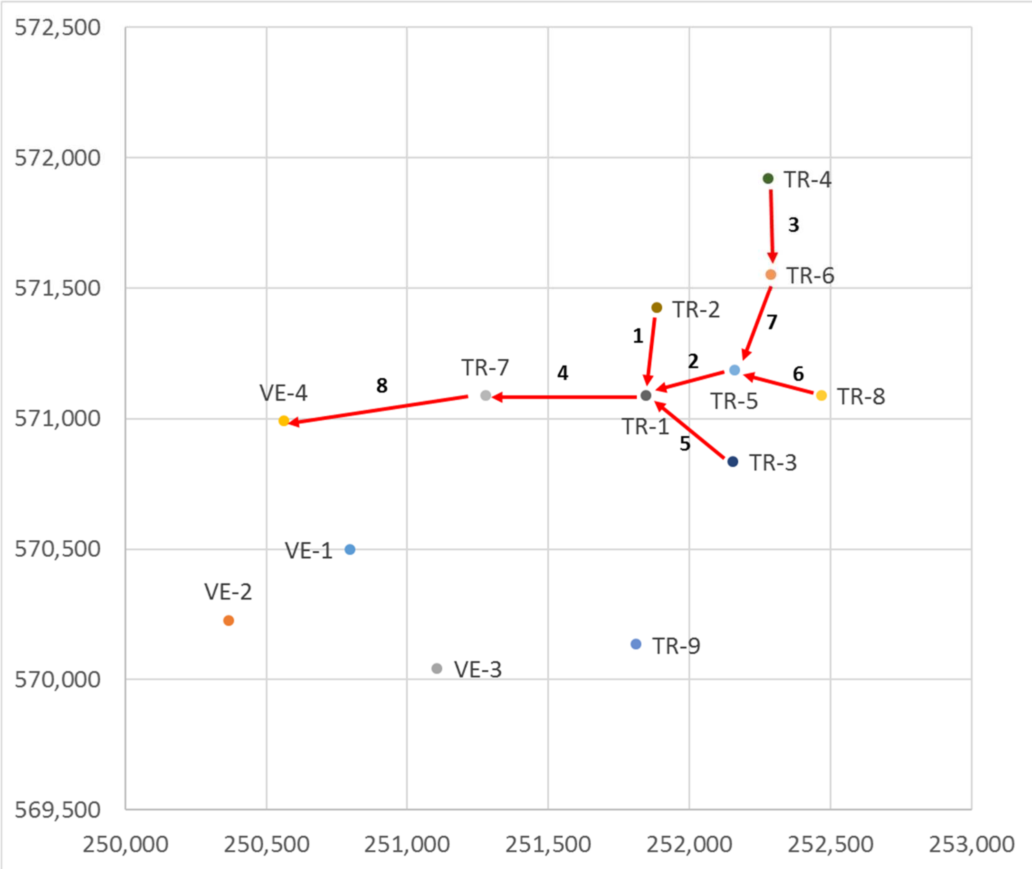

Figure 4: Development of the Nedmag cluster connections from 1984 till 2009

In Table I the distances between injection points across a Bischofite layer, the overall inclination, dissolved volume an well as overall connection rates are given.

Connection	Wells	Distance	Start Bischofite leaching	Moment of connection	Time to connect	Overall 1b inclination	Dissolved Bischofite lower well	Connection rate
		m			year	degrees	m^3	m per year
1	TR-2 -> 1	342	jul-84	okt-89	5.3	10	79,780	65
2	TR-5 -> 1	331	jan-89	nov-96	7.8	9	369,768	42
3	TR-4 -> 6	376	jul-84	jan-98	13.5	12	219,059	28
4	TR-1 -> 7	571	feb-84	jul-99	15.4	6	260,577	37
5	TR-3 -> 1	403	jun-84	nov-99	15.4	9	312,844	26
6	TR-8 -> 5	326	mei-92	mrt-01	8.8	9	613,536	37
7	TR-6 -> 5	398	jun-87	okt-02	15.3	12	284,576	26
8	TR-7 -> VE-4	725	okt-93	sep-09	15.9	4	980,841	46

Table I: Distance, duration of Bischofite dissolution until permanent connection, overall inclination, dissolved volume and overall connection rate

The observed connection rates have an average value of 38 m/year with a maximum of 65 m/year. Opposite to expectation its variation does not show a significant correlation with the Bischofite inclination, dissolved Bischofite volume or injected water volume.

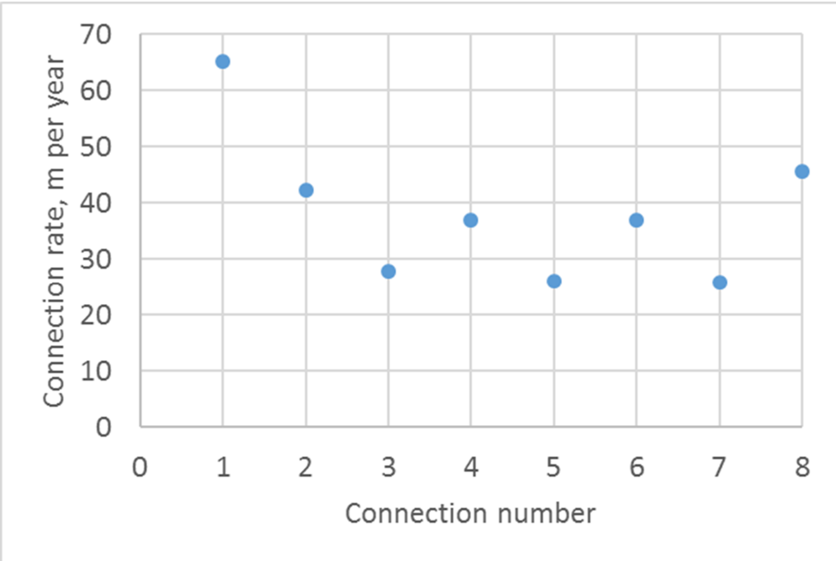

Figure 5: Overall connection rates

2.4 Theoretical Bischofite and Carnallite dissolution rates

The dissolution rate of magnesium salts can be estimated following the Durie and Jessen[3)] assumption that it is determined by the concentration gradient over a thin boundary layer at a vertical cavern wall. The dissolution rate being dependent on the salt type, its concentration in the solvent, cavern temperature and height (H) of the dissolving wall.

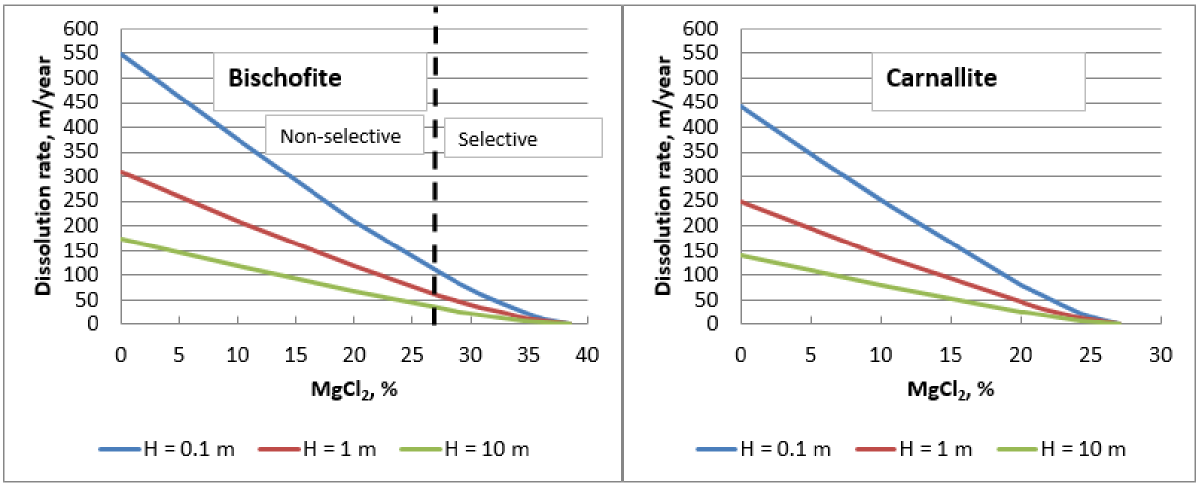

Figure 6: Dissolution rate of Bischofite at 67 °C and Carnallite at 62 °C as a function of cavern concentration at salt face heights of: 0.1, 1 and 10 m.

For a height of 1 m the dissolution rate of Bischofite in pure water at 67 °C is about 300 m/year, whereas Carnallite dissolved at a rate of 250 m/year at 62 °C.

Under the action of turbulent plume mixing injected water will readily mix with saturated cavern brine producing a mildly diluted brine that acts as solvent. From the applicable phase diagram can be inferred that for selective dissolution of Bischofite a minimum solvent concentration of 27 % $MgCl_2$ [1)] is required. At lower $MgCl_2$ concentrations parallel dissolution of Carnallite, Halite and Kieserite occurs giving a less pure Carnallitic brine.

Given a volumetric water injection rate of 20 – 50 m^3/h, which is small compared to a typical 1b cavern volume of 500,000 m^3, efficient turbulent plume mixing [4)] can be expected to reduce local dilution more like to a 33 % $MgCl_2$ concentration.

Height	Dissolution rate, m per year	
m	@ 27 % $MgCl_2$	@ 33 % $MgCl_2$
0.1	106	42
1	60	24
10	34	13

Table II: Theoretical Bischofite dissolution rates at 27 and 33 % $MgCl_2$

The theoretical dissolution rates at 33 % $MgCl_2$ for a Bischofite thickness of 1 m or less compare well to the observed cavern connection rates of 26 – 65 m/year.

This leads to the conclusion that hydraulic connections between ZE-III 1b caverns can arise from dissolution of continuous Bischofite layers thinner than 1 m. The resulting dissolution paths will follow the strongly deformed Bischofite structure forming a tortuous network of channels between connected caverns.

3. POSSIBLE FUTURE CONNECTIONS

3.1 Production scheme extraction plan 2018

In the 2018 extraction plan [1)] a production of 315 ktpa $MgCl_2$ is foreseen. Initially major brine production will come from bleed-off the big TR-1..8/VE-4 cluster. While brine production from the big cluster gradually decreases due to a decreasing free brine content, it must be supplemented by production from existing caverns TR-9 and VE-3.

Assuming they are drilled under the 2013 extraction plan in 2019, after initial cavern development VE-5 en VE-6 will support brine production under near-lithostatic pressure conditions in 2020 when the easy squeezable brine from the big cluster gets depleted. After 2 – 3 years of near-lithostatic conditions their pressures will be reduced to start squeeze production.

In 2020 VE-7 en VE-8 will be drilled that after initial cavern development will support brine production under near-lithostatic pressure conditions in 2021. After approximately 2 – 3 years of near-lithostatic pressure conditions squeeze production will also be started from these caverns.

This scenario is shown in Figure 7, whether this will be executed depends on many factors which can only partly be influenced by Nedmag.

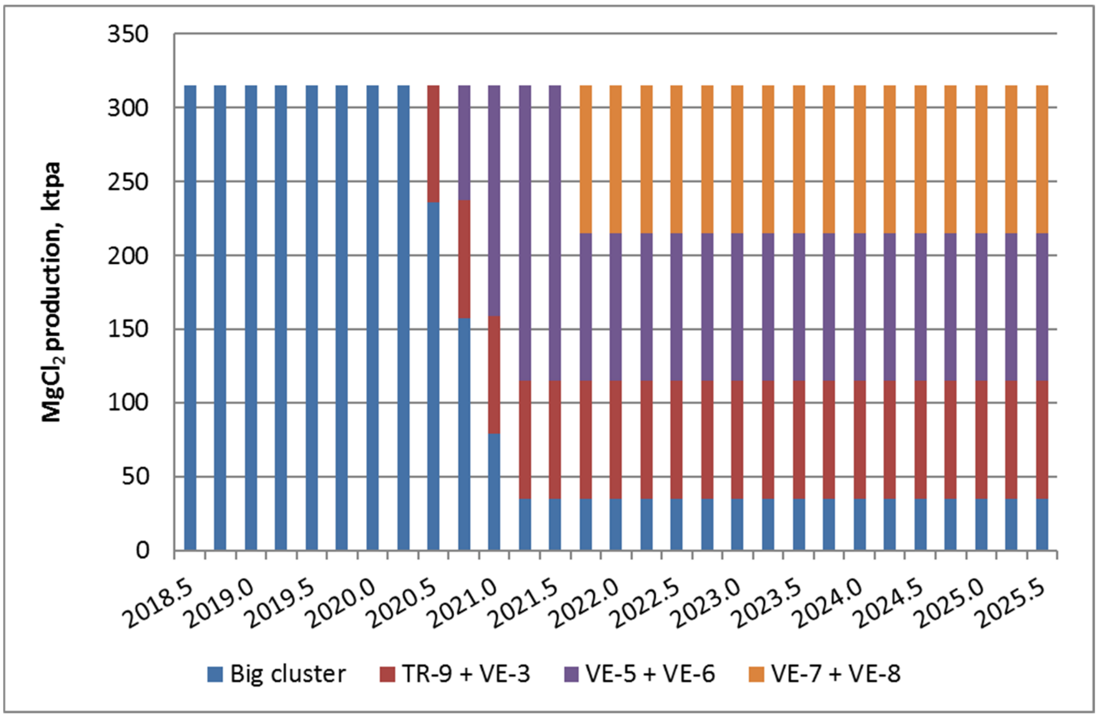

Figure 7: Production scheme for 315 ktpa $MgCl_2$ production according to the 2018 extraction plan

Caverns/cluster	Brine production
	m^3/h
Cluster TR-1..8/VE-4	105 --> 10
TR-9 + VE-3	23
VE-5 + VE-6	28 - 56
VE-7 + VE-8	28 - 56

Table III: Provisional cavern production flows for 315 ktpa $MgCl_2$ production according to the 2018 extraction plan

3.2 Position of existing and new wells caverns and their mutual distances

The position of the new wells VE-5…8 is based on seismic interpretation using 1b layer thickness and low acoustic impedance as a proxy for the presence of areas with thick Bischofite.

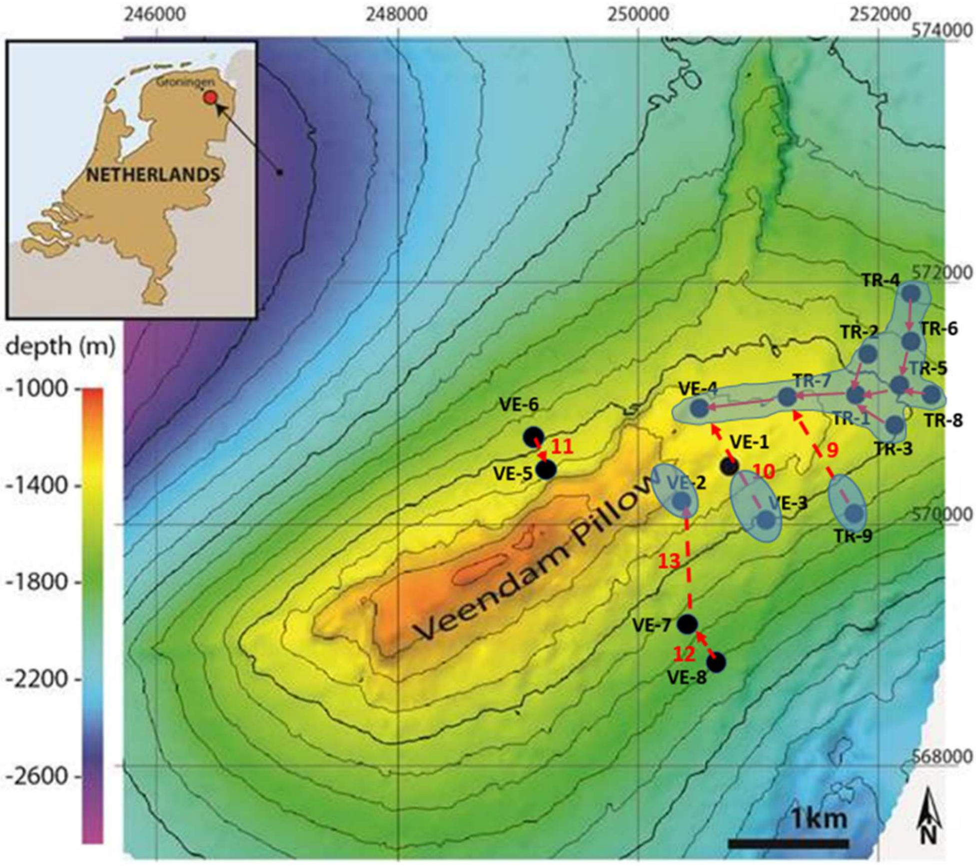

Figure 8: Depth contours of top salt, current cavern and cluster outline in ZE-III 1b, position of existing and new caverns, directions of existing (solid arrows) and potential new (dashed arrows) hydraulic cavern connections

Directions of up-dip Bischofite dissolution paths (9 till 13) which potentially can lead to hydraulic connections between existing separate and new caverns are shown in Figure 8.

Please note that no connection between cavern VE-5 and neighboring caverns is expected since this would involve physically unrealistic downward dissolution.

A potential connection (10) between caverns VE-3 and VE-4 will not result in contact with VE-1 since the latter is developed in the more shallow 2b/3b Carnallitic area only.

3.3 Estimated duration of Bischofite dissolution for new connections

The observed average and maximum connection rates of 38 and 65 m/year respectively allow a rough estimate of the average and minimum time needed to hydraulically connect from start Bischofite leaching.

Potential connection	Wells connected	Distance	Overall 1b inclination	Time till connection	
				@ 38 m per year	@ 65 m per year
		m	degrees	year	year
9	TR-9 -> 7	1,094	13	29	17
10	VE-3 -> 4	1,093	6	28	17
11	VE-6 -> 5	382	23	10	6
12	VE-8 -> 7	359	22	9	6
13	VE-7 -> 2	1,076	19	28	17

Table IV: Estimated time to connect from start Bischofite leaching

The time required for hydraulic connection (9) between existing caverns TR-9 and TR-7 is estimated at between 17 and 29 years. Given the start of Bischofite leaching in 2012 TR-9 the connection will occur the earliest in 2029.

The time required for hydraulic connection (10) between existing caverns VE-3 and VE-4 is estimated at between 17 and 28 years. Given the start of Bischofite leaching in 1992 VE-3 can connect to the big cluster through VE-4 in 2009 what has not yet been observed.

The time needed for pairwise hydraulic connections (11 and 12) between the new caverns VE-5 and VE-6 and VE-7 and VE-8 is estimated at between 6 and 10 years. Contrary to what has been stated in the introduction, this makes it unlikely that the new VE caverns will interconnect during Period 1 of the 2018 extraction plan.

The estimated time for connecting of VE-7 to VE-2 is at 17 and 28 year, which makes it extremely unlikely that these connections will occur in during Period 1 of the 2018 extraction plan.

4. OPERATIONAL EFFECTS OF CAVERN CONNECTIONS

4.1 **Cavern volume development during Period 1 of the 2018 extraction plan**

The expected development of cavern brine volumes during Period 1 of the 2018 extraction plan according to in section 3.1 described scheme is shown in Figure 9.

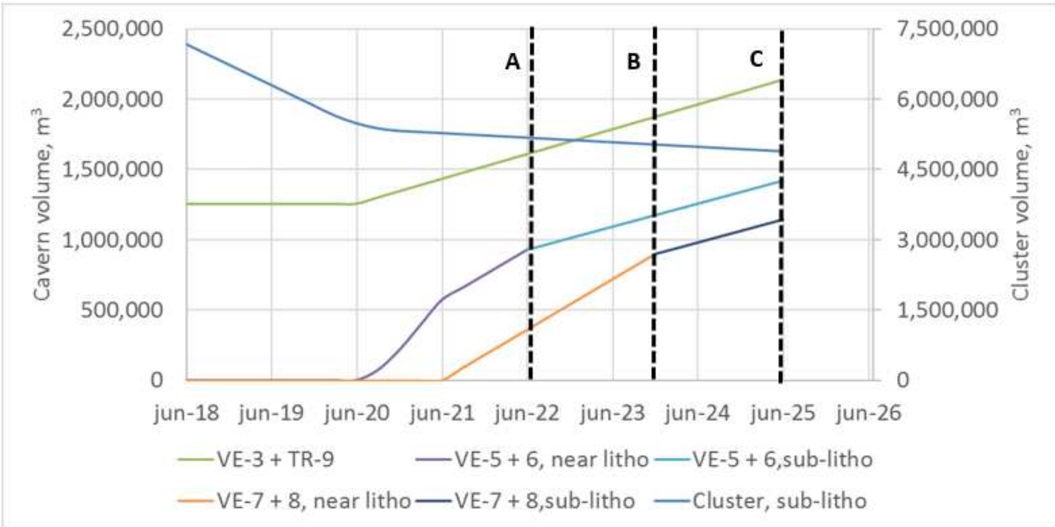

Figure 9: Cavern brine volume development of cluster and separate caverns according to 2018 extraction plan in Period 1

4.2 **Effect cavern connections during Period 1 of the 2018 extraction plan**

Because the detailed structure of Bischofite between existing drilling holes is not known and VE-5..8 have not been drilled, the accuracy of prediction of new cavern connections is limited. In view of this uncertainty an analysis was made of the possible operational effects of new cavern connections at moment indicated in above Figure 9 at:

A. End near-lithostatic production period of VE-5 and VE-6.
B. End near-lithostatic production period of VE-7 and VE-8.
C. End of Period 1 after the production of 1.7 million tons $MgCl_2$, provisionally assumed in 2025 but depending on actual production demand and other factors.

The volumetric exchange between connecting existing caverns was calculated on basis of pressure equalization through a connection point formed at the position of Bischofite layers as derived from drilling cores and logs. For the new VE wells the connection point was assumed at average 1b depth as derived from seismic interpretation. Corresponding cavern pressure effects were evaluated on basis of cavern compressibility's assuming a ratio of 337 m^3/bar per million m^3 cavern volume as derived by analysis of historical data from the big cluster [5].

Possible hydraulic connection (9) between TR-9 and the big cluster via TR-7

Cavern TR-9 is expected to operate at a sub-lithostatic pressure of about 75 bar with respect to casing shoe. While the big cluster bleeds-off and its free brine volume decreases, cluster pressure measured at the TR-7 annulus, will reduce in time.
Due to the higher TR-9 pressure up to 13,000 m^3 brine will flow to the cluster upon hydraulic contact.

Moment	Pressures, before			Brine	Pressures, after		
	TR-9, 1b	Clust. TR-7	TR-7, ann.	exchange	TR-9, 1b	Clust. TR-7	TR-7, ann.
	bar	bar	bar	m^3	bar	bar	bar
A	305	222	63	8,886	246	228	68
B	305	218	58	10,980	242	224	65
C	305	212	53	13,399	239	220	61

Table V: Brine exchange and pressure effects in case of a 1b connection between cavern TR-9 and the TR1..8/VE-4 cluster via cavern TR-7

As a result the cluster pressure increases by a maximum of 8 bar but will remain far below the pressure of 96 bar to reopen the fracture that occurred on 20 April 2018. The cavern pressure of TR-9 will decrease by a maximum of 56 bar and has to be maintained at this level to prevent further brine flow to the cluster. This will lead to a higher TR-9 squeeze rate but will be compensated by the reduced cluster squeeze rate.

In case of a connection directly at restart of injection in cavern TR-9 at an expected cluster pressure of 67 bar the maximum pressure increase to 72 bar is well below the cluster fracture reopening pressure of 96 bar.

Possible hydraulic connection (10) between VE-3 and the big cluster via VE-4

Cavern VE-3 will operate at its regular sub-lithostatic pressure of 26 bar with respect to casing shoe. Upon contact of cavern VE-3 with the big cluster through cavern VE-4, depending on the moment up to 33,000 m^3 brine will flow from VE-3 to the big cluster due to the relative high initial pressure difference.

Moment	Pressures, before			Brine	Pressures, after		
	VE-3, 1b	Clust. VE-4	TR-7, ann.	exchange	VE-3, 1b	Clust. VE-4	TR-7, ann.
	bar	bar	bar	m^3	bar	bar	bar
A	314	224	63	23,842	250	238	76
B	314	219	58	28,408	249	236	75
C	314	214	53	33,374	247	234	73

Table VI: Volumetric exchange and pressure effects in case of a 1b connection between cavern VE-3 and the TR1..8/VE-4 cluster via cavern VE-4

As a result the cluster pressure increases by a maximum of 20 bar to 73 bar which is far below the reopening pressure of 96 bar. The VE-3 cavern pressure will reduce by a maximum of 56 bar which theoretically will its squeeze rate, but the increase will be moderate given its very low practically observed squeeze potential. An increased VE-3 squeeze rate will be compensated by a cluster squeeze rate reduction.

In case of a connection directly at restart of injection in cavern VE-3 at an expected cluster pressure of 67 bar the maximum pressure increase to 80 bar is well below the cluster fracture reopening pressure of 96 bar.

Possible hydraulic connection (11) between VE-6 and VE-5
New caverns VE-6 and -5 will initially operate at a sub-lithostatic pressure of 20 bar with respect to casing shoe for a period of 2 – 3 years. In the unlikely case of a premature connection cavern pressure up to 800 m^3 brine will flow from VE-6 to VE-5. As a result the VE-5 cavern pressure will increase by 6 bar at the expense of a 5 bar pressure reduction at VE-6. To be below the minimum limit of 20 bar sub-lithostatic at cavern VE-5, the sub-cluster pressure has to be reduced by 5 bar which will also prevent further brine exchange allowing further cavern development towards desired cavern sizes for future sub-lithostatic squeeze production.

Moment	Pressures, before		Brine	Pressures, after	
	VE-6, 1b	VE-5, 1b	exchange	VE-6, 1b	VE-5, 1b
	bar	bar	m^3	bar	bar
A	390	357	808	385	363
B	325	292	1,023	320	298
C	325	292	1,238	320	298

Table VII: Volumetric exchange and pressure effects in case of a 1b connection between caverns VE-6 and VE-5

In case of a connection during squeeze production a similar 5 bar pressure change will arise and maximum of 1,200 m^3 is exchanged. As a result cavern VE-6 pressure reduces by 5 bar which may increase its squeeze rate that will be automatically compensated by a squeeze rate reduction from cavern VE-5.

Possible hydraulic connection (12) between VE-8 and VE-7

New caverns VE-8 and -7 will initially operate at a sub-lithostatic pressure of 20 bar with respect to casing shoe for 2 – 3 years. In the unlikely case of a premature connection, up to 1,000 m^3 brine will flow from VE-8 to VE-7. As a result the VE-7 cavern pressure will increase by 7 bar at the expense of the same pressure reduction at cavern VE-8. In case of connection the VE-8 cavern pressure has to be reduced by 7 bar in order retain a minimum sub-lithostatic casing shoe pressure of 20 bar at cavern VE-7 as well as to limit brine exchange during the near lithostatic development.

Moment	Pressures, before		Brine	Pressures, after	
	VE-8, 1b	VE-7, 1b	exchange	VE-8, 1b	VE-7, 1b
	bar	bar	m^3	bar	bar
A	417	384	391	410	391
B	417	384	977	410	391
C	352	319	1,245	345	326

Table VIII: Volumetric exchange and pressure effects in case of a 1b connection between caverns VE-8 and VE-7

In case of a connection during sub-lithostatic production an identical 7 bar pressure change will arise and 1,200 m^3 brine will be exchanged. As a result the VE-8 cavern pressure decreases increasing its squeeze rate that will be automatically compensate by a squeeze rate reduction from cavern VE-7.

Possible hydraulic connection (13) between VE-7 and VE-2

As mentioned above there is no proof for a hydraulic connection between suspended caverns VE-2 and VE-3. Unfortunately since its casing is cement plugged the actual VE-2 cavern pressure in unknown. In this analysis lithostatic pressure is assumed. Due to the vertical height difference of 287 m between the 1b Bischofite layers there is very little pressure difference upon connection during the period that cavern VE-7 operates at near-lithostatic conditions.

Moment	Pressures, before		Brine	Pressures, after	
	VE-7, 1b	VE-2, 1b	exchange	VE-7, 1b	VE-2, 1b
	bar	bar	m^3	bar	bar
A	384	345	16	384	346
B	384	345	26	384	346
C	319	345	4,763	344	305

Table IX: Volumetric exchange and pressure effects in case of a 1b connection between VE-7 and VE-2

In case of a connection during squeeze operation of cavern VE-7 pressure some 4,800 m^3 brine will flow in from VE-2 resulting in a pressure increase of 25 bar at cavern VE-7. As a result cavern VE-7 squeeze rate will reduce but can be corrected by increasing its production, as a side-effect promoting bleed-off of high quality brine from cavern VE-2.

4.3 **Cavern connections during the Period 2 of the 2018 extraction plan**

In period 2 of the 2018 extraction plan all water injection is stopped with the exception of occasional flushing for tubing clearance. Since the volume of injected water will be minute dissolution will practically hold which makes it unlikely that new hydraulic cavern connections arise.

5. CONCLUSIONS

Analysis of the history of hydraulic cavern connections shows that observed connection rates are similar to dissolution rates of Bischofite with the mass transfer rate being limited by diffusion through a boundary layer at the dissolving Bischofite interface.

Cavern connections arise from up-dip selective dissolution of Bischofite, present in continuous veins with a thickness up to 1 m, in mildly diluted cavern brine finally forming a tortuous network.

Given an average dissolution rate of 38 m/year with a maximum of 65 m/year it is unlikely that TR-9 will connect to the TR-1..8/VE-4 cluster during Period 1 of the extraction plan. However a connection between VE-3 and the TR-1..8/VE-4 cluster cannot be fully excluded. Should such a connection occur after restart of injection in VE-3 the cluster pressure increase will remain far below the cluster fracture reopening pressure of 96 bar.

It is unlikely that the new caverns VE-5 & 6 and VE-7 & 8 at their planned positions pairwise connect during Period 1. Should they possibly connect than their pressures will have to be reduced by 5 bar.

A connection between cavern VE-5 and the TR-1..8/VE-4 cluster is not possible since this will involve physically unrealistic down-dip dissolution.

Given the large distance between caverns VE-7 and VE-2 is not likely that they will connect during Period 1. Their possible connection will increase the VE-7 pressure by some 25 bar which can corrected by decreasing the VE-7 injection/production balance.

Given the negligible water injection during the cluster and caverns bleed-off in Period 2 the risk of additional cavern connections in this phase is minimal.

--REFERENCES---

1. Nedmag, Winningsplan 2018
2. J. Visser. Mass balance study of the Nedmag caverns. Modelling of magnesium salt dissolution and calculated squeeze volume, version 2, 24 February 2017
3. R.W. Durie and F.W. Jessen. Mechanism of the dissolution of salt in the formation of underground salt cavities. Society of Petroleum engineers Journal, June 1964, p. 183 – 190.
4. W.R Velema, H. Bruining, J. Bullen and J. Visser. Natural Convection Effects on Magnesium Solution Mining. 12th European Conference on the Mathematics of Oil Recovery, Oxford UK, 6-9 September 2010.
5. P. Fokker. Evaluatie oorzaak pekellekkage in Nedmag pekelcluster 20 april 2018, update juli. Well Engineering Partners, 18 Juli 2018, p. 5.