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[redacted]

[redacted]ysis of worldwide salt cavern storage

and its implications for the Dutch cavern storage industry

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Title page: "Salt houses" from De Marssteden diesel storage in Enschede, the Netherlands, photograph by Wim Eising.

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Abstract

The safety of cavern storage is important, to prevent incidents and to have society's support of this storage solution. Storage in the Netherlands is compared to other country's storage by means of an inventarisation of cavern storage, which shows among other things, how many incidents of different types have occurred. It helps understand in what kind of circumstances safety of cavern storage cannot be guaranteed. There can be a correlation between incidents and cavern depth, as well as different susceptibility to incidents depending on the nature of the salt body, however more research needs to be conducted. Bow-tie analysis of the incidents give us guidelines on what kind of prevention or mitigating measures need to be taken. To prevent incidents preventative measures like cavern design, pressure management and well design are critical. Another conclusion is that monitoring of cavern parameters is important, but ultimately void without subsequent actions. Storage in the Netherlands proves to be well-regulated and prevention and mitigating measures are part of storage plans.

Public summary

Storage in salt caverns has many benefits, for example, storing products underground safes space on the surface and products stored hundreds of meters underground are less susceptible to outside impacts like fires. However, storage in salt caverns comes with its challenges. This study aims to assess the risks associated with storage of liquids and gasses in salt caverns.

Therefore, the research question this study tries to answer is the following: *"What can we learn in the Netherlands from the published examples of storage caverns, for liquids and gases, in other countries?"*.

To answer this research question, an inventarisation of worldwide storage caverns was conducted and a list of all the published incidents was made. The incidents are classified in 5 different groups, to better understand which causes affect which kind of incident.

The inventarisation shows that there have been more incidents in domal salt as opposed to bedded salts, suggesting bedded salts are better suited for cavern storage. They also showed that caverns which are situated relatively shallow (up to 500m deep) and relatively deep (deeper than 1500m) have had more incidents, implying cavern storage is safer in depth ranges between 500 and 1500m at least. These assumptions are based on a low amount of incidents (87) and thus require more research to be confirmed.

To be able to prevent incidents and increase the safety of salt cavern storage, preventative measures are important. This study shows that cavern design, pressure management and well design are integral to the safety of a cavern. Another essential preventive measure is monitoring, this needs to be complimented with an action, to be able to respond to an irregularity in the data adequately and in a timely fashion.

Regulation in the Netherlands prevents effects of incidents from causing large impact, because many barriers are in place. It is recommended in this study for the Dutch industry to prevent incidents from occurring by having cavern and well design be a vital part in the building and design stage of a storage cavern.

Publiekssamenvatting

Opslag in zoutcavernes heeft veel voordelen, het scheelt ruimte aan het oppervlak (sommige cavernes zijn groter dan een voetbalstadion) en omdat de producten diep ondergronds opgeslagen worden zijn ze minder vatbaar voor impact van buitenaf, zoals brand. Opslag in zoutcavernes brengt echter wel uitdagingen met zich mee. Het doel van dit onderzoek is de risico's van opslag van vloeistoffen en gassen in zoutcavernes in kaart te brengen.

Daarom is de volgende onderzoeksvraag opgesteld: "Wat kunnen we in Nederland leren van de gepubliceerde voorbeelden van opslagcavernes, voor vloeistoffen en gassen, in andere landen?"

Om deze onderzoeksvraag te beantwoorden is een inventarisatie van wereldwijde opslagcavernes uitgevoerd en is een lijst gemaakt van alle gepubliceerde incidenten. De incidenten zijn gegroepeerd in 5 verschillende groepen, om beter te begrijpen welke oorzaken van invloed zijn op welk soort incident.

Uit de inventarisatie blijkt dat er meer incidenten zijn geweest in cavernes in zoutdiapieren dan in cavernes in gelaagd zout, dit suggereert dat gelaagd zout beter geschikt is voor opslagcavernes. Het toonde ook aan dat cavernes die relatief ondiep (tot 500 m diep) en relatief diep (dieper dan 1500 m) liggen meer incidenten hebben gehad, wat suggereert dat caverneopslag veiliger is in dieptes tussen 500 en 1500 m. Deze veronderstellingen zijn gebaseerd op een laag aantal incidenten (87) en vereisen meer onderzoek om te worden bevestigd.

Om incidenten te kunnen voorkomen en de veiligheid van opslag in zoutcavernes te vergroten zijn preventieve maatregelen belangrijk. Deze studie toont aan dat caverneontwerp, drukbeheer en putontwerp van groot belang zijn voor de veiligheid van een caverne. Een andere preventieve maatregel die essentieel is, is monitoring, dit moet worden aangevuld met een actie om adequaat en tijdig te kunnen reageren op een onregelmatigheid in de gegevens.

Regelgeving in Nederland voorkomt dat effecten van incidenten grote impact hebben, omdat er veel barrières zijn. In dit onderzoek wordt de Nederlandse industrie aanbevolen om incidenten te voorkomen door caverne en putontwerp een essentieel onderdeel te laten zijn van de bouw- en ontwerpfase van een opslagcaverne.

1. Introduction

Salt caverns have potential for large scale storage (products like natural gas, petroleum products and hydrogen) because salt formations are very impermeable for fluids and gases and both fires and explosions are virtually impossible underground. The Netherlands currently has three storage sites in the subsurface, storing diesel, natural gas and nitrogen gas. Several other countries make use of cavern storage, starting in the 1950s. Since then, several incidents have taken place, both small-scale as large-scale. The storage of products in salt caverns comes with challenges, both in the technical feasibilities as well as risks during leaching, operation and subsequent abandonment.

The goal of this thesis is to provide the Dutch State Supervision of Mines (Staatstoezicht op de Mijnen, SodM) guidance and more general knowledge on all the risks associated with salt cavern storage in general, as well as focused on the specific challenges most relevant for the Dutch (sub)surface. To get a better understanding of the risks and challenges associated with cavern storage the following research question is posed.

"What can we learn in the Netherlands from the published examples of storage caverns, for liquids and gases, in other countries?"

The research question states the focus lies on liquids and gases, as such, storage of solids are not in scope. This is mostly because there are no plans as of yet to store these type of products in the Netherlands. To be able to adequately answer the research question, it is divided in the following three parts. These focus on the different aspects of the research question.

1. To create an overview of the salt storage caverns worldwide
2. To create an overview of incidents, risks, learnings and research associated with these salt cavern storages
3. Draw some lessons that the Netherlands can learn from international cavern storage

The first part aims to get a better overview of all the salt cavern storage sites in the world, to lay the groundwork to analyse the different incidents and risks. In this inventarisation results chapter, an overview of all the sites is given, and for more detailed information on different storage sites, Appendix 1: "Inventarisation of published storage caverns" has a list of most of storage sites found across the globe. This provides SodM a quick summary of the storage site with relevant references should more details be required. The second part consists of an overview of the (published) incidents, as well as relevant, published risk assessments, associated with these caverns. This information is synthesised to a risk analysis complimented by bow-tie diagrams for clarity between the different top events, causes and effects. It is followed by risk management in which preventive and mitigating control measures are discussed. The final part consists of showing trends of the research results of several papers, lessons learned and the relevance to the Dutch subsurface. It gives recommendations for minimizing risks and future research and touches on the main concerns resulting from this literature review.

If the reader wants to gain a better understanding of both salt and its potential for cavern storage the following reports/papers provide a solid basis (Bérest & Brouard, 2003; Brouard, 2019; Rowan et al. 2019). Previous authors have given summaries on worldwide cavern storage (Horváth et al. 2018) as well as research papers focussing on incidents (Bérest et al. 2019; Réveillère et al. 2017; Yang et al. 2013).

2. Geological background

This chapter briefly summarises the essential geological and design aspects of salt cavern storage to support the concepts that follow (regarding the storage of products in salt caverns and its difficulties).

The formation of evaporites occurs in marine or continental environments, in sedimentary basins where the rate of evaporation is higher than the inflow of water (Horváth et al. 2018). For this situation to arise, it is necessary that the environment is at least partially isolated from open sea. Salt precipitates due to oversaturation and evaporation of the water, and over time, an evaporite sequence forms. Only one of those salts is halite. The chemical formula of halite, which is also known as rock salt, is NaCl, and it is highly soluble. Halite precipitates out when the concentration of the sea water is increased eight to ten-fold (Horváth et al. 2018). This mineral is the most common occurring salt that is mined during solution mining. Because rock salt is impermeable, ductile, flows easily under high pressure and temperature, and does not contain many fractures, it is interesting for underground storage. However, it is a common misconception that salt structures are composed of only homogeneous halite. Other salts that are important for brine production are the salts carnallite ($KCl.MgCl_2{\cdot}6(H_2O)$), Sylvite (KCl) and bischofite ($MgCl_2{\cdot}6H_2O$), these have lower viscosities than halite, and thus, flow more easily (Rowan et al. 2019). Another salt that typically occurs in an evaporite sequence is anhydrite ($CaSO_4$), which has a much higher viscosity than halite (the actual viscosity contrast between halite and anhydrite and the rheological behaviour of anhydrite is highly debated, as shown by Burchardt et al. (2012) where Zulauf et al. (2009) argues that the viscosity of anhydrite is 27 times higher than halite and Chemia et al. (2009) argues that the viscosity of anhydrite is 100 to 10000 times higher than halite) and higher density (2200 kg/m^3 for halite and 2900 kg/m^3 for anhydrite Burchardt et al. (2010)). Anhydrite deforms in a brittle manner when submitted to high pressure and temperature, but can deform in a ductile manner as well. Anhydrite is insoluble in water. Evaporite sequences can also contain layers that are non-evaporitic, like carbonates, clays and sandstones; these interbeds are generally stronger than rock salt Rowan et al. (2019). In most cases, a salt body contains evaporites with interbeds and other heterogeneities.

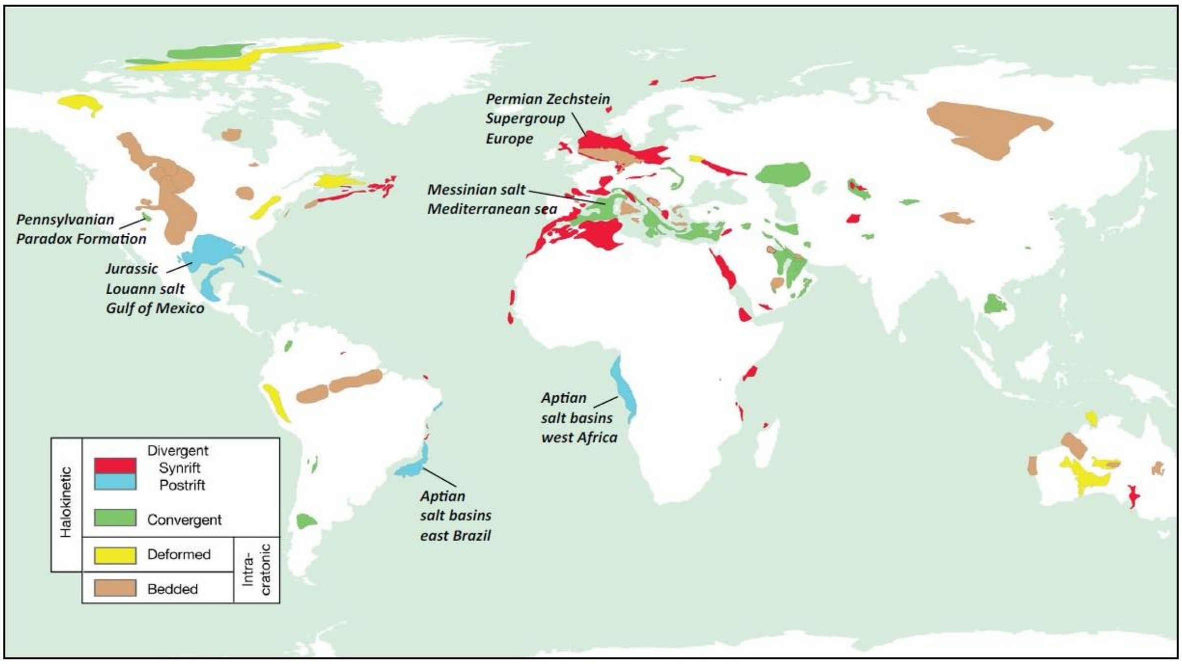

Figure 1 Major salt basins across the world, colours showing the tectonic setting. Modified by Clara Rodríguez, from Warren (2010).

Figure 1 from Warren (2010), shows most salt basins in the world, including the tectonic setting of the area. Salt basins are widespread in Europe and North America, which is where most storage caverns are located. The Netherlands has two main salt depositions of Permian and Triassic age, the depositions are part of the Central European Basin Horváth et al. (2018). The Upper Permian Zechstein formation is the most widespread as can be seen in figure 2 from Juez-Larré et al. (2019), and its thickest parts are located in the northern regions of the Netherlands. The Zechstein formation in the Netherlands consists of several evaporitic cycles, Z1-Z5. The Werra formation (Z1) contains 300m of rock salts, the Z2 (Stassfurt formation) salt is over 600m thick in the northern region of the Netherlands, and forms most diapiric salt structures Horváth et al. (2018). The Z3 Leine has a thickness of 300-400m, while the Z4 Aller has a thickness of about 150m, and lastly, the Z5 Ohre formation has halites up to a thickness of 15m Horváth et al. (2018). Most brine production and storage caverns are located in Z2 and Z3. The bedded salts of the Röt formation are being mined in Twente (province of Overijssel), these salts are deposits of Lower Triassic age. Another salt deposit worth noting is present locally the Rotliegend formation which is of Lower Permian age, it is located in the offshore regions of the Netherlands. Some other minor, local salt bearing formations which occur underground in the Netherlands are the Muschelkalk formation (Middle Triassic age), the Keuper formation (Upper Triassic age) and the Malm formation (Jurassic age) Horváth et al. (2018).

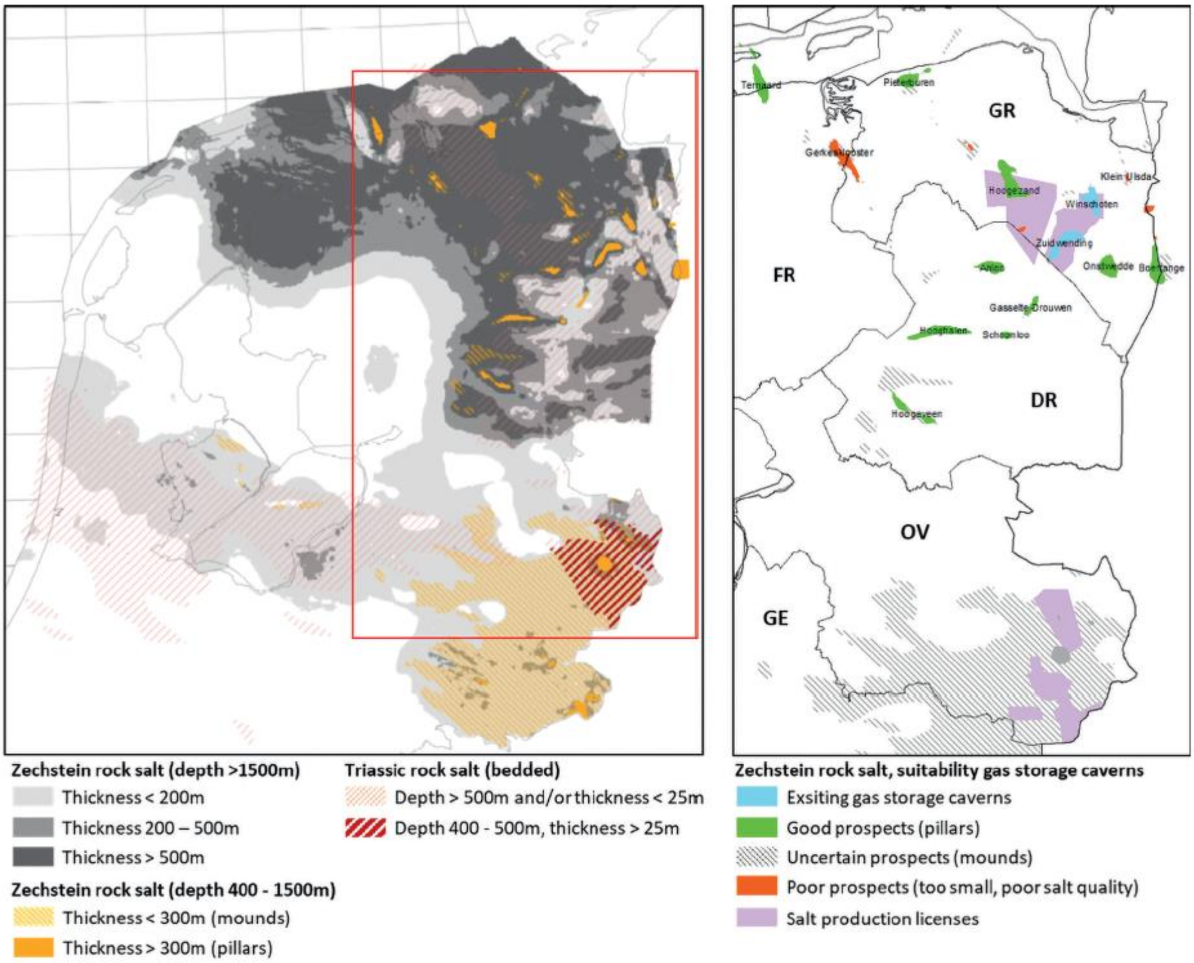

Figure 2 Left: Distribution of the Zechstein and Triassic rock salt. Right: Underground storage and salt production areas, from Juez-Larré et al. (2019).

Salt bodies underground have different shapes, evaporites are generally deposited horizontally. There are thick-bedded salt beds or thin-bedded salt beds, where the former is usually more suitable for cavern storage as interlayers of other lithologies can have negative impacts on the cavern. These salt beds can be thick- or thin-bedded due to local differences in deposition, sediment input and fresh water supply. Halotectonic processes can alter these bedded salts to form salt breccias (general tectonics in mountain belts can also form salt breccias). This process can also form salt domes, which are used extensively for brine production and cavern storage. Figure 3 from Gillhaus et al. (2006), shows the classification of the different salt bodies. The shapes of these salt bodies can get quite complex, as well as their internal structure; a salt pillow (not shown) is an in-between stage of a bedded salt and a salt dome. Furthermore, a salt dome can stay connected to the layer from which it originated or disconnect completely. The figure also shows the area affected by the stress field of the cavern depending on the nature of the salt body. More about salt body shapes can be found in Hudec & Jackson (2007).

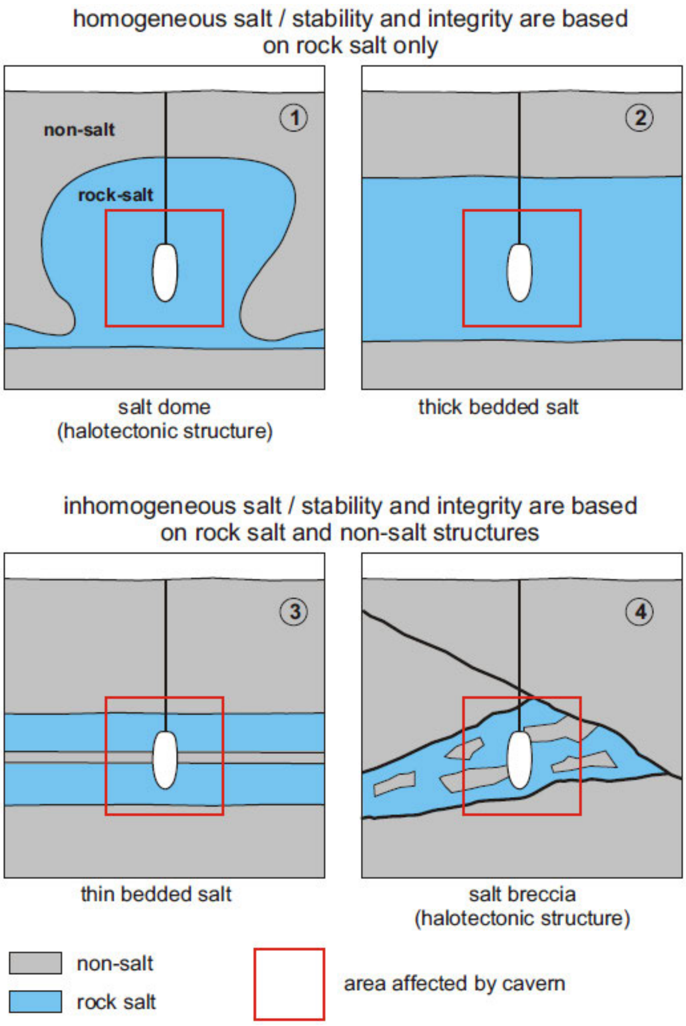

Figure 3 Basic classification of the different salt bodies, from Gillhaus et al. (2006).

A salt dome can form due to pressure differences underground (either due to tectonics or sediment loading); the salt wants to move from high-pressure areas to lower pressure areas and this can be accomplished by differential loading. In areas of active tectonics, a salt diapir can form in a regional extensional setting. In this setting, diapirs can rise up graben axes, filling in the spaces which are created by the extension. This phenomenon is called reactive diapirism (figure 4b) from Hudec & Jackson (2007), because when the period of extension stops, the diapir rise also stops. Active diapirism is an effect of gravitational forces acting on the salt by way of the overburden pressurizing the salt (figure 4c). Another form of active diapirism occurs during regional shortening. Commonly, this type of diapirism occurs with precursor salt diapirs, but it is also possible that a salt diapir forms with no precursor structures. When there are no precursor structures, the salt acts as a detachment during compression, where salt rises into the cores of anticlines. Pre-existing diapirs can be rejuvenated by shortening as they are mechanically weak. Passive salt domes (figure 4d) can form when the salt breaches the overburden (for example, after active diapirism), after which sediments accumulate around the diapir as it grows. If the diapir grows faster than sedimentation can keep up with, and salt reaches the surface, an allochthonous salt sheet (figure 4e) might form. These namakiers[1] or salt glaciers can be found exposed on the surface in the Zagros fold belt in Iran Mohr et al. (2007).

[1] More information and pictures on salt glaciers of the Zagros fold belt can be found at: http://geology.com/stories/13/salt-glacier/

Rock salt and other salts can be extracted for economic reasons and to not be dependable on other countries. The extracted salt is used for the chemical industry, feeding humans and animals, and road safety during the winter (among other uses). The salt is leached by pumping undersaturated water through a well inside the salt formation. This process dissolves the salt, and brine pushed back up due to the pressure inside the cavern. This brine is then evaporated, leaving the salts ready to be harvested. As material is removed from the subsurface, over time this process creates a cavern filled with brine under pressure. These caverns can be used for storage. Most of the time, brine production caverns are not suited for storage. Storage caverns are designed and leached more precisely than brine production caverns. Their shape is more important and they usually have a lower volume, as well as have a different well design. After leaching, the cavern is ready for the storage of products like gaseous or liquid hydrocarbons, hydrogen and nitrogen. Some countries also store solid materials (like nuclear waste) in salt caverns; this is not the case in the Netherlands. As such, the focus of this study is not on the storage of solids. Another type of storage is hard rock cavern storage, which is storage inside carved out halls underground. An example of this is Marathon cavern no. 2 in Catlettsburg, Kentucky, where liquid butane is stored[2] since 2012. The storage in these type of caverns is not in scope. Information about CAES (compressed air energy storage) in hard rock caverns can be found in "*Experimental and Numerical Investigations of Small-Scale Lined Rock Cavern at Shallow Depth for Compressed Air Energy Storage*" by Jiang et al. (2020), it also contains more information about hard rock cavern storage.

Salt caverns are widely used for storage across the world. One of their major advantages is their size. Volumes of salt caverns can reach up to several million m^3, space that is not needed at the surface to build storage tanks. These caverns are protected from external forces (accidents or intentional sabotage at the surface), as they are at least a couple of hundred meters below the surface.

After these caverns have been used for storage, they are abandoned in the same way as a brine cavern. The caverns are filled with brine, and the borehole is cemented. Abandoning caverns comes with challenges; for example, where do you get enough brine to fill up the cavern, is it desirable to fill a cavern with brine or with fresh water, can you shut in a well after filling it with relatively cold brine, does the filling of the cavern with brine or fresh water result in more salt dissolution? There are still some

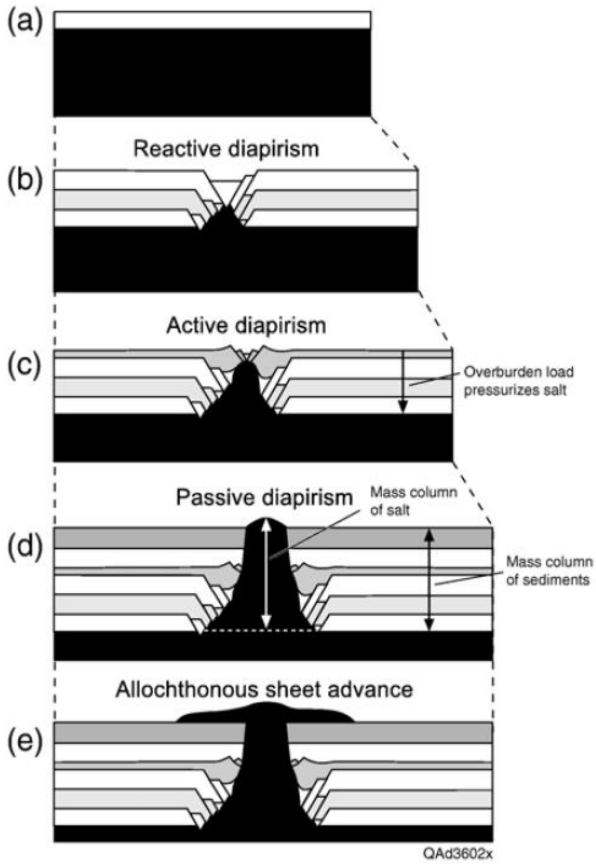

Figure 4 Schematic of different kinds of diapirism present in an extensional regime. A: Original state of the salt. B: Reactive diapirism, salt rises up due to the space created by extension. C: Active diapirism, overburden pressurizes salt and the salt is forced upwards. D: Diapir has breached the overburden, and becomes a passive diapir. E: Passive diapir rises faster than sedimentation can keep up with, and thus overflows onto the sediments, forming a salt sheet. Taken from Hudec & Jackson (2007).

[2] More on the hard rock cavern storage in Catlettsburg, Kentucky can be found here: https://www.wsp.com/en-US/projects/marathon-cavern-no-2

unknowns about cavern abandoning. Another concern after plugging a cavern is pressure increase of the brine inside the cavern, up to and above geostatic pressure, which can lead to fractures and subsequent negative effects, see Brouard, (2019). This can be avoided by letting the brine inside the cavern reach thermal equilibrium, allowing for the cavern to reach equilibrium pressure. If the reader wants to know more about cavern abandonment and its risks, "*A generic model for predicting long-term behaviour of storage salt caverns after their abandonment as an aid to risk assessment*" from Thoraval et al. (2015) and references therein is a good place to start.

There are several salt cavern storage facilities in the Netherlands. In Marssteden, Enschede, lie 2 caverns for diesel storage in the bedded salts of the Röt formation. In Heiligerlee (Oldambt municipality), 1 cavern for the storage of nitrogen is located in the Winschoten salt dome (Zechstein). This nitrogen is mixed in with imported high-caloric gas to form low-caloric gas, which is suitable for Dutch households. Finally, in Zuidwending, Veendam, natural gas is stored in 6 caverns. They were leached in the Zuidwending salt dome (Zechstein) and are able to store a working volume of 300 million m^3 of gas. There are plans to store both CAES (compressed air energy storage) and hydrogen inside caverns in this dome.

The following chapter will look more in depth at storage caverns across the world. For a more detailed view of most storage caverns, the appendix contains a list of storage cavern locations which is alphabetized per country.

3. Results: an inventarisation

3.1. Cavern field overview

In the search for storage caverns worldwide, a great quantity of academic works (and websites like the SMRI, the Solution Mining Research Institute) was consulted. Some papers gave relatively complete overviews of cavern storage worldwide Horváth et al. (2018), incidents worldwide Bérest et al. (2019); Evans (2008); Yang et al. (2013) while others gave more concrete information on specific sites/incidents For example the storage caverns in the Danish Tostrup salt dome, a quite detailed history can be found within the following papers, Jacobsen & Nielsen (1992); Kepplinger (2016); Rokahr et al. (2007). On the other hand, lots of information on specific sites was hard to find, or in some cases, confidential. As such, this inventarisation may not contain all storage caverns in the world, but the most that can be found in a readily available literature.

Below, in figure 5, the number of storage cavern fields is shown. These are fields, where one or more operators have one or several storage caverns. The total number of fields worldwide is 1678, which is a rough estimate, as it possibly contains inactive fields and new fields are under construction all the time. All the fields found were located in the Northern hemisphere. As the top 5 list shows (in table 1), the United States of America has the most cavern fields. Over half of these fields are located in the states of Kansas and Texas. See the appendix to find detailed information on the storage cavern fields found as a part of this study.

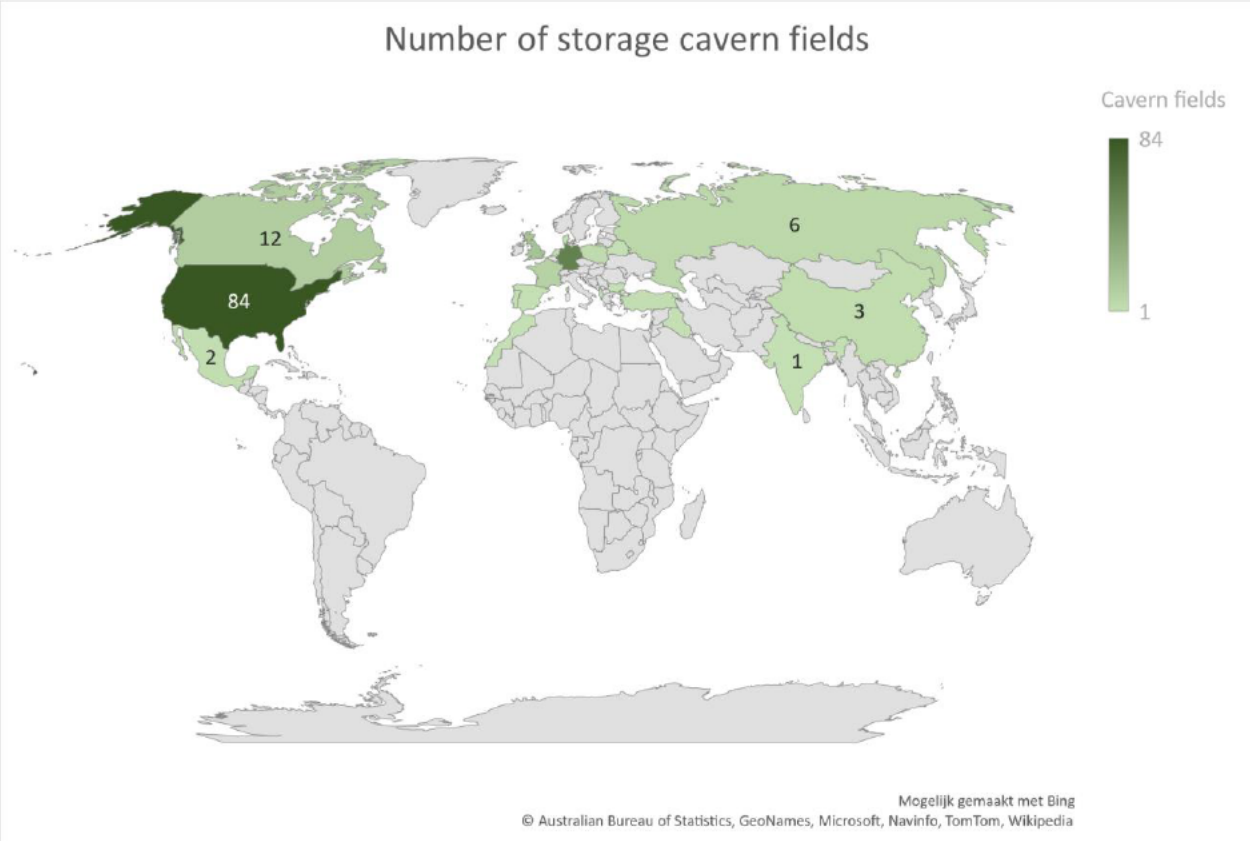

Figure 5 Number of storage cavern fields across the world.

Number of cavern fields per country (top 5 + the Netherlands)	
United States of America	84
Germany	58
United Kingdom	18
Canada	12
France	9
The Netherlands (8th)	3
Total number of fields	**211**

Table 1 Number of cavern fields per country.

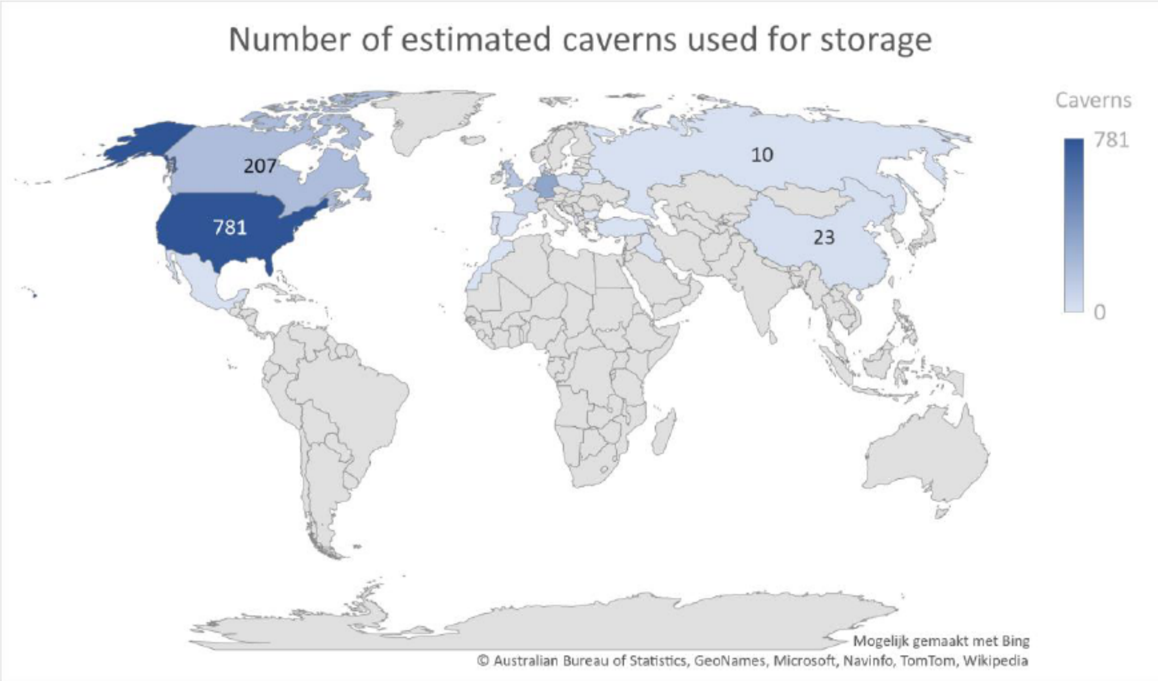

Figure 6 Number of estimated caverns used for storage.

Number of caverns per country (top 5 + the Netherlands)	
United States of America	781
Germany	337
Canada	207
United Kingdom	163
France	70
The Netherlands (11th)	9
Total number of caverns	**1678**

Table 2 Number of caverns per country.

Storage product	Number of caverns
Natural gas	770
LPG	628
Crude oil	202
Unknown	53
Diesel	6
Helium	6
Hydrogen	6
Nitrogen	4
CAES	3

Table 3 Number of caverns per product type.

Figure 6 shows the number of caverns used for storage worldwide. These numbers are a conservative estimate, for the same reasons mentioned above, with the added fact that for several cavern fields, it is unclear (or confidential) how many storage caverns are present in the underground. For some multipurpose cavern fields the ratio of brine production to storage caverns was unclear and a reasonable estimate was made, this also alters the results slightly. The United States of America has the most storage caverns, as shown by table 2. Most of these caverns are located in the states of Kansas (382), Texas (216), Louisiana (76) and Michigan (70). The nine storage caverns of the Netherlands store the following products; nitrogen (1), diesel (2) and natural gas (6).

As mentioned in the 2. Geological background, several different products can be stored inside a storage cavern. Table 3 shows the number of caverns that contain a specific product. Most caverns store natural gas (both low-caloric and high-caloric gas), some type of liquefied petroleum gas (LPG) like propane, ethane or butane, or crude oil. There are several more products which are stored in salt caverns. Compressed air energy storage (CAES) is a type of energy storage where compressed air is stored underground, which can be used to produce energy. Compressed air (off peek excess energy) is used to store and generate energy with gas turbines, this occurs via a diabatic process, as heat is lost. Currently, there are 2 diabatic CAES locations in Germany (Huntorf) and 1 in the United States of America (McIntosh, Alabama). Helium is stored in Russia (5 caverns) and Germany (1 cavern). Nitrogen is stored in the United Kingdom (3 caverns) and in the Netherlands (1 cavern). Finally, caverns sometimes store hydrogen (not pure, but around 95%). These caverns are located in the United Kingdom (3 caverns) and the United States of America (3 caverns). Hydrogen storage has good prospects for an increase in storage in the coming years, as short term storage of uncontrolled energy sources such as wind and sun energy. There are plans for hydrogen storage in the Netherlands, and further storage caverns in the United States of America. More information can be found in the report written by TNO (Netherlands Organisation for Applied Scientific Research), *Large-Scale Energy Storage in Salt Caverns and Depleted fields* (2020).

3.2. Incidents

Unavoidably, during storage in caverns, or during creation, incidents can take place. Table 4 below shows the countries where published information on incidents was found during this study. See the appendix for more detailed explanations of the incidents. It should be noted that a low number of published incidents does not mean nothing happened.

To give a bit more understanding of the number of published incidents, they are normalised to the number of caverns per country. It shows that while the United States of America has the most incidents, when normalising it to the number of caverns, it only has a slightly above average number of incidents (compared to all other countries). The severity of the incidents are not taken into account in the table above.

Country	# of published incidents	# of caverns	Normalised incidents
United States of America	52[3]	781	0.07
Germany	6	337	0.02
Russia	6	10	0.60
Canada	5	207	0.02
France	4	70	0.06
Iraq	4	5	0.80
Denmark	4[4]	7	0.57
Armenia	2	19	0.11
China	2	23	0.09
Poland	2	20	0.10
The Netherlands	*1*[5]	9	*0.11*
The rest of the world[6]	0	190	0.00
Total	**87**	**1678**	**0.05**

Table 4 Number of incidents per country.

3.2.1. Overview of storage cavern incident statistics

To be able to place constraints on the incidents and group them, incidents were categorised them in 5 distinct groups (cavern instability, cavern integrity loss, well integrity loss, well control loss and pipeline integrity loss), they are (briefly) explained below. For a more extensive explanation, see the chapter on 4. Risk Analysis. Insights from the dataset will be discussed in the lessons learned chapter.

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[3] One incident (Mineola) has been classified in two incident groups, and has been counted twice.
[4] One incident (Tostrup TO-9) has been classified in two incident groups, and has been counted twice.
[5] The Heiligerlee well leakage incident is not added to the number of published incidents, as not much is known other than the occurrence of a minor leakage, and the only information found is in news articles. News article (in Dutch): https://www.rtvnoord.nl/nieuws/170817/gasunie-geen-gevaar-geweest-bij-ontsnapping-stikstofgas
[6] No published incidents were found in the rest of the world, however some incidents go unreported or are confidential. It is likely that there are several other incidents which are not included in this study.

During **cavern integrity loss** incidents leakage has taken place outside the salt formation or to a neighbouring cavern. This can happen, among other things, due to faults, fractures and salt heterogeneities. An incident can be categorised in the **cavern instability** group when the cavern evolves to have an irregular shape, or (partially) collapses (migrates upwards). This may or may not result in leakage of gas or liquid from the cavern.

An important part of a storage cavern are the well and pipelines, which are not without their problems. Therefore, there are 3 categories for incidents with the pipelines of a storage cavern. **Well integrity loss** is characterised by leakage through the casing, this casing can be subject to corrosion, metal fatigue, faulty maintenance and salt movement (among other causes) and can tear, leak or break. In this work, well integrity is defined as maintaining tubing and annulus integrity, only. While well integrity relates to the mechanical integrity of the components of the well, well control has to do with keeping the liquids in the well stable and contained. Incidents in this **well control loss** group can be caused by drilling, testing and workovers on the well. It can also be caused by process errors (like human errors or measurement errors), resulting in overfilling of the cavern. These incidents take place when the hydrostatic pressure and formation pressure are not maintained and influx of fluids into the wellbore (or outflow of storage products) takes place. The last group comprises of incidents aboveground, in the piping of the installation surrounding a storage cavern. This **pipeline integrity loss** group describes leakage or damage to the pipelines. It encompasses the so-called Christmas tree (the assembly of valves, spools, and fittings at the surface) and the wellhead, as well as all other aboveground infrastructure surrounding a storage cavern. The incidents per group can be found in table 5.

Country	Cavern instability	Cavern integrity loss	Well integrity loss	Well control loss	Pipeline integrity loss
Armenia	-	-	2	-	-
Canada	-	1	2	1	1
China	2	-	-	-	-
Denmark	3	-	1	-	-
France	2	-	-	-	2
Germany	2	-	3	1	-
Iraq	4	-	-	-	-
Poland	2	-	-	-	-
Russia	-	6	-	-	-
United States of America	8	11	22	5	6
Total	23	18	30	7	9

Table 5 Number of incidents per country, categorised in the 5 main groups used during this study, cavern instability, cavern integrity loss, well integrity loss, well control loss, pipeline integrity loss.

Incident type	Bedded salt	Domal salt	Unknown
Cavern instability	6	14	3
Cavern integrity loss	1	11	6
Well integrity loss	8	18	4
Well control loss	2	4	1
Pipeline integrity loss	1	3	5[7]
Total	18	50	19

Table 6 The number of incidents per type of salt body.

Storage in caverns takes place in different kinds of salt bodies. To see if there is a possible effect, the incidents have been split between domal salt and bedded salt in the following table (table 6). The table is

[7] The cavern in Manosque, France has an anticlinal (or salt saddle) salt structure, Horváth et al. (2018).

complemented by figure 7 (on the following page). To be able to make sense of these numbers, it is good to know how many bedded salt caverns there are as opposed to domal salt caverns. This is shown in table 7. The data shows there are relatively few incidents in bedded salts as opposed to domal salt, which are ~2% and ~9% respectively, when normalised to the number of caverns. Domal salt has more complex structures, and potentially difficult to find steeply dipping structures, Strozyk et al. (2012). Incidents where salt body type is unknown top the list. This overview did not divide the different kinds of bedded salt (thin- versus thick-bedded salts), as there is not enough data available.

Country	Caverns in bedded salts	Caverns in domal salt	Unknown
Armenia	-	19	-
Canada	207	-	-
China	23	-	-
Denmark	-	7	-
France	-		70
Germany	134	189	14
Iraq	5	-	-
Mexico	-	13	-
Morocco	2	-	-
The Netherlands	2	7	-
Poland	2	18	-
Portugal	-	-	6 in salt walls
Russia	3	-	7
Turkey	-	-	6
United Kingdom	145	-	18
United States of America	468	313	-
Total (% of total number of caverns)	**991 (~59%)**	**566 (~34%)**	**121 (~7%)**
Incidents normalised to total number of caverns per salt type (in %)	**~2%**	**~9%**	**~16%**

Table 7 The number of caverns per salt body type. It also shows the incidents normalised to the total number of caverns per salt body type.

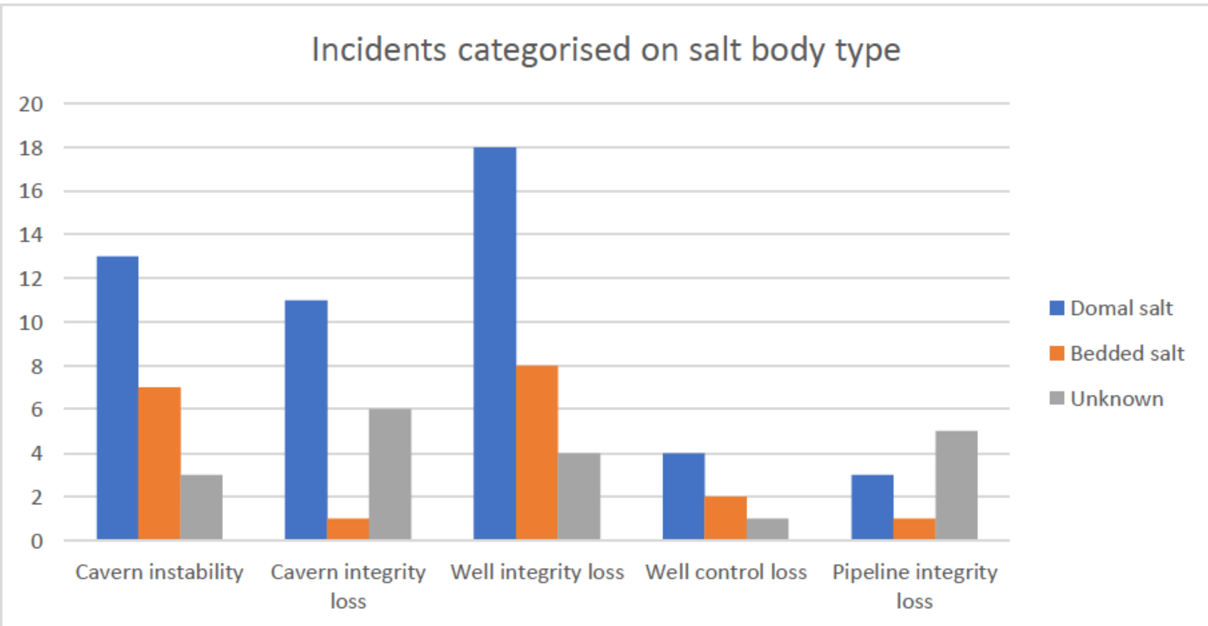

Figure 7 Incidents per type of salt body. Showing the results for all 5 incident groups.

Another important feature of a cavern is its depth. The table (table 8) below shows the amount of incidents at different depths per incident group. Most incidents are in the 0-500m and 1000-1500m depth ranges. The table on the next page (table 9), shows all caverns from the dataset, categorised by depth range. It also shows the incidents normalised to total number of caverns per depth range. When cavern depth is known, most caverns are leached in the two middle groups, 500-1000m and 1000-1500m. It should be noted that, when a cavern falls in between 2 depth ranges, that deeper depth range was chosen. Finally, figure 8 complements the data given by these tables. As can be seen, there are relatively many well integrity loss incidents in the shallowest depth range. Relatively, most incidents occur at cavern depths of the 0-500m and 1500m+ range, ~35% and ~12% respectively.

Cavern depth / Incident type	0-500m	500-1000m	1000-1500m	1500m+	Unknown
Cavern instability	1	1	9	3	9
Cavern integrity loss	1	-	3	-	14
Well integrity loss	9	1	4	2	14
Well control loss	-	1	1	-	15
Pipeline integrity loss	1	1	1	-	6
Total	**12**	**4**	**18**	**5**	**48**

Table 8 Showing the number of incidents per depth category.

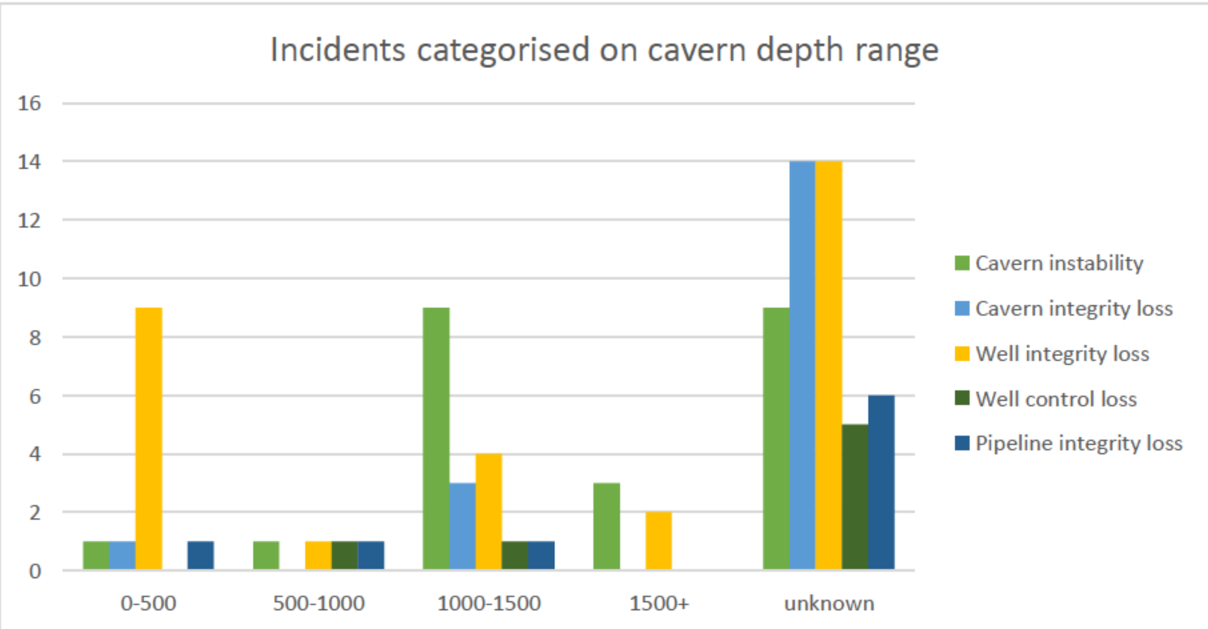

Figure 8 The number of incidents per cavern depth group.

Country	0-500m	500-1000m	1000-1500m	1500m+	Unknown
Armenia	1	-	-	-	5
Canada	-	79	24	6	98
China	-	-	23	-	-
Denmark	-	-	7	-	-
France	-	28	-	15	27
Germany	-	113	158	3	63
Iraq	-	-	-	-	5
Mexico	-	13	-	-	-
Morocco	-	-	-	-	2
The Netherlands	-	2	1	6	-
Poland	-	7	13	-	-
Portugal	-	-	6	-	-
Russia	-	-	5	-	5
Turkey	-	-	6	-	-
United Kingdom	14	44	-	9	96
United States of America	20	-	92	4	665
Total (% of total number of caverns)	**34 (~2%)**	**305 (~18%)**	**335 (~20%)**	**43 (~3%)**	**961 (~57%)**
Incidents normalised to total number of caverns per depth range (in %)	**~35%**	**~1%**	**~5%**	**~12%**	**~5%**

Table 9 Showing the number of caverns per depth category. It also shows the incidents normalised to the total number of caverns per depth range.

4. Risk Analysis

This risk analysis covers the 5 groups of incidents; cavern instability, cavern integrity loss, well integrity loss, well control loss and pipeline integrity loss. Each incident type has its own chapter and the chapters preface with a case study and its so-called 'bow-tie diagram', to show a real life example of the incident group. For each group, comprehensive bow-ties (figure 9) represent all generally applicable causes, preventive measures, escalation factors (before and after the top event), the top event (or unwanted event), the mitigating measures and the effects which were found during the inventarisation. Bow-ties provide a clear way of structuring and visualising the different steps that are part of an incident, and in turn help with creating a roadmap for prevention or mitigation of these incidents. These are constructed by combining all the relevant case specific bow ties (see Appendix 2: "Inventarisation of worldwide published incidents in cavern storage" for an analysis of all the published incidents). Occasionally however the location, or contents of boxes in de case-specific bow-ties have

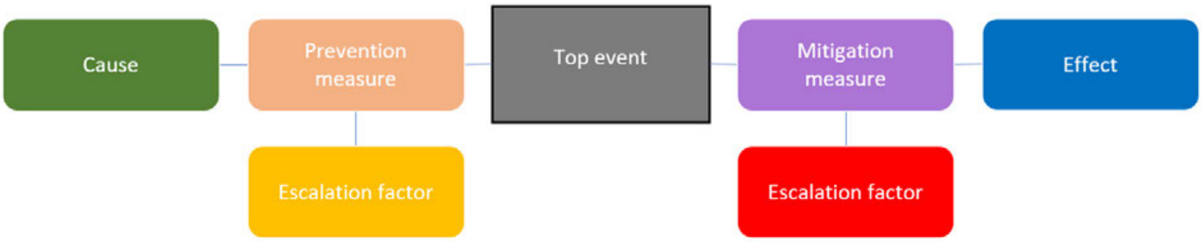

Figure 9 Example of the bow-tie structure used in this study.

been changed in the comprehensive bow-ties, to reflect more general scenarios. Also included in the combination bow-ties are some additional relevant 'theoretical' entries, for which a real-life case study is not always available. Here inspiration was drawn from theoretical barriers or design features (see for example: Cyran (2020); Liu et al. (2021) on salt cavern shape in relation to geological features and on pressure management, respectively), or from analogous events in other industries. For example, incidents found in the oil and gas industry, and brine production industry have been used. The wells drilled in these industries have strong similarities to cavern storage wells, and therefore are especially useful in the well integrity loss, well control loss and pipeline integrity loss incident groups, and many of the cavern stability and cavern integrity incidents in the brine production industry are relevant for storage in salt caverns, either in operation, or in development. Further insights are shown in the lessons learned chapter.

It is however fair to say that the 'theoretical' studies and examples from other industries are not extensive and exhaustive. Also, real life examples of causes, effects, escalating factors, mitigating and preventive measures can sometimes be transposed from one summary bow-tie to another one of a different group of incidents. This has not happened, and only actual causes are shown. This cross-referencing, as well as additional theoretical studies and examples from other industries are recommended for a follow-up study.

4.1. Cavern instability

The top event group, "cavern instability" in this study, includes several slightly different top events that all somehow influence the shape of the cavern. These are: block fall, or salt fall (a block of salt falling), spalling, intersection with more or less soluble layers, creep closure and compaction of insolubles. As their effects are all similar, they have been included in one incident group. The block fall is described in the case study of this incident group. Spalling is the event were a piece of rock salt chips of the wall or roof of a cavern, which can occur due to increased pressure inside the cavern. Spalling has been documented in a Danish storage cavern, see the Appendix 2, under Denmark, and Rokahr et al. 2007). Intersection of a more soluble layer, means that a layer in close proximity to the cavern preferentially leached out, with several effects which are described in this chapter, an example of heterogeneous dissolution is Denmark cavern TO-8, where the cavern intersected with the soluble "*Veggerby*" potassium zone, see Appendix 2: Denmark and Jacobsen & Nielsen (1992). On the other hand, intersection with in- or less soluble layers can also modify the shape of caverns (like in the case described above). Creep closure and compaction of insolubles have effect on the volume and shape of the cavern.

Cavern stability is an important aspect of cavern safety. When a cavern becomes unstable, it can lead to partial or full collapse, capacity loss and other effects like (extremely) fast subsidence (for an example of extremely fast subsidence, see Appendix 2: Hull, Texas) or an undesired irregular shape, possibly affecting whether the cavern is still fit for storage (see the irregular shape paragraph under effects of cavern instability for an example). A key difference between cavern instability and cavern integrity, is that there may not be leakage during a partial cavern collapse, the cavern could maintain its integrity in the salt body. It must be stated that cavern instability can lead to a leakage from the cavern or well (example: Danish cavern TO-9 described in the case study below, or Bryan Mound, Texas, where salt falls resulted in crude oil leakages, see Appendix 2: Bryan Mound, Texas) or leakage resulting in instability.

4.1.1. Case study

The case study for this incident group is cavern TO-9, located in the Tostrup salt dome, Denmark. More information on the storage site can be found in the Denmark section of Appendix 2, and in Jacobsen & Nielsen (1992). In this cavern a block fall (top event) occurred, which place this incident in the cavern instability incident group. The cavern was leached in Na2-salt of the Zechstein-2 cycle. According to Jacobsen & Nielsen (1992), this lithology contains both rock salt and anhydrite. They also state that the cavern is not far from an anhydrite-dolomite zone, and that the risk of encountering blocks of these zone was predicted before the leaching process started (by the use of structural interpretation). It would appear however that the prediction was tried to be implemented in the design of the cavern. The later change in step-leaching (described in the following paragraphs) was therefore not a preventive barrier during this incident, but a mitigating measure.

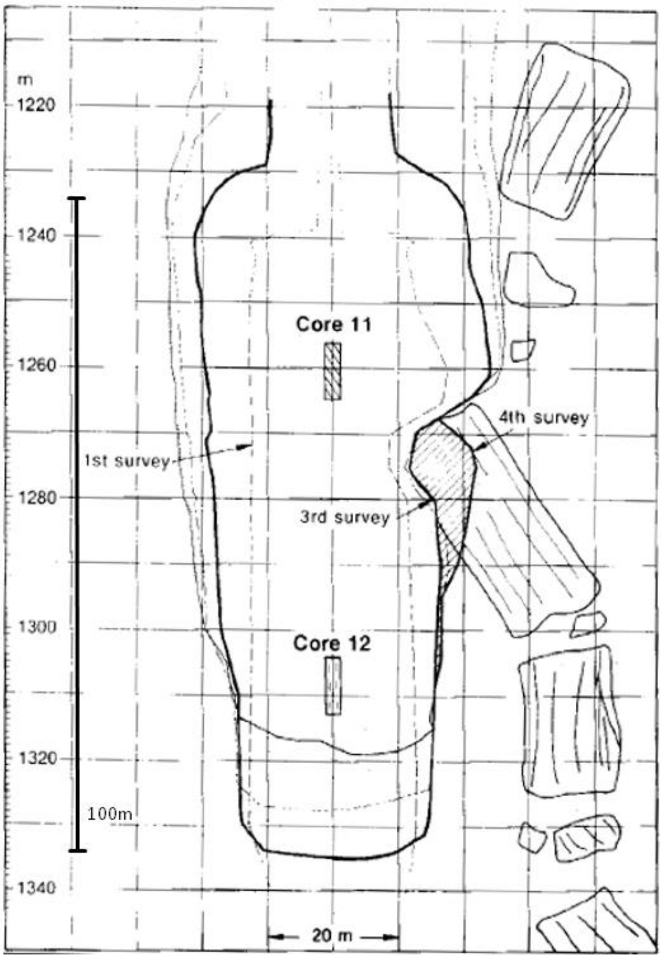

Figure 10 Cavern TO-9 in the Tostrup salt dome, Denmark. From Jacobsen & Nielsen (1992).

Figure 10 shows the shape of cavern TO-9 during several sonar surveys. At the time of the incident (unknown date), the cavern was being leached and it had a height of around than 100m.

The bow-tie in figure 11, shows the events that took place during the incident. The top event was a block fall. This type of event is characterised by the breaking off of a rock from the wall or roof of a cavern. These blocks can be salt or non-halite inclusions in the salt body. In this case, the block fall was noticed during a sonar survey, as the shape of the cavern changed significantly from the previous survey. The cause of this block fall is interpreted to be salt heterogeneity, a large insoluble block, with very different mechanical properties, was present near the edge of the cavern wall. This piece of upright boudinaged anhydrite-dolomite broke off the wall. Vertical features are difficult to find with seismic sonars, as the seismic shots reflect off of the vertical feature and do not necessarily go back towards the surface. The block fall resulted in the brine string being buried in debris and damaging it.

After the fourth survey, step-leaching was used as a mitigating measure, and no more block falls were reported. We assume that step-leaching is the leaching of the upper parts of the cavern, as to not affect the lower regions of the cavern, by heightening the leaching string. It could also mean small volumes are leached before carrying out a sonar survey, rather than leach large volumes at once. This term is not further described in Jacobsen & Nielsen (1992). This way, when the sonar shows an overhanging block, the leaching string depth can be adjusted, and the leaching of the area around the heterogeneity stops. In the case study, the cavern instability incident led to a well integrity loss incident, as the brine string became buried in debris.

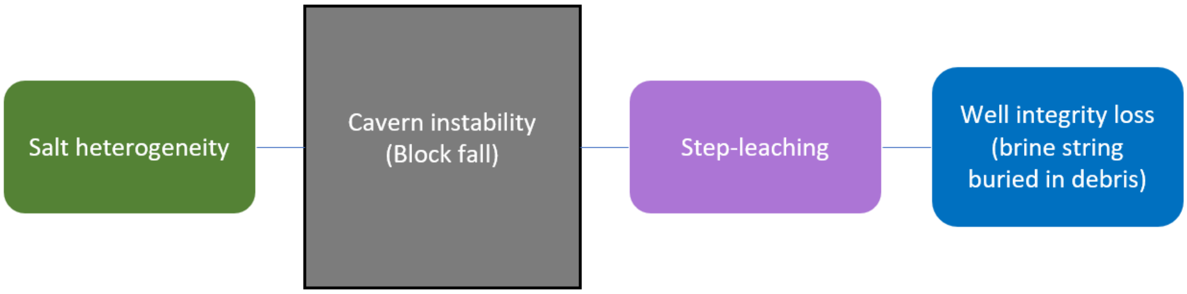

Figure 11 Bow-tie of the TO-9 cavern instability incident.

4.1.2. Cavern instability bow-tie

This section describes all the significant aspects of a cavern instability incident. These aspects can be found in figure 12 on the next page.

4.1.2.1. Causes

Large-span flat roof

Cavern instability incidents have several causes. One of these is a mechanical instability due to a large-span flat roof, as described by Wang et al. (2018). A good example of this is cavern JK-A in Jintan, China, described by the same author. They describe that due to this flat roof, the capacity to resist vertical creep deformation decreases. The large roof is also unable to release stress in a timely fashion according to Wang et al. (2018), for example when gas pressure is decreased significantly in a short period of time. More on that later in this chapter.

Mechanical testing

Another cause of cavern instability can be the testing of the cavern, which is normally done to assess the cavern. One of these tests is a rock mechanical test (in this case lowering of the pressure) to see how the cavern reacts to increased salt creep. An example of this can be found in Appendix 2: Denmark,

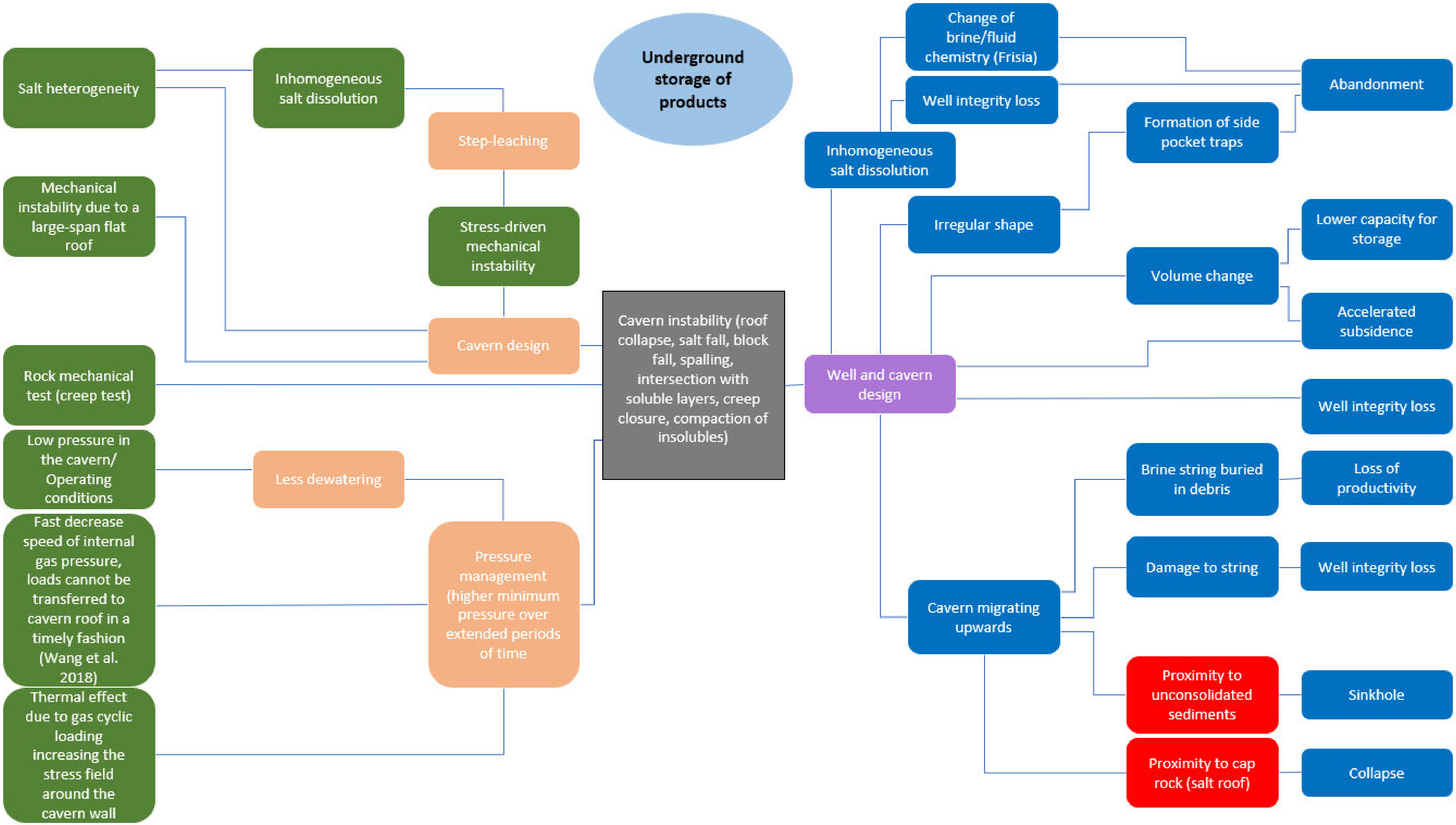

Figure 12 Cavern instability bow-tie.

cavern TO-6, where rock mechanical testing was conducted to asses salt creep behaviour, this ultimately resulted in spalling. See Rokahr et al. (2007) for a more in-depth look at the incident.

Salt heterogeneity

Salt heterogeneity plays a large role when discussing cavern instability. It can lead to inhomogeneous salt dissolution, causing stress-driven mechanical instabilities. As found in the case study, salt heterogeneity can mean interference of insoluble blocks. It can also mean dissolution of more soluble layers like carnallite, causing the cavern to become unstable.

Low pressure

A low internal pressure of the cavern can also cause cavern instability, and this relates to operating conditions. When the pressure of a cavern is too low, salt creep starts playing a larger role in the stability of a cavern. As briefly described above, a rapid drop in gas pressure can cause cavern instability like block fall (Wang et al. 2018). In the case described in this paper, the rapid gas pressure drop in combination with a large span flat roof lead to a cavern instability incident. It is plausible that these causes could also individually lead to cavern instability. As such they are separated in the general bow-tie.

Thermal effects

Finally, the last cause found during this study, is the thermal effect created by gas cyclic loading. When gas is injected, it is compressed, increasing the temperature of the gas. When gas is produced the gas inside the cavern decompresses, and thus cools down. This thermal effect can change the stress field around the cavern wall. This, combined with possible thermal effects during pressure cycles, can result in tensile failure, which can help trigger events like block fall in combination with mechanical loading. An example of this is cavern L, in the Jintan Sinopec cavern field, where tensile failure due to gas cyclic loading led to the occurrence of block fall and ultimately, an irregular shape. More on this case can be found in Appendix 2: China and more on thermal stress due to cyclic loading and the case can be found in Li et al. (2021).

4.1.2.2. Preventive measures

Leaching strategy

To prevent cavern instability, there are a number of barriers. Step-leaching, as described in the Danish case study as a mitigating factor, is used in the general cavern instability bow-tie as a possible prevention measure. In the case study, this technique was applied to prevent further block falls. In most cases, this technique could be used as a preventive measure, to stop block fall from occurring in the first place.

Cavern design

Another important preventive measure is cavern design. Cavern design as a preventive measure describes all different kinds of factors like size of the cavern, shape of the cavern, its location within the salt body, the geology of the surrounding area (including the presence and orientation of in-soluble and layers more soluble than halite), depth, proximity to the cap rock or other salt caverns, among other factors. More on cavern design can be found in Habibi (2019). Incidents due to salt heterogeneity can be prevented if one or more of these factors are extensively investigated, and subsequent actions are taken, e.g. changes in the design of the cavern. Issues due to a large span flat roof can be prevented by these factors as well. It is important to note that there can always be uncertainties, heterogeneities cannot always be found, even if they are present.

Dewatering

Another prevention measure, which has an effect on the pressure of a cavern, is to dewater less or less frequently. Dewatering is the act of injecting gas under high pressure (higher than hydrostatic pressure) which pushes out the brine inside the cavern, see Costa et al. (2017), and then lowering the pressure to form a gas cushion. Dewatering can be considered as an extreme case of cyclic loading. How counterintuitive this sounds, this dewatering can cause low pressure, and in combination with low minimum operating pressure can lead to excessive creep. This technique was used in the Eminence salt dome, in Mississippi, as a mitigating measure to prevent further salt creep, after the volume of the cavern had decreased by more than 40%, see Bérest et al. (2019). Creep had an extra-large effect due to the cavern depth of about 2000m. Higher temperature and larger differential stress both result in higher creep rate, more information can be found in Rowan et al. (2019). The cavern was reported to have shrunk about 46 meters in height over two years, as its bottom elevated to a depth of about 1953m. It is important to have a minimum operating pressure that is high enough to prevent excessive creep, see the following paragraph.

Pressure management

The barrier of reduced dewatering can be generalised to proper pressure management. In that case dewatering is part of a broader pressure management strategy. When pressure management is executed adequately, causes like tensile failure due to gas cyclic loading, transfer of fast changing pressures (more on this in the paper by Wang et al. (2018)) and excessive cavern convergence can be reduced or prevented. One of the ways to do this is maintaining a higher minimum pressure. More on pressure management can be found in Chen et al. (2021) who describes stability of a cavern in relation to operating pressures. Finally, constraints on maximum gas production rates can be found in Liu et al. (2021) and Brouard (2019).

4.1.2.3. Effects

Inhomogeneous salt dissolution

Inhomogeneous salt dissolution can be caused by cavern instability, for example, by a roof block fall, opening the area above the cavern where other lithologies can be present, when a layer of highly soluble rock is present (escalating factor), these can start to leach. This can change the brine/fluid chemistry of the cavern (this incident occurred in a brine production cavern, but is a logical effect to include in the storage cavern incident risk analysis) and possibly the abandonment of a cavern. An example of inhomogeneous salt solution is a cavern operated by Frisia Zout B.V. where a leakage path occurred between caverns BAS-3 (previously abandoned) and BAS-3O (operational brine production cavern). This was likely the result of partial dissolution of a soluble carnallite layer. Cavern BAS-3 had a magnesium rich brine, which became connected to BAS-3O, contaminating the brine composition and ultimately leading to an early abandonment of the cavern. For more information on this case and why it happened see Lange (2012), and *Integrity issues BAS-3O: Abandonment and risk analysis* (2019)[8].

Inhomogeneous salt dissolution can also mean an insoluble block is exposed, potentially triggering another block fall. This can lead to well integrity issues, similar to the case study of cavern TO-9 in Denmark, and ultimately to abandonment of the cavern.

Irregular shape

An immediate effect of several cavern instability events is an irregular shape. This is undesirable, as this can change the stress field around the cavern, leaving the cavern more vulnerable to further rock

[8] Correspondence (in Dutch) between State Supervision on Mines and Frisia Zout B.V. from the website of State Supervision on Mines : https://www.sodm.nl/documenten/brieven/2019/10/24/reactie-sodm-op-sluiten-bas-3o-caverne-oosterbierum

failure. The formation of side pocket traps due to irregular shape can mean early abandonment of the storage cavern, as these are unfit to store products. An example of this is the fuel storage in Góra, Poland. The case is described in more detail by Mrozinski (2004) and in Appendix 2, under Poland.

Volume change

A cavern instability incident can also lead to volume change, the volume can increase or decrease. It can decrease due to lower pressures, increasing cavern creep. A decrease leads to a lower capacity for storage while excessive cavern convergence (volume increase) can lead to accelerated subsidence. An example of capacity loss due to salt creep is a cavern in Kiel, Germany, where a 12.3% loss of capacity was recorded in 45 days. See Appendix: 2, Germany and Yang et al. (2013) for more information.

Well integrity loss

A cavern instability incident can also directly lead to a well integrity loss incident, as previously described in the Danish case study. When a cavern collapse takes place, this can result in the cavern migrating upwards, as material is taken away from the roof and displaced to the bottom of the cavity. This can, in time, lead to damage to the tubing by falling blocks or the brine string being buried in debris (see case study), and (temporary) losing productivity. Upwards migration of the cavern roof can also lead to damage to the string, which can lead to well integrity incidents.

Cavern collapse

The second to last effect, collapse of the cavern, occurs when material breaks off and is deposited on the cavern bottom. Rubble has a larger volume than the rock mass it came from. This phenomenon is called bulking and can ultimately lead to the cavern shrinking considerably and disappearing completely, as long as the cavern stays within consolidated sediments.

Sinkhole

The final and most dramatic effect, a sinkhole, can also results from the cavern migrating upwards. The main difference is that a sinkhole forms when the cavern reaches up into the unconsolidated sediments, from there extremely fast subsidence leads to a sinkhole. An example of this is the sinkhole of Hull, Texas, United States of America. In 2008 an upwardly migrating cavern resulted in a sinkhole of 45m deep and 180m in diameter. More information on this case can be found in Appendix 2, under United States of America, or in Horváth et al. (2018).

4.1.2.4. Mitigation measures

Mitigation measures are put in place to lessen the impact or prevent the effects from the top event. The main mitigation measure, well and cavern design, is similar to the prevention measure cavern design. It is however, necessary to place these design aspects both before and after the top event, as the design can have an impact in both stages of an incident. A cavern is less susceptible to inhomogeneous salt dissolution (and all other effects) when cavern design is done properly. For example, as discussed in the prevention chapter, the location of the cavern in the salt dome and the geology of the nearby salt. A block fall does not have to result in inhomogeneous salt dissolution if there are few heterogeneities above the cavern. Similarly, a cavern instability incident like a block fall does not have to mean that a well integrity issue has to occur if the well is designed with sufficient space between the well and the potential block fall.

More details on the effects of well integrity issues can be found in the risk analysis chapter well integrity loss.

4.1.2.5. Escalation factors

A (partial) collapse of the cavern, can be escalated when the cavern is in close proximity to the salt roof or cap rock, or the edge of the salt body or a neighbouring cavern. In some designed caverns, the salt roof, or in most cases, the consolidated rock mass above the salt is large enough to accommodate upwards migration until the cavern disappears due to bulking. An example of prevention of this escalating factor is from the extraction plan[9] "*Ganzebos Fase 3*" for a salt extraction cavern operated by Nobian[10]. They prevent bulking by choosing a maximum cavern height which is able to accommodate this bulking until the disappearance of the cavern before reaching the unconsolidated sediments. *"The maximum allowable height of a cave space is chosen to be inherently safe. This means that if a cavern, despite all precautions and against expectations, should eventually migrate towards ground level, only limited bowl-shaped subsidence will occur and no trough or sinkhole can form at ground level."*, taken and translated from the extraction plan, see the footnote.

If the cavern breaches through the cap rock, it has a higher chance of leaking its liquid or gaseous content, and thus can result in further negative effects like pollution or personal safety issues.

If the cavern is in close proximity to unconsolidated sediments, as explained above, a sinkhole can form. The smaller the distance between the original cavern and these unconsolidated sediments, the more cavern volume is left when breaching through these sediments. This results in larger sinkholes. A previously mentioned example of the formation of a sinkhole from a LPG storage cavern occurred in 2008 in Hull, Texas, United States of America. A 45m deep, 180m diameter sinkhole formed after the cavern collapsed and migrated upwards resulting in extremely fast subsidence, see Horváth et al. (2018). An extreme case of a sinkhole is the Bayou Corne sinkhole lake (over 16000m^2 surface area) in Napoleonville, Texas, United States of America. The formation of the sinkhole was an effect of the collapse of a major brine production cavern. As the cavern was located close to the edge of the salt dome, the wall collapsed, allowing a disturbed rock zone to collapse and enter the cavern. More on this case can be found in Horváth et al. (2018).

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[9] "*Ganzebos fase 3*" extraction plan: https://www.nlog.nl/sites/default/files/170531%20verzoek%20tot%20instemming%20wp%20ganzebos%20fase%20iii%20%28publiek%29%20%28gelakt%29.pdf

[10] As per 1 July, 2021, Nouryon created a spin-out business; Nobian. For clarity, this study uses the latter. Linked here is the news article explaining the spin-out: https://www.nouryon.com/news-and-events/news-overview/2021/nouryon-completes-spin-out-of-nobian-and-reinforces-its-strategic-focus/

4.2. Cavern integrity loss

The integrity of a cavern is compromised when a leak path forms to the overburden, adjacent layers or neighbouring caverns. This small or large leakage is the unwanted top event of cavern integrity loss, and what separates it from the previously analysed cavern instability incidents. These leakages can be the result of several causes which are described in this section.

One of the main causes is the formation of faults or fractures. Cavern integrity loss can be the result of a cavern instability incident, when a leak path is formed (which is described in the following case study on the Clovelly storage facility).

It can be difficult to determine the exact cause of integrity loss, for example, the hydraulic connection between a gas storage cavern and a brine production cavern in Spindletop, Texas, United States of America. The incident occurred in 2001 and the cause is a debated topic: *"It is unknown whether the gas is migrating through an induced fracture, a fault plane or a seam of porous and permeable salt intersecting both caverns at an unknown altitude"* from Johnson (2003). More information on this case can also be found in Brouard (2019).

4.2.1. Case study

The following incident is an example of a cavern where integrity was lost. The incident occurred in cavern 14 of the Clovelly storage facility, in Louisiana, United States of America, where oil is temporarily stored, later to be sent to oil refineries. The bow-tie of this incident can be found on the following page, figure 14. The top event; leakage of brine outside the salt formation, was the result of salt heterogeneity. As only brine leaked and no oil was lost, the assumption was made that the leak was below the brine/oil interface.

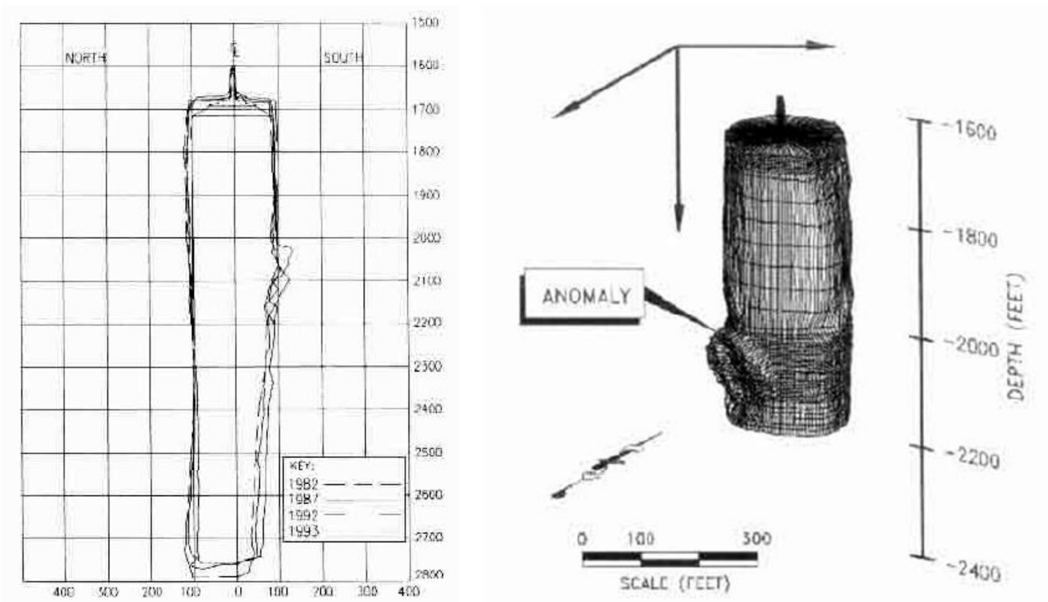

Figure 13 Left: Cavern 14 anomaly growth. Right: sonar survey showing the anomaly bulge. From McCauley et al. (1998).

In 1992 the cavern failed to pass its mechanical integrity test after which oil was removed from the cavern. A leak was detected. A sonar survey showed that there was a bulge in the wall of the cavern, see figure 13 for cavern shape and the bulge. "*This survey better defined the anomaly as a pronounced bulge with a flattened face suggestive of an intersection with a wedge of extraneous material (possibly more soluble than the typical Clovelly domal salt) within the dome*" (McCauley et al. 1998). A pressure survey showed that the leak depth was at the same depth as this anomalous bulge.

An escalating factor was found during a salt proximity survey (surveying the salt wall thickness around the cavern), it showed that the edge of the salt dome was 120m from the cavern wall. The leak path was not through a fracture, but through an inhomogeneity, which had different physical or chemical properties than the Clovelly dome salt. The leak path was likely into a sandstone layer. The effects of this leak path were an irregular shape, the cavern leaching to the caprock and finally, abandonment of the storage cavern. For more information, consult papers written by Brouard (2019); McCauley et al. (1998); Yang et al. (2013) and more information on this storage location can be found in the United States of America section of Appendix 2.

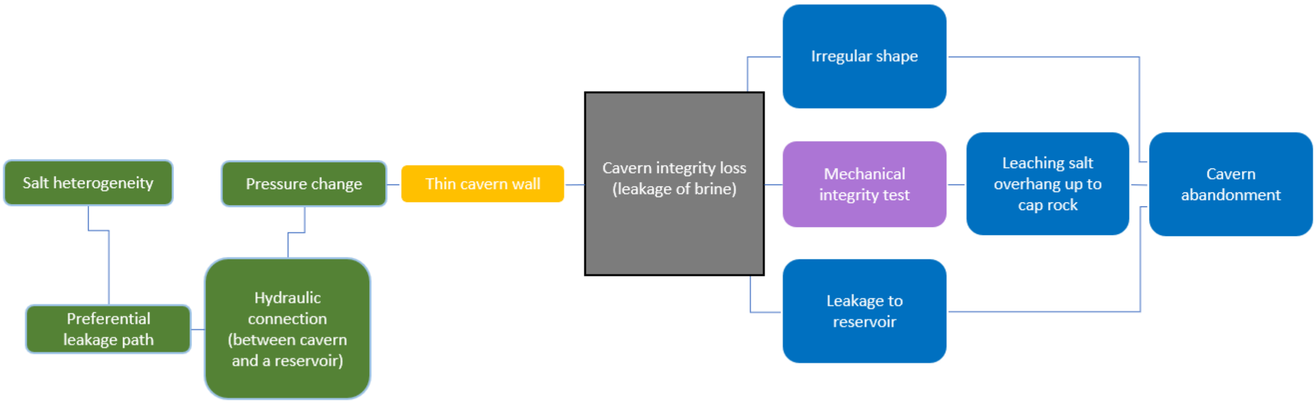

Figure 14 Bow-tie of the Clovelly brine leakage.

4.2.2. Cavern integrity loss bow-tie

In this section the most important aspects of the cavern integrity loss incidents are described. The summary bow-tie of this incident group can be found on the following page, figure 15. The top event is cavern integrity loss (leakage), which can occur through preferential leakage paths, as described in the case study for this incident group, as well as fractures and faults. The definition of a preferential leakage path includes, for this study, all leakages resulting of salt heterogeneity.

4.2.2.1. Causes

Salt heterogeneity

Cavern integrity loss can have many causes. One of the main causes is salt heterogeneity, one example was described in the case study of this section, where it leads to the formation of a preferential leakage path and a hydraulic connection.

Another result of salt heterogeneity can be a roof collapse, this incident only fits in this incident group when this leads to leakage (otherwise it is a cavern instability incident). For example a block of insoluble material collapses and the cavern becomes hydraulically connected to another layer, leading to pressure change. An example of roof collapse resulting in leakage is the Regina South leakage in 1989, it is described by Brouard (2019). The roof collapse was accompanied by a large pressure drop, suggesting fast leakage into a reservoir layer.

Uncontrolled dissolution by salt heterogeneity can also directly influence the pressure of the cavern, as the shape changes, and when the cavern migrates to the caprock, the pressure changes and the products leak away. This was likely the cause for the sinkhole in Bayou Choctaw, Louisiana, United States of America, an incident that occurred in 1954 in a brine production cavern. The cavern leached to the thin caprock via uncontrolled dissolution (which in this case, was due to human error), resulting in a large pressure drop. The effects were a sinkhole, abandonment of cavern BC-4 and collapse of developing cavern 7. More about this incident can be found in Looff (2017); Munson (2007); Yang et al. (2013) and Appendix 2: United States of America.

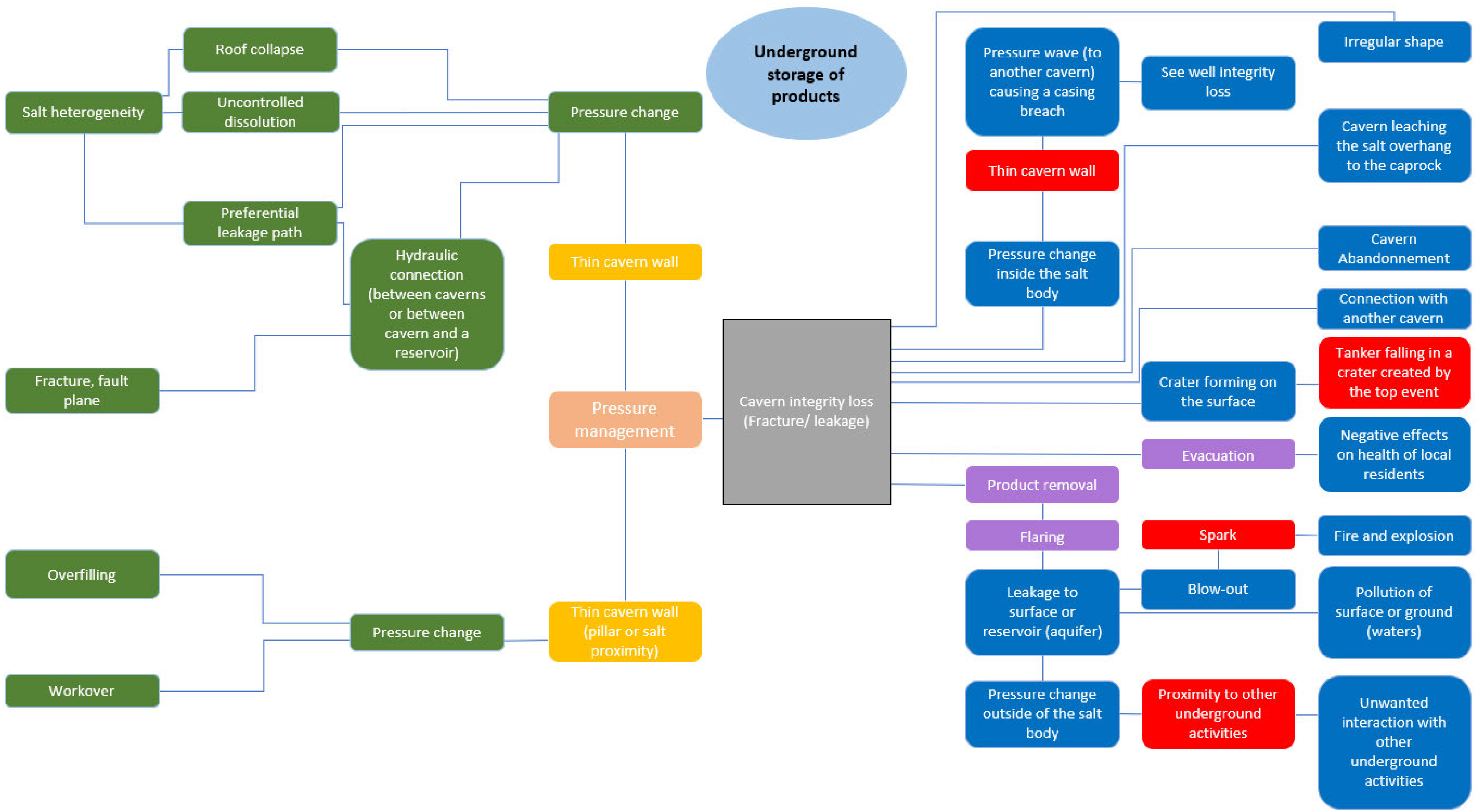

Figure 15 Cavern integrity loss bow-tie.

Fractures and fault planes

Fractures and fault planes can also lead to pressure change, when the cavern becomes connected to another cavern or a reservoir and forms a hydraulic link.

Overfilling

Other pressure changes can happen due to overfilling of the cavern, increasing the pressure on the weaker parts of the cavern wall. This human error resulted in high pressure in the cavern in Petal, Mississippi, United States of America. This incident occurred in July of 1986, and resulted in the loss of structural integrity of two storage caverns, and subsequently in leakage and the formation of a crater at the surface. This case is described in detail in "*Past Salt Caverns Incidents Database Part 1: Leakage, Overfilling and Blow-out" by* Réveillère et al. (2017) and Appendix 2: United States of America.

Hydraulic fracturing

Hydraulic fracturing can in some cases be caused by high pressures during workover. This occurred in a cavern in Mineola, Texas, United States of America. Where the high pressure was escalated by a thin pillar between two caverns, resulting in a hydraulic fracture and a well integrity incident in the second cavern due to a pressure wave. More on this case can be found in Bérest et al. (2019; Brouard (2019); Yang et al. (2013) and Appendix 2: United States of America. Another example is the salt production cavern in Veendam, the Netherlands. A hydraulic fracture in the roof of the cavern resulted in leakage. More information can be found in Brouard (2019). And in the reaction[11] of State Supervision of Mines.

4.2.2.2. Prevention measures

All the described causes lead to pressure changes inside the cavern, and as such, pressure management is one of the main prevention measures. This can mean several different precautions like understanding the local lithology surrounding the cavern and other aspects of cavern design (cavern depth, proximity to other underground activities, proximity to the edge of the salt, pressure management to prevent the thermal effects of cyclic loading and other unwanted effects of low or high pressures).

4.2.2.3. Escalation factors

The main escalating factor of leakage away from the cavern is the thickness of the salt surrounding the cavern. If the salt pillar between two caverns is small, or when the cavern is in close proximity to the salt edge (vertically or horizontally), the chance of leakage increases. It also escalates the formation of fractures, as a small cavern wall has less overall strength.

4.2.2.4. Effects

Irregular shape

One of the effects is irregular shape, which results from salt heterogeneity (roof collapse, preferential leakage paths and uncontrolled dissolution), as well as fractures and fault planes. Irregular shapes can cause other top events, such as well integrity loss.

Connection with another cavern

A connection with another cavern can be the result of a cavern integrity incident. This can happen due to the dissolution of a soluble layer between two caverns. Another example of this is described in the following paragraph.

[11] Reaction of State Supervision on Mines on the Veendam incident: https://www.sodm.nl/actueel/nieuws/2019/04/19/oordeel-sodm-over-overkoepelend-rapport-lekkage-nedmag-april-2018

Pressure wave

As described in the causes chapter, in the Mineola incident example, a pressure change inside the salt body can result in a pressure wave to another cavern, and in turn can result in well integrity losses like a casing breach (when the rubble of a roof collapse damaged the well).

Leaching into the caprock

Another effect is the leaching of the cavern into the salt overhang up to the caprock. This is what happened in the Clovelly dome, described in the case study of this section.

Sinkhole

The overfilling example (Petal, Mississippi, United States of America) described earlier led to the formation of a crater of about 90 meters wide on the surface. The subsequent gas cloud led to an explosion and a fire, destroying parts of the above-ground infrastructure and tanker trucks[12]. More details on the escaping of product are described in the next section.

Leakage into a reservoir or to the surface

When the leakage reaches to the surface or reservoir like an aquifers, this can result in a pressure change outside the salt body. This can have unwanted interactions with other underground activities. One example of this is the Sulphur mines, Louisiana, United States of America, leakage. Pressure build up in the surrounding formations resulted in the blow-out of a nearby oil and gas exploration well. More information on this incident can be found in Appendix 2: United States of America and Evans (2008). Another effect of a leakage reaching a reservoir is pollution of surface- or groundwaters. A leakage to the surface can also lead to a blow-out, and a subsequent fire and explosion and loss of life, if the gas cloud is sparked.

Health of local residents

Cavern integrity loss incidents can result in negative effects on the health of the local residents, via pollution of waters, blow-outs and craters, among other effects.

4.2.2.5. Mitigation measures

The effects of leakage to the surface or reservoirs can be mitigated by directly removing the product from the cavern (this requires a suitable container). Another way to mitigate these leakages is to flare off the product, and thus creating a controlled environment.

Evacuation is the most important mitigation measure for health of the local residents, up to loss of life, and is especially important when there is a chance of blow-out, or when storage product flows into reservoirs like aquifers and thus increases the range of the leakage incident and possible negative effects to the health of local residents. Pumping out the leaked products from the groundwater or underground reservoirs is an important mitigation measure.

4.2.2.6. Escalation factors

There are a number of ways to escalate effects of the leakage. As described in the example on the Mineola cavern, a thin wall allows for a pressure surge to affect a nearby cavern. When a pressure change has reached outside of the salt body, proximity to other underground activities is an escalating factor, as it can give unwanted interaction. This is described previously in the Sulphur Mines example. One highly specific escalation factor occurred in the previously described Petal example, where a surface crater formed. A tanker fell in the crater, further complicating the incident. The same incident resulted in a blow-out of gaseous liquid propane, which was escalated by a spark, resulting in a fire and explosion. Despite over 200 evacuees, there were 14 burn injuries, Réveillère et al. 2017).

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[12] News article on the Petal incident: https://apnews.com/article/0694a024d10f47c1a53d7fa06150c35e

4.3. Well integrity loss

A key part of cavern operations is the well. In this section the incidents are characterised by mechanical failure of the materials of which the well is composed. This means damage to the casing, tubing or other well components. All incidents which were consulted for this group lost well integrity, e.g. there was leakage away from the well. This group has some similarities to both the well control loss group and the pipeline integrity loss group. The former only has to do with keeping the liquids inside the well (and cavern) stable and contained, the latter group has one defining difference, it contains incidents above ground, where the well integrity loss group describes underground incidents exclusively. See Dusseault et al. (2001), for a more in-depth look at causes and prevention measures for casing damage.

4.3.1. Case study

A crude oil storage cavern in Epe, Germany, had well integrity issues in 2014. Cavern S5 experienced a pressure drop of 3.6 bar in February, but no leakage was found after inspection. On April 12th an oil spill was found in a nearby meadow, suggesting a leakage. The bow-tie on the following page (Figure 17) shows the different steps of this incident.

The cause of the damage to the (single barrier) well was movement of the rock mass surrounding the cavern. This induced movement of the rock mass up to the leakage depth of the well. The location of the leak was found using pressure tests and a casing inspection. Casing damage was found at a depth of 217m (Figure 16), just below the double casing/single casing border, a weak point of the well. The cause of the leakage was a pressure difference between the crude oil and the surrounding lithology, the wellhead pressure of the oil was 8.1 MPa, while the capillary entrance of the surrounding material was 4.7 MPa. This allowed the crude oil to reopen fractures and shear zones and flow into them. Over the course of about a month the oil reached the surface, forming an oil spill.

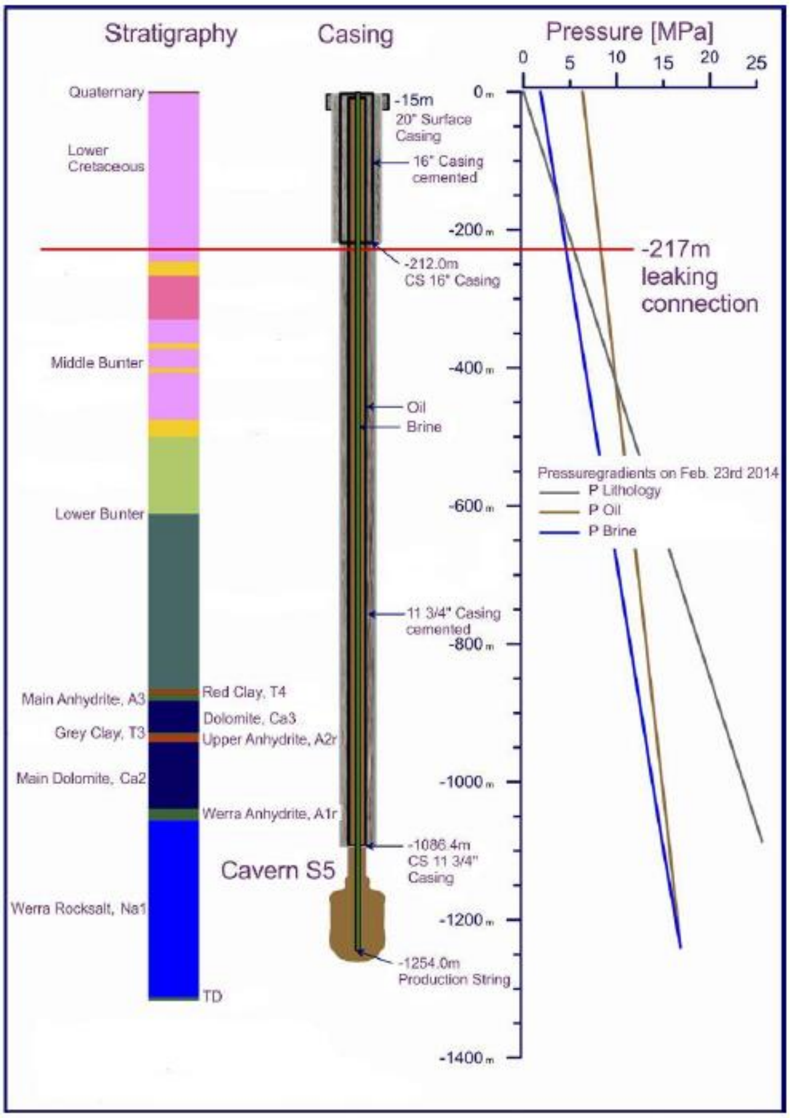

Figure 16 Stratigraphy and pressure of cavern S5 in Epe, Germany. From Hengst (2014).

To reduce pollution, mitigation measures were taken immediately after locating the oil spill. They consisted of lowering the cavern pressure to a wellhead pressure of 2.5 MPa, allowing for back flow of the oil remaining in the fractures. This low pressure allowed the fractures to seal within a few months. Soil and water remediation to sanitize the oil spills were other mitigation measures, as well as pumping out the storage product to reduce pressure.

To prevent negative effects to the health of the local residents, a family was evacuated and some cows were put down after drinking from the polluted water.

Going forward, storage in salt caverns in Germany require a double barrier installation for all wells. More information on this case can be found in Hengst (2014), as well as Réveillère et al. (2017) and references therein. More information on the storage location can be found in the Germany section of Appendix 2.

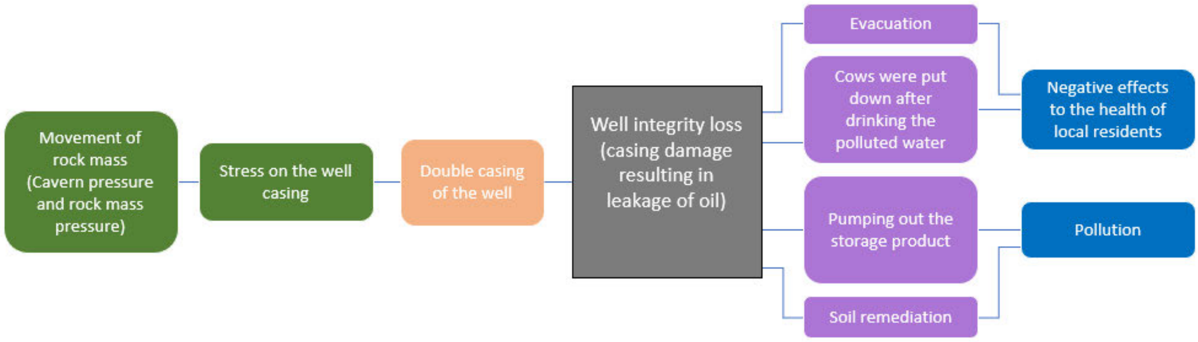

Figure 17 Bow-tie of Epe crude oil spill incident in cavern S5.

4.3.2. Well integrity loss bow-tie

The general bow-tie for well integrity loss summarises the most important causes and effects for this incident group. The bow-tie (Figure 18), can be found on the following page. The top event of this group is leakage through casing damage.

4.3.2.1. Causes

Corrosion

Casing damage can have several causes. One of these is corrosion of the pipelines. Parts of the casing can oxidise depending on the material of which it is made, what is stored in the cavern, underground conditions or other properties. Another cause is weak cementation a the neck of the cavern. If a weak spot forms here, a leakage can occur. These two causes led to an incident that occurred in 1980 in the Barbers hill dome, Texas, United States of America. A storage cavern for liquid propane had a breach in the well casing due to corrosion damage and weak cementation at the cavern neck, this formed cracks in the pipelines above ground, commencing leakage. The leaky well was 22 years old. The propane leaked away from the wellbore at caprock depth. More information on this case in the paper "Review and analysis of historical leakages from storage salt caverns wells" by Bérest et al. (2019) and "Safety of Salt Caverns Used for Underground Storage" by Bérest & Brouard (2003), as well as Appendix 2: United States of America.

Rock mass movement

Movement of the rock mass is another cause of damage to the casing. This movement can occur through a number of different means. In some cases, cavern convergence (creep) incited rock mass movement just above the cavern roof. This can put stress on the casing, like in the Epe case study. Another example of this are leakages of caverns 1, 2 and 4 in 2005, which are located in the Boling salt dome, Texas, United States of America. The casings were overstretched due to tensile failures. Cavern 3 did not experience casing coupling partings because the last cemented casing shoe was located not near the neck of the cavern, but rather a couple of tens of meters higher. Thompson et al. (2007), suggests some space between the cavern neck and the last cemented casing is a necessity to ensure the long-term integrity of the casing. More information on this case can be found in the previously

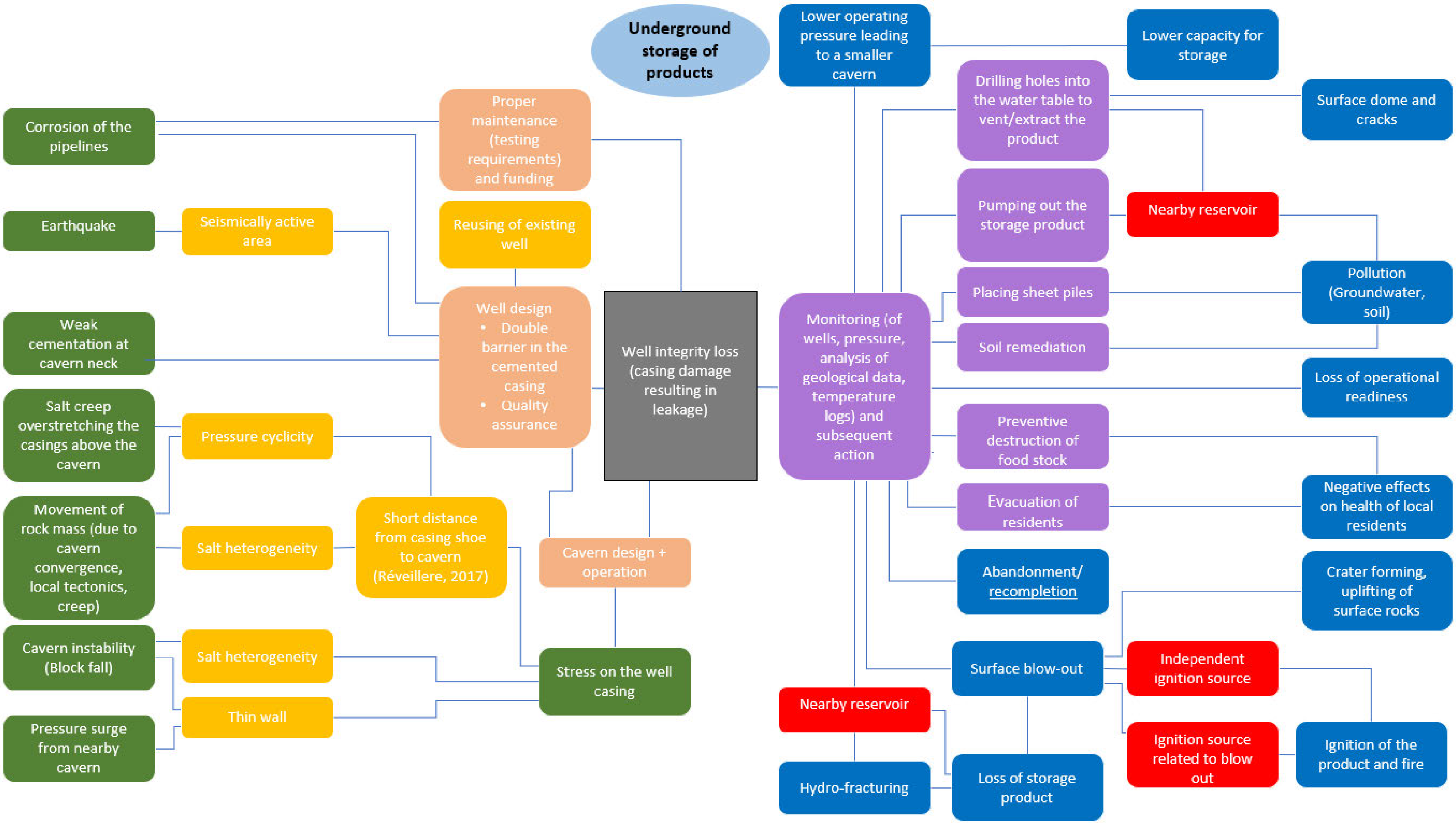

Figure 18 General bow-tie of well integrity loss incidents.

stated paper by Bérest et al. (2019), as well as Appendix 2: United States of America.

Salt movement can also be caused by other means of salt creep and finally, by local tectonics, like described in the following paragraph on earthquakes.

Earthquakes

An earthquake can lead to casing damage, as the stress on the casing increases and the rock formation fractures and shears. In the Abovyan underground gas storage in Armenia, this led to two leakages (caverns N6 and N9). The poor maintenance due to insufficient funds escalated the damage to the casing. More information can be found in Appendix 2: Armenia and in a report[13] by the Energy Charter Secretariat (2008).

Cavern instability

Cavern instability incidents like a block fall can also result in damage to the well. This was described in the effects paragraphs in the cavern instability chapter (Danish cavern TO-9, Appendix 2: Denmark). When the salt fall comes in contact with the well it can decrease productivity or even damage the well.

Pressure surge

Similarly, a pressure surge from another cavern can result in a well integrity incident. Because this incident migrated from one cavern to another, this cause fits best in the cavern integrity incident group. An example was described in the cavern integrity incident chapter (Mineola cavern, Appendix 2: United States of America), under effects.

4.3.2.2. Prevention measures

Well design

All effects of well integrity incidents can be prevented, or reduced, with proper well design. This can be done in a number of ways, most noteworthy is the placement of a double barrier in the cemented casing, this way, there needs to be damage to the inner and the outer casing before the product can leak away from the wellbore. Double casing also allows for monitoring, to identify issues early. It would be fair to say the Epe well integrity incident would have had much reduced consequences if the well had a monitorable double casing. Another part of well design is quality assurance, like making use of the right, high-quality materials.

Maintenance

When a well integrity incident is the result of corrosion of the pipelines, or an earthquake, the effects can be reduced by proper maintenance, including testing requirements and sufficient funding. When these are in order, it can lessen the impact of an earthquake, or prevent corrosion altogether.

Cavern design

Lastly, cavern design and operation can prevent or reduce the effects from movement of the rock mass (through creep, local tectonics and cavern convergence) and stress on the casing caused by cavern instability incidents and issues caused by pressure surges from nearby caverns. Cavern design is a measure that is set in place during the building and design stage of the storage cavern. Understanding the local geology, knowing about surrounding underground activities like other storage caverns and other parameters like cavern depth are all part of cavern design. Operation is also part of cavern design, and includes pressure cyclicity and maximum/minimum cavern pressures to prevent creep or fracturing.

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[13] A report from 2008 on the investment climate and market structure of the energy sector in Armenia, which can be found here: https://www.energycharter.org/what-we-do/investment/investment-climate-and-market-structure/investment-in-armenia-2015/

4.3.2.3. Escalation factors

Seismically active area

The causes of a well integrity incident can also be escalated. When the cavern is situated in a seismically active area, chance of earthquakes increases, or at least, the magnitude of earthquakes are relatively higher.

Well reuse and well conversion

An escalation factor of well design is the reuse of existing wells and well conversion. An incident in Hutchinson, Kansas, United States of America, in 2001 resulted in new well regulations. A formerly plugged and abandoned cavern was redrilled for storage, however, a leakage through the well resulted in the lateral migration of gas of 8 kilometers. The gas reached the surface and resulted in several blow-outs. These resulted in 2 deaths. This major incident resulted in restrictions on well-conversion (caverns designed for LPG storage cannot be converted to store gas) and plugged and abandoned caverns cannot be reopened and reused. More on this example can be found in the previously stated paper by Bérest et al. (2019) and Appendix 2: United States of America.

Pressure cyclicity

One escalating factor which can result in a change of the stress field around the well casing is pressure cyclicity, as this could increase salt creep, or cause other movements of the rock mass and potentially fracturing. Other escalating factors which have an effect are salt heterogeneity (which can change the stress field above the cavern roof) and, as previously stated in the causes of well integrity incidents, distance of the last casing shoe to the cavern, Thompson et al. (2007).

Salt heterogeneity

Salt heterogeneity can also impact cavern instability incidents, as roof falls are more prominent in highly heterogeneous salt formations (for example anhydrite blocks at the cavern roof or wall, see the Danish case study described in the cavern instability incidents chapter).

Cavern wall thickness

Finally, a thin cavern wall can escalate both the cavern instability and pressure surge from a nearby cavern causes, the former because a thin wall can increase the risk of salt falls and the latter as a this thin wall transfers pressure more easily to caverns in close proximity.

4.3.2.4. Effects

Capacity loss

There are several effects that are the result of damage to the well and subsequent leakage. One of these is that the operating pressure is lowered, this can lead to higher creep rates and thus, reducing the volume of the storage cavern. When the cavern is smaller, it has a lower capacity for storage of products.

Surface dome and cracks

There is one case where leakage away from the wellbore resulted in the formation of a surface dome (uplift of 1.5m) and cracks on the surface. This incident occurred in 1988, in Bad Lauchstädt, Germany. As the gas that was stored inside the cavern slowly accumulated in a nearby aquifer, the rock mass damaged the casing further, allowing for faster leakage. More on this case can be found in Appendix 2: Germany, and the previously stated paper by Bérest et al. (2019).

Pollution

As discussed in the case study, pollution is one of the effects of a damaged well and subsequent leakage. This pollution can be underground, in groundwaters, as well as surface water.

Operational readiness

Another effect is that a cavern can lose operational readiness, for example when several tests need to be conducted before storage can resume or when pressure needs to be lowered before usage can continue.

Health of local residents

Negative effects on the health of local residents is an important effect of well leakage. It is possible that workers or local residents get severely injured, or even die, due to effects of a well leakage. An example of this is mentioned in the causes paragraphs in this chapter. This incident in Barbers Hill, Texas, a well leakage led to 1 fatality. See Appendix 2: United States of America for more details of the incident.

Early abandonment

Abandonment, or early abandonment, can be an effect of well integrity loss. When the leakage or its effects are severe, caverns are plugged and abandoned. Sometimes, it is a possibility to recomplete a cavern, but it is shown by the Hutchinson incident example (see causes paragraph of this chapter) that this can have other negative consequences.

Hydro-fracturing

Casing damage and leakage can lead to hydro-fracturing, when the pressure of the stored product is higher than the surrounding rock formation can accommodate. When this happens faults and shear zones are reopened, see the Epe case study, and there is a loss of storage product. When the leaked product travels up to the surface, a blow-out can ensue. This happened in 2014 in the Prud'Homme Saskatchewan storage, in Canada. Here the casing failed, and the high pressure gas release that followed resulted in a blow-out. See Réveillère et al. (2017) and Appendix 2: Canada for more information.

Surface disruptions

A blow-out can catch fire and explode and it can also cause a crater to form, uplift surface rocks and tilt trees. This happened in 1973, in Elk City, Oklahoma, in the United States of America. A leakage accumulated into a reservoir after which the cavern formed a crater and lifted several 30-ton boulders. More on this case can be found in Bérest et al. (2019) and in Appendix 2: United States of America.

4.3.2.5. Mitigation measures

Monitoring and action

There are many mitigating measures which can be used to reduce the effects of well integrity incident. One of these is monitoring. This monitoring is only effective when an action is coupled with an anomaly found during monitoring. There are a number of ways to monitor a leakage, some of these are monitoring of the well, pressure monitoring (for example by comparing the pressure in the annulus and the inner tubing of the well), analysis of geological data and temperature logs.

Soil remediation

In the case of pollution, some mitigating measures are soil remediation (see the Epe case study), placing sheet piles to physically block the storage product from entering an aquifer or, for example, a nature reserve. Another measure to reduce the effects of pollution is pumping out the storage product, this means less product is lost, and less product can leak away as pressure is reduced (this was also done in the Epe case study).

Another way to reduce the effects of pollution, and reduce the effect of forming a surface dome and cracks on the surface, is to drill holes in the water table to vent the product or extract the product. This can prove especially helpful if the product is gaseous. An example of this is the leakage in the Eminence salt dome in 2010, after the leakage was reported, gas extraction wells were drilled. More information on this case can be found in Appendix 2: United States of America, and Bérest et al. (2019).

Evacuation

As mentioned in the case study, evacuation can reduce or negate negative effects on the health of local residents. Another mitigation measure noted in the case study is the destruction of food stock, in this case the killing of cows that drank polluted water. It can also apply to other agricultural food like vegetables that are polluted by storage products.

4.3.2.6. Escalation factors

Nearby reservoir

One of the main escalating factors is the presence of a nearby reservoir, it allows for the leaked product to go away from the wellbore faster and a reservoir can hold large volumes. It is an escalating factor for hydro-fracturing when a fracture reaches into a reservoir, and it is also an escalating factor for pollution, for it allows faster and wider spread of the stored product.

Ignition of a blow-out

Another escalation of a leakage is related to surface blow-outs, these can be ignited independently (not related to the blow-out), as well as ignition related to the blow-out directly (for example; damage to a building due to the blow-out resulting in a spark). In both cases, the storage product can catch fire and explode. An example of this occurred in Yaggy, Kansas, a leakage resulted in a blow-out that ignited and exploded. Two fatalities were recorded. More on this case can be found in Appendix 2: United States of America and Yang et al. (2013).

4.4. Well control loss

Well control loss occurs when hydrostatic pressure and formation pressure are not maintained and influx of fluids into the wellbore (or outflow of storage products) takes place, all while the well remains intact. This can be caused by process errors (human errors and measurement errors, among others) and encountering unexpected pressures during drilling, testing and workovers on the well.

4.4.1. Case study

The case study describes an incident that took place on September 21st in 1978, in West Hackberry, Louisiana, United States of America. This incident belongs to the well control loss group, as it has to do with the fluid pressure within the well, and the well remained intact during the incident. The bow-tie specific to this incident can be found on the following page, figure 20.

One of the caverns was undergoing repairs; "*withdrawing the 5.5-in tube, repairing a leak on the 12.75-in casing, and reinforcing the wellhead equipment*", Bérest & Brouard (2003). To bring the pressure at the wellhead to zero a high-viscosity mud was placed in the annular space between this 5.5-in casing and the larger 9.62-in casing as a barrier. Finally, to seal the well off from the cavity, an inflatable packer was placed (figure 19, left). As the casing was pulled towards the surface, this packer slipped (figure 19, middle), and due to the increasing pressure differential between the pressure above the packer and the cavern pressure, it shot up, creating a geyser of oil at the surface (see the figure 19 on the right).

This geyser killed one worker, and resulted in one injury. Further escalating the incident, the geyser caught fire through a spark. The oil leakage (apart from loss of product) also resulted in environmental pollution, with an influenced area of 90000m^2.

Bérest & Brouard (2003) note that another precaution could have been taken; which is releasing the wellhead pressure on the oil to zero. This would make the chance of a blow-out zero. More information on this case can be found in papers written by Bérest & Brouard (2003); Réveillère et al. (2017); Yang et al. (2013) and more information on this storage location can be found in the United States of America section of Appendix 2.

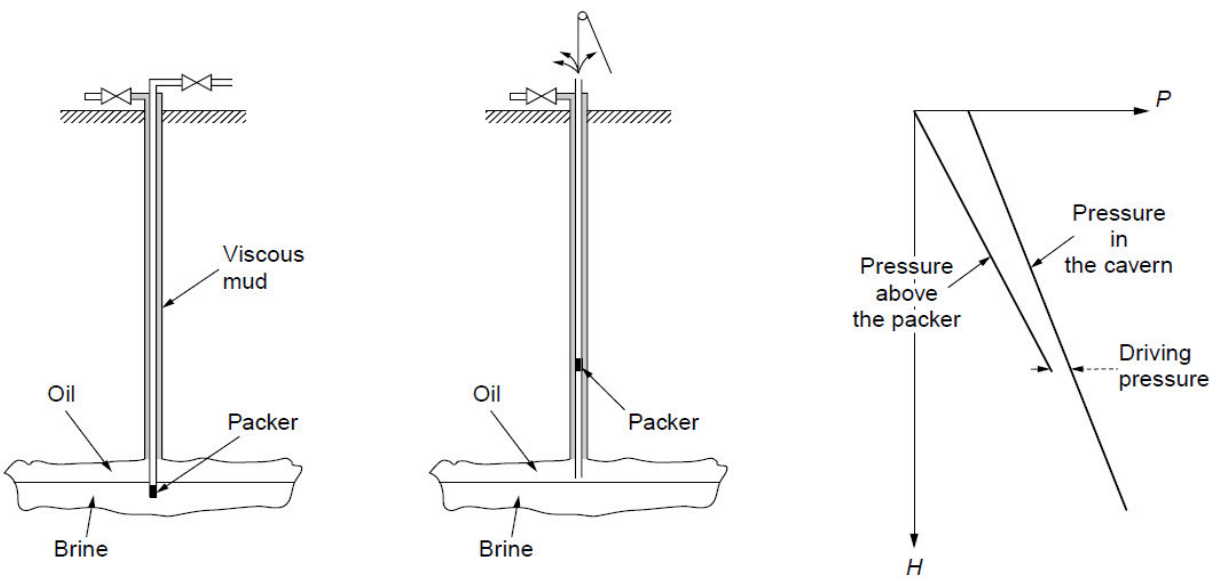

Figure 19 Schematic of the West Hackberry blow out. Showing the rise of the inflatable packer on the left and middle figure. The figure on the right shows the increasing pressure differential between the pressure above the packer and the pressure in the cavern. From Bérest & Brouard (2003).

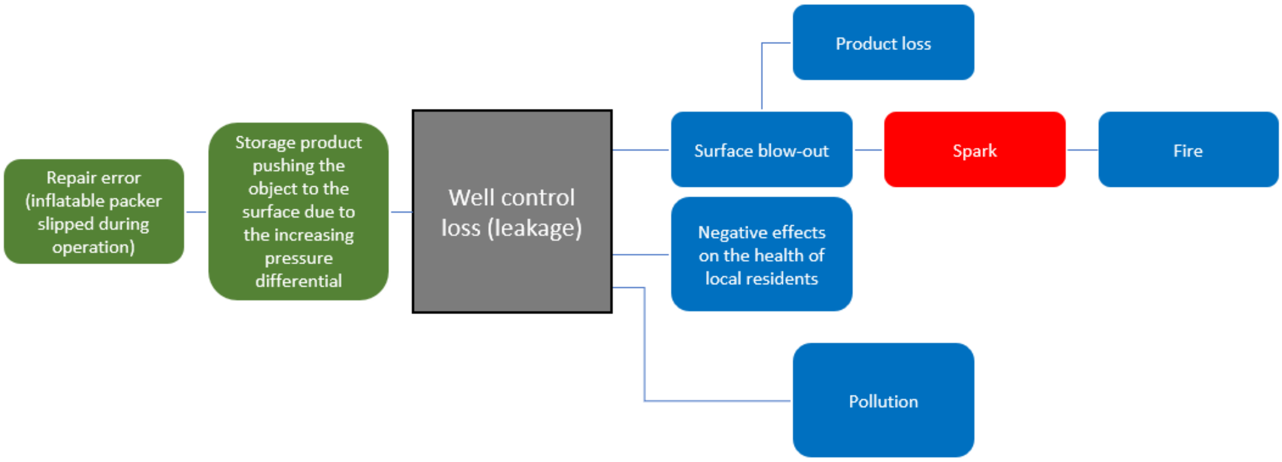

Figure 20 Bow-tie of the West Hackberry well control loss incident.

4.4.2. Well control loss bow-tie

The general bow-tie on well control loss incidents can be found on the following page, figure 21. This incident group has the top event leakage to the surface, through the well, without damage to the well.

4.4.2.1. Causes

Repair errors

As described in the case study, repair errors (for example during drilling operations and other workovers) can cause leakage, when a barrier like an inflatable packer slips and is pushed to the surface.

Procedural errors

A similar cause is a procedural error, there is one example where a tool got stuck in the well during a wireline survey. This happened in 1984, in Teutschenthal/Bad Lauchstädt. The tool got stuck, after which the upper part of the wellhead had to be lifted up. Immediately when it was lifted up, pressure build up and the wellhead pressure increased uncontrollably leading to a blow-out. More on this case can be found in the previously stated paper by Réveillère et al. (2017) and Appendix 2: Germany.

Operating errors

Operating errors can cause well control loss incidents. One of these errors is overfilling. An example of this is the overfilling due to LPG injection in a Brenham storage cavern, in Texas, United States of America. This incident took place in 1991, due to overfilling and a valve failure, a blow-out and ignition of LPG resulted in severe effects; most notably, 3 deaths and 23 injuries. See "*Analysis of major risks associated with hydrocarbon storage caverns in bedded salt rock*" by Yang et al. (2013) and references therein as well as Appendix 2: United States of America for more details.

4.4.2.2. Prevention measures

One of the prevention measures was described in the case study; the filling of an annular space with highly viscous mud. This is called a top kill fluid, it can be used during repairs, and has prevented a leakage in 2011, in Moomosin, Saskatchewan, Canada. See the previously stated paper by Réveillère et al. (2017) or Appendix 2: Canada for more information on this case.

Other potential prevention measures can be proper training of workers to prevent procedural errors, as well as strict guidelines on working conditions preventing long hours causes fatigue, and pressure management to prevent overfilling.

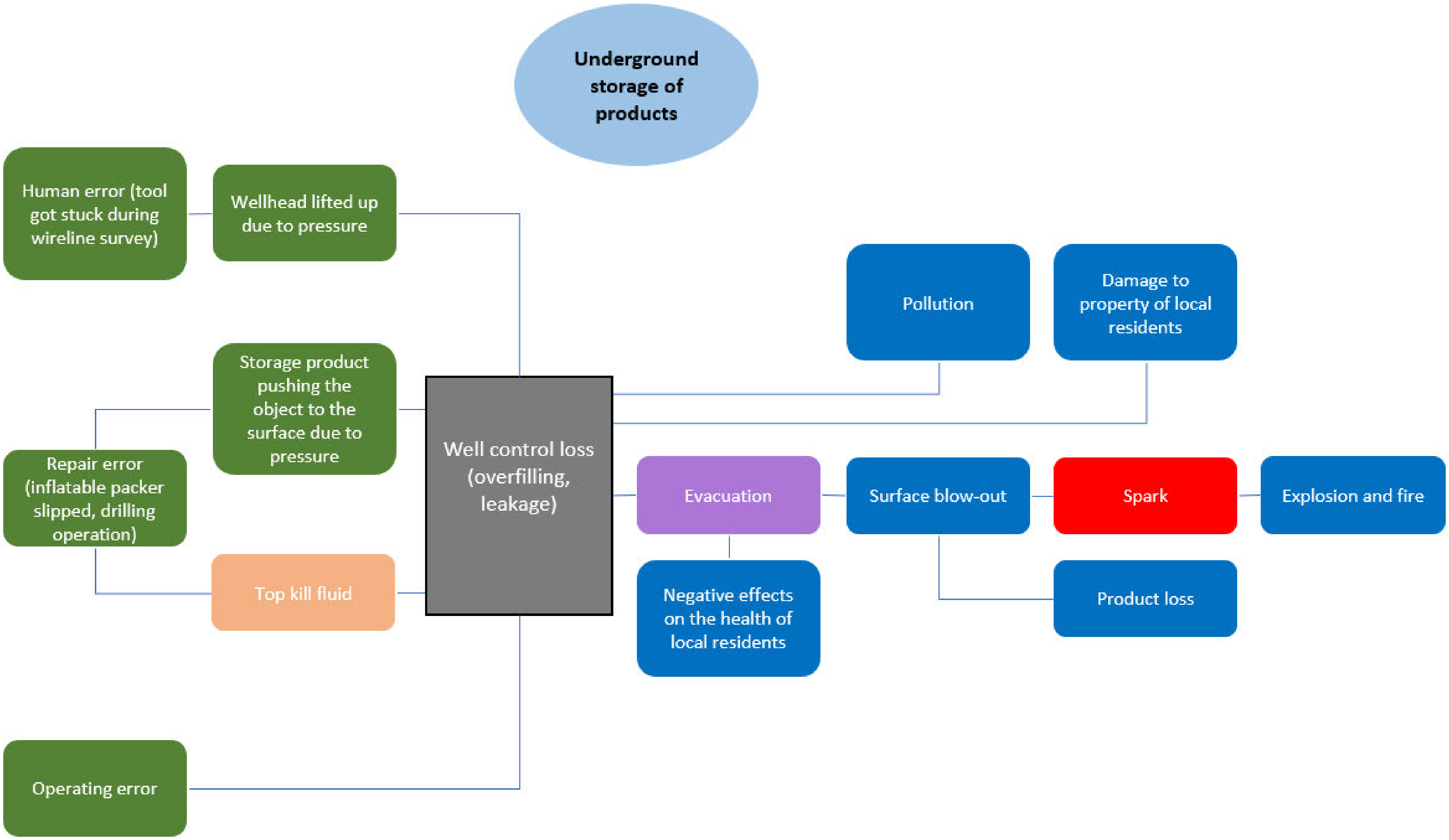

Figure 21 General bow-tie of well control loss incidents.

4.4.2.3. Effects

Most effects have been described in the case study; pollution, negative effects on the health of local residents, a surface blow-out and its potential to ignite, causing fire and an explosion, and the loss of the storage product.

Other potential effects are damage to the property of the operator, and local residents, for example damage to buildings, or infrastructural or agricultural damage.

4.4.2.4. Mitigation measures

The most important mitigating measure is evacuation, this reduces the negative effects to the health of local residents and workers during blow-outs and potential subsequent explosions and fires. It can also reduce the negative health effects of pollution, especially when storage products enter groundwater that is used for human consumption, cattle or crops.

Similar to the well integrity incident chapter, flaring and product removal are mitigating measures.

4.4.2.5. Escalation factors

When a blow-out occurs it can be escalated by a spark, which can ignite the storage product and cause fires and explosions. This spark can be generated by several different means, there is one example where a gas cloud was ignited due to a spark created by a car on-site. This happened in the Brenham incident, which is described in the causes section of this chapter.

4.5. Pipeline integrity loss

This last group encompasses aboveground integrity losses to the pipelines around a storage cavern. This includes the "Christmas tree" and the wellhead, and any other aboveground infrastructure. Incidents which describe damage or leakage of these pipelines were added to this group. As the geology of the underground is not as relevant in this incident group, the bow-tie is not discussed as extensive as the other groups. There is however a section where the bow-tie is compared to other research on pipeline integrity loss incidents, as there have been several risk analysis studies on the subject.

4.5.1. Case study

This case study and the bow-tie are based on the pipeline integrity loss of a cavern in Fort Saskatchewan in the province of Alberta, Canada. On the 26th of August, 2001, surface pipelines leaked ethane. "*The cause of this leakage was elbow failure due to a non-metallic inclusion from the internal diameter to external diameter of said elbow, which formed during the forging process*", Réveillère et al. (2017) and references therein. This resulted in the following effects. Two hours after the failure, ethane started leaking and a surface blow-out resulted in loss of the product. This gas plume was ignited by electric arcs, and thus ignited resulting in an explosion and fire. Another effect was that the two wellheads of the caverns double well system were linked. Learnings after the incident resulted in the following two measures; the 2-inch line between the two wells was eliminated and all the natural gas liquid wellhead lines were to be equipped with emergency shutdowns. More information on this storage location can be found in the Canada section of Appendix 2. The case was described by Réveillère et al. (2017), and Yang et al. (2013).

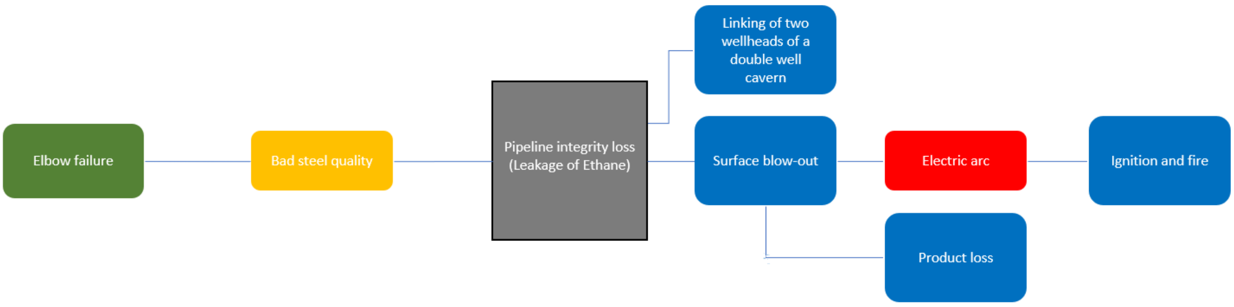

Figure 22 Fort Saskatchewan case study bow-tie.

4.5.2. Pipeline integrity loss bow-tie

The pipeline integrity loss bow-tie can be found on the following page, figure 23. Comparing the bow-tie to bow-ties written by Muniz et al. (2018), figure 26 and Shahriar et al. (2012), figure 24 and 25, there are a couple things to note. These are described in the following paragraphs.

4.5.2.1. Shahriar et al. (2012) bow-tie

The bow-tie by Shahriar et al. (2012), partly modified after Sklavounos & Rigas (2006) is shown on page 43, figure 24 and 25.

The causes of the bow-tie are subdivided into natural gas release through a puncture and a fracture, where underlying causes are described in a separate bow-tie (figure 25). This distinction was not made during this study, and where causes like corrosion are generally described here, it is extensively described in the study by Shahriar et al. (2012), including several sub bow-ties for underlying causes.

As for the effects of pipeline integrity losses, they described effects with and without the escalation factor ignition. The effects without ignition are largely similar to our work, product loss and a blow-out, but they did not specify that there can be negative consequences to the health of local residents

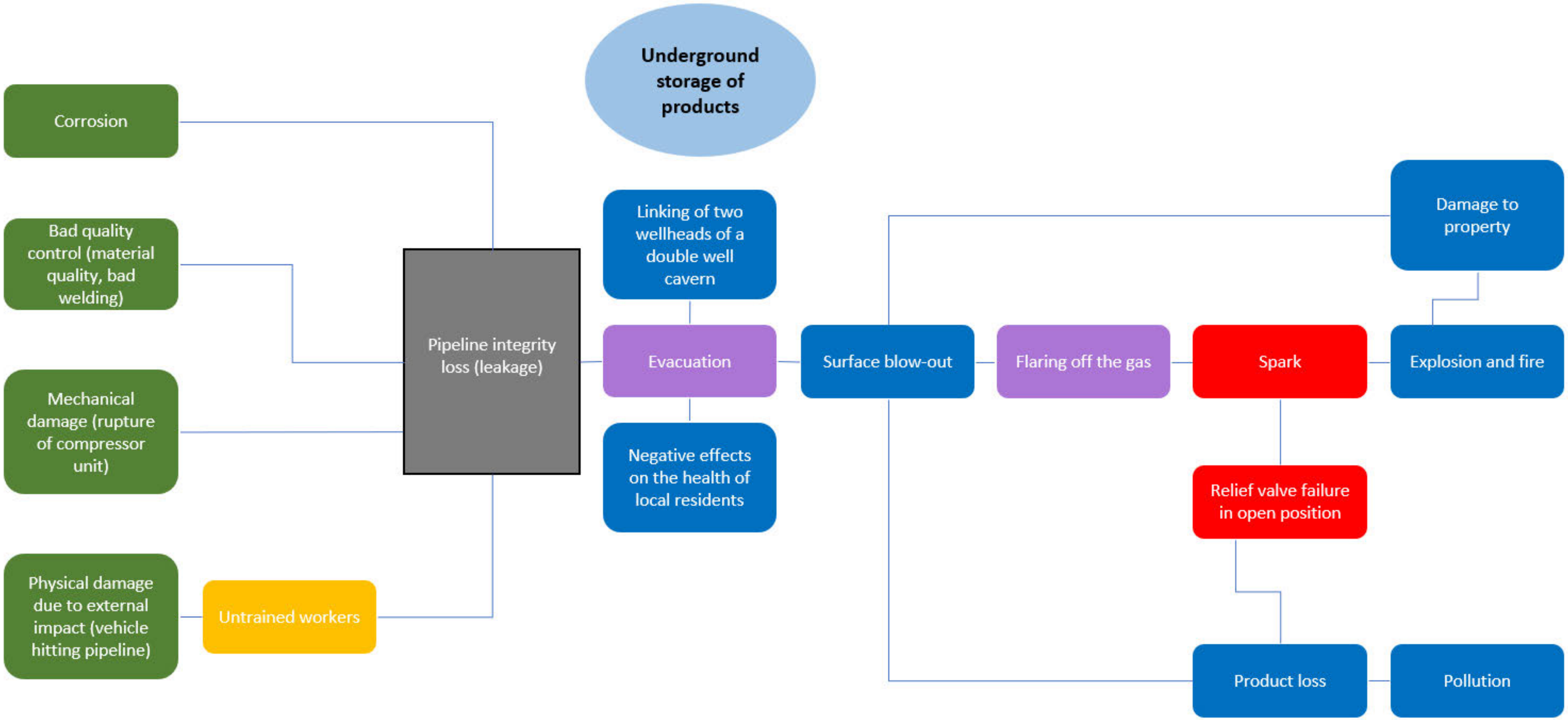

Figure 23 General pipeline integrity loss bow-tie.

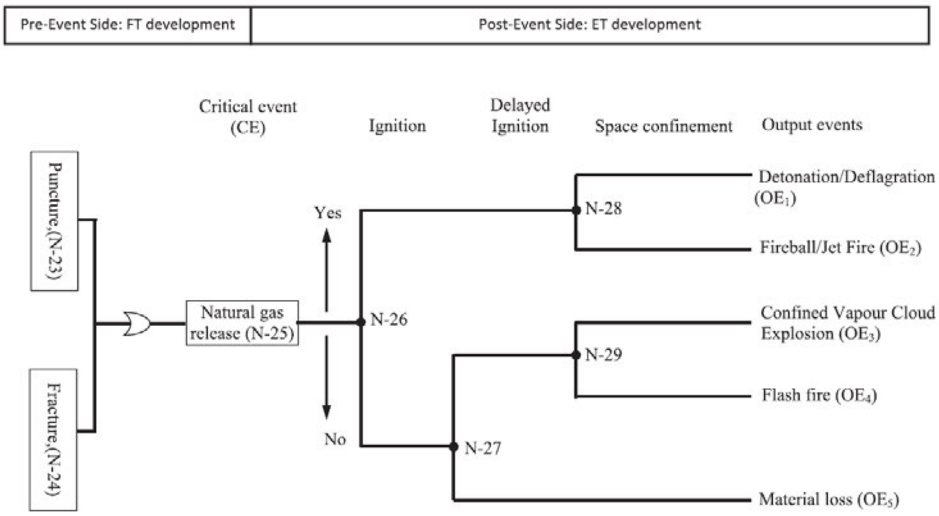

Figure 24 Bow-tie for pipeline integrity loss incidents in gas storage caverns, from Shahriar et al. (2012), who partly modified it from it from Sklavounos & Rigas (2006).

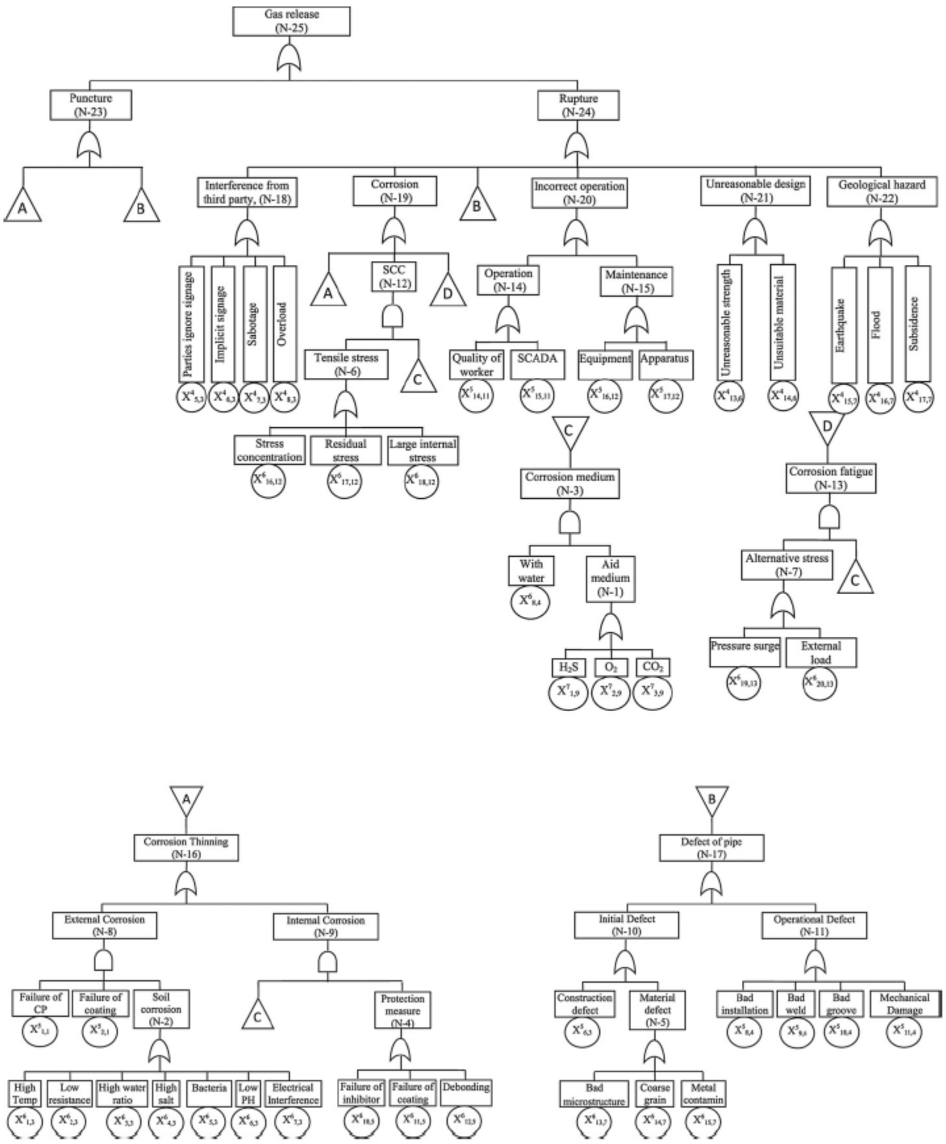

Figure 25 Extensive bow-tie for pipeline integrity loss causes in gas storage caverns, from Shahriar et al. (2012).

in the bow-tie or a connection of several wellheads of the same cavern. They made a distinction between delayed ignition and immediate ignition, as well as the presence of space confinement: where space confinement results in in detonation and no space confinement results in a fire ball. Here these effects are described in one group; fire and explosion.

Finally, there seem to be no prevention measures on the left-hand side and no mitigation measures on right-hand side of the bow-tie, to be able to have more control on the outcome of incidents.

The escalation factor ignition has been described in more detail by Shahriar et al. (2012), as they included delayed and immediate ignition, and the possible presence of space confinement.

There is a lot to learn about the bow-tie by Shahriar et al. (2012), as they go rather in-depth on the causes of pipeline integrity losses. They included theoretical scenarios like sabotage (there has not been found any record of a cavern storage incident due to sabotage on storage sites during this study) and extensive physical effects on corrosion (bacteria, low PH and high temperatures, among other things). One example of sabotage was during the Gulf War in 1991. Saddam Hussein's '*Scorched Earth*'[14] strategy involved the Iraqi army blowing up oil wells in Kuwait. This caused major environmental impact and showcases the real possibility of incidents due to sabotage.

4.5.2.2. Muniz et al. (2018) bow-tie

The causes of the bow-tie from Muniz et al. (2018), figure 26, include rupture due to material failure, rupture due to internal corrosion, rupture due to external corrosion, rupture due to external interferences like digging (in this study physical damage, like a vehicle hitting a pipeline), rupture due

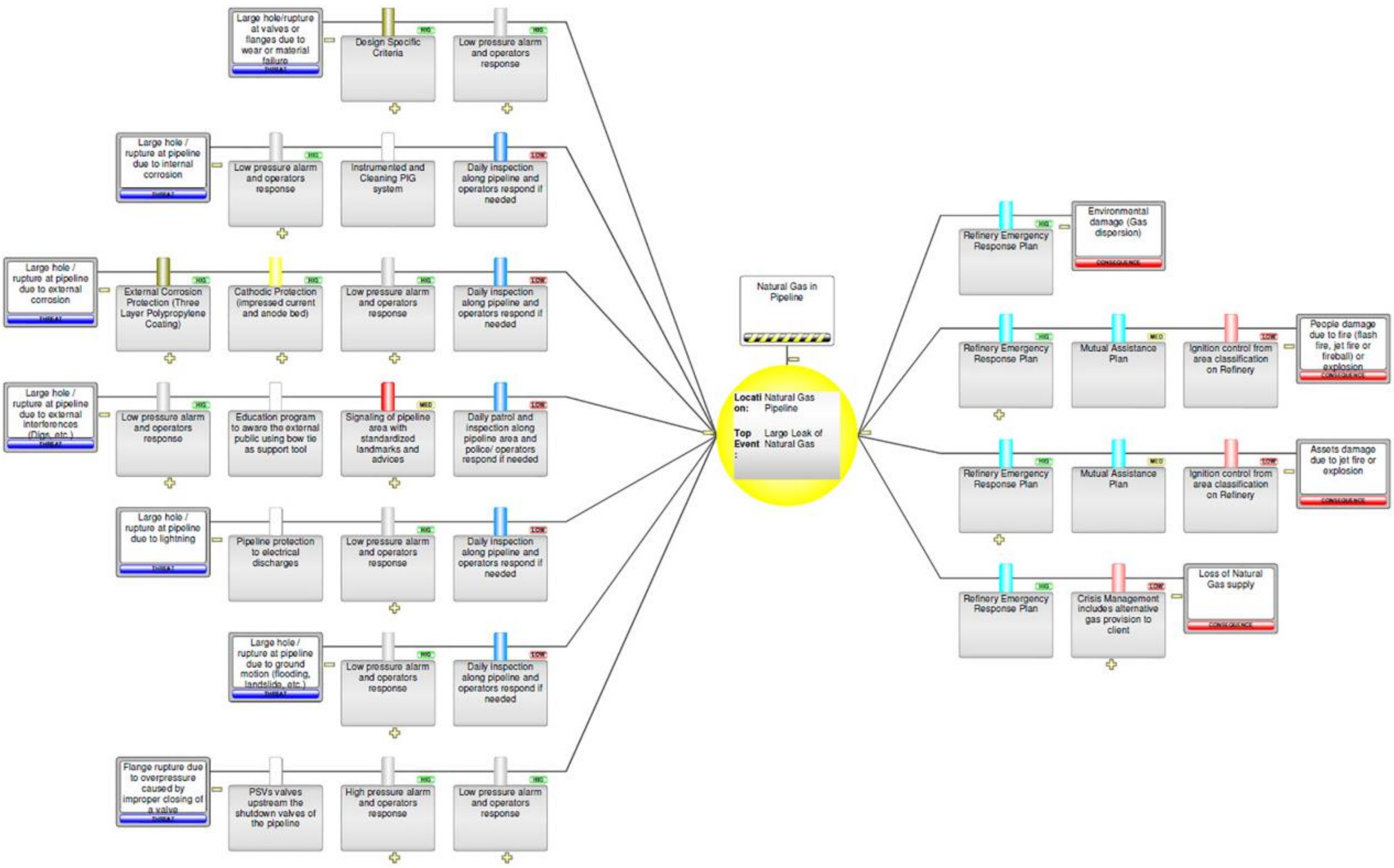

Figure 26 Bow-tie on natural gas pipeline leakages from Muniz et al. (2018).

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[14] News article on the 'Scorched Earth' strategy of Saddam Hussein: https://www.npr.org/templates/story/story.php?storyId=988641

to lightning, rupture due to ground motion and finally flange rupture due to overpressure caused by improper closing of a valve. All of these causes contain several prevention measures, and an estimation for their effectiveness. These causes are more extensive than the general bow-tie created for this study.

Effects of the gas release include environmental damage (pollution in this study), people damage due to fire or explosion (which is included in this study), assets damage due to fire or explosion (damage to property in this study) and loss of natural gas supply (product loss in this study). All effects are similar to the general bow-tie created in this study, but fire included several different examples. The effects include several mitigating measures.

It is apparent that both authors describe pipeline integrity loss incidents in greater detail, especially in on the left-hand side of the bow-tie, where the causes are discussed in more detail than this study. As the scope of this study is focussed on geological factors on the storage cavern itself, pipeline integrity was described in lesser detail.

5. Discussion

5.1. Inventarisation

In this chapter, the potential correlations between several parameters and incidents are discussed. These are not statistically significant as there is a low number of reported incidents in salt cavern storage. Their potential significance and meaning are described to entice future research on incidents that occur during salt cavern storage. Perhaps it may prove necessary to include incidents at brine production caverns and theoretical work in this research, as these share many properties with storage in caverns. As there are more reported incidents in brine production caverns (because brine production has been ongoing for a longer time, at a larger scale), these types of caverns may be useful to find statistically significant correlations between several different parameters and incidents in salt cavern storage.

5.1.2. Bedded vs domal salt

As shown in table 7, more incidents have been reported in caverns in domal salt (50 incidents) than in bedded salt bodies (18 incidents). In 19 incidents, it was unknown in what kind of salt body the incident took place. The incidents have been normalised to the total number of caverns per salt type. This showed that ~2% of storage caverns in bedded salt have had an incident. Comparing this to the ~9% of caverns that have had an incident in domal salt shows that bedded salts have relatively fewer incidents. Of the caverns where the salt body type was unknown, ~16% have experienced incidents. This suggests that bedded salts are better suited for cavern storage than domal salt. However, local conditions apply, like the geology and heterogeneity of the rock mass.

Figure 7 shows a histogram where incidents are categorised per group and in what kind of salt body the incidents have occurred. In all cases, caverns have had more incidents in domal salt, strengthening the above statement. One thing of note is that cavern integrity loss incidents seem to occur almost exclusively in domal salt (and unknown salt bodies), as there is only one reported incident in bedded salt.

In trying to find out why domal salts may be more likely to have incidents, one can think of several causes. Bedded salts might be relatively predictable, as they are still layered in their original horizontal positions, while the inside of domal salt bodies is more complicated and hard to determine. For example, seismic's difficulty to find layers or anomalies that are steeply dipping or oriented vertically, see Strozyk et al. (2012) on seismic interpretation of vertical stringers. In line with this, heterogeneities like insoluble or soluble layers in bedded salts may be more evenly spread and horizontally oriented across a cavern, whereas in domal salts those layers are likely to be at an incline or all broken up (like the Danish cavern TO-9, from the cavern instability case study). As the stress field of domal salt is more complicated than that of bedded salts, due to their more intricate shapes and past movement, it is reasonable to assume this translates to more anisotropic stresses in both the cavern and the well, aggravating salt movement and potential incidents.

5.1.3. Depth range for incidents

Depth is the other parameter that was analysed. It should be stated that in ~57% of the storage caverns found during this study the depth range was unknown. This means the data can be heavily skewed, and if more information on the depth of caverns is found, the results and the respective interpretation may change.

Table 8 shows that most incidents take place in the 1000-1500m depth range. However, when we normalise the incidents to the total number of caverns in each depth category (see table 9), it is apparent that relatively, most incidents occur between 0 and 500m depth. ~35% of studied caverns in this range have had an incident. The other most incident prone depth category, 1500m+, has ~12% of its caverns compromised. Remarkably, both the deepest and shallowest depth categories seem most prone to incidents. For the deepest category, an argument can be made that higher temperatures and higher pressures result in higher creep rates, thus allowing for more rock mass movement, increasing the stress field on the cavern and the well. As shown in figure 8, most incidents in the shallowest depth region come from the well integrity loss incident group. This can indicate that shallow caverns are more prone to well integrity incidents or that more prevention measures are taken for deeper caverns.

Another striking observation is that caverns from the 1000-1500m depth region have had relatively many cavern instability incidents. This may be because creep rates at lower depths are higher and caverns are more prone to form irregular shapes. These creep rates may also facilitate a higher amount of salt falls.

The abovementioned observations are important because they can place constraints on cavern design, most notably favourable locations in the subsurface. Likely, correlations with other parameters might exist and may be more important.

5.2. Risk analysis

For each incident group, the notable results are stated, and interpretations on what they mean are made. Bow-ties give a clear representation of the different steps of an incident, and therefore can be helpful for understanding cavern storage better, as well as give insights into possible points of improvement. They also provide guidance to both operators and regulators, for possible scenarios that may occur during a storage cavern incident.

Bow-ties do have their limitations, as they can be both complicated and oversimplified. The general bow-ties in this study are relatively simple, but some lose clarity due to cluttering of different causes and effects. As shown by Shahriar et al. (2012), one way to mitigate this is to make sub-bow-ties. This, however, has consequences on the readability as well.

5.2.1. Cavern instability and cavern integrity loss

The most important prevention measure for incidents in caverns is cavern design. When it is applied in a good fashion, it can significantly improve cavern safety. This is especially important during the building and design phase of a storage cavern. Cavern instability incidents have many different causes, and many of these have to do with the geological conditions around the cavern. This is apparent when looking at the Danish case study on cavern TO-9 (Appendix 2: Denmark), where block fall occurred. The main driver of this was salt heterogeneity; insoluble blocks were standing in near-vertical positioning, which means they are difficult to find during a seismic survey. This shows that one of the big challenges of cavern storage is that there are many unknowns; a salt body is not necessarily one homogeneous mass of rock salt.

Thorough geological surveys are important to understand the complications due to salt heterogeneity, as the presence of heterogeneities can lead to many incidents. This is not just the case in the cavern (instability and integrity loss) incident groups but also in the well integrity loss group. Geological surveys are part of the cavern design, but it also contains several other parameters and measures. These include pressure management, the shape of the cavern to decrease the stress field around the neck of the cavern, depth, salt body type, and the proximity to other caverns or the edge of the salt.

The cause of cavern integrity loss incidents also lies frequently in salt heterogeneity. One of these is the forming of a preferential leakage path, resulting in a hydraulic connection. Salt heterogeneity can be escalated by thin cavern walls (both to other caverns and to the edge of the salt). This again shows that geological research on the local salt lithology is very important to prevent incidents, furthering the importance of cavern design in the pre-leaching phase.

Another key part of cavern design is pressure inside the cavern; low-pressure, fast pressure changes and cyclic loading can make the cavern unstable. This proves that pressure management is an important prevention measure. Furthermore, all causes of a cavern integrity loss incident relate to pressure changes, both inside and outside the cavern. As shown in the cavern instability chapter, thermal stress due to cyclic loading can result in incidents; it is, therefore, important for salt cavern stability assessment, Li et al. (2021). Research on fast pressure changes and their risks can be found in Wang et al. (2018). It contains an example of an incident due to bad pressure management (cavern JK-A in China), also previously discussed in the cavern instability risk analysis (Chapter 4.1).

More recommendations on safe pressure operation can be found in Chen et al. (2021), and theoretical maximum gas production rates can be found in Liu et al. (2021). These are all part of pressure management, which is a key part of cavern design.

5.2.2. Well integrity loss

Cavern design and the operation of the cavern is important for the safety of the well, as it can influence the behaviour of the rock mass (convergence of the cavern due to creep increasing the stress on the well). Cavern design can prevent escalations due to a thin wall (proper geological surveying). It can also prevent interference of salt heterogeneities (location picking). As such, cavern design is of high importance to well safety.

The primary prevention measure is well design. This can mean several things, most notably a double barrier in the cemented casing to prevent leakage, and quality assurance, which can prevent corrosion and other causes of well integrity loss. When well design is considered, many causes for well integrity loss incidents can be negated or have their impact lessened. One example is the Boling salt dome (see Appendix 2: United States of America), where 3 of 4 storage caverns had well integrity loss, Thompson et al. (2007) state that some distance of the last cemented casing shoe to the cavern is integral to prevent stress on the well casing. The one cavern with sufficient space between the cavern and the last cemented casing did not experience leakage. In another example, a Hutchinson storage cavern never came into production because the reuse of an existing previously abandoned well resulted in leakage, Bérest et al. (2019).

Proper maintenance, which should occur during the operational lifespan of the storage cavern, also influences important causes like corrosion. Testing requirements for storage caverns is one such way to conduct maintenance to assess the safety of the cavern and the well. It can also mean sufficient funding, which should be considered before leaching, to ensure the longevity of the cavern. An example of this are the Abovyan caverns N6 and N9, in Armenia, where insufficient funding contributed to well leakage, Energy Charter Secretariat (2008).

When the top event, leakage, has occurred, it is important that there are mitigating measures. One of these is monitoring, which includes many different surveys. However, it is key that monitoring is coupled with subsequent action. When something is wrong, a reaction is critical to prevent further effects. There is a wide range of mitigating actions that can be taken to prevent these effects, like placing sheet piles and soil remediation to prevent pollution. More can be found in the well integrity risk analysis chapter.

5.2.3. Well control loss

Loss of well control can lead to several effects, like a blow-out, pollution and damage to property of local residents and the operator. The causes of the incidents are often related to operating errors, repair errors or human errors as these can all change the pressure in the well. It is important for workers to be properly trained and to be able to be well-rested to prevent human errors. Operating errors like overfilling can be prevented with proper pressure management. It is also important to have mitigation ready like kill fluids.

5.2.4. Pipeline integrity loss

The difference between the general bow-tie made for this study and the bow-ties made by Muniz et al. (2018) and Shahriar et al. (2012) is the considerable amount of causes and sub-causes they added to theirs. However, in our attempt to make the bow-ties as general and easy to understand as possible not all underlying causes have been added. Both authors take into consideration several hypothetical causes like rupture by lightning and sabotage. As these are hypotheticals and are not found in any published incidents used for this work, they have not been added to the general bow-tie. Overall, all three bow-ties show the main causes and effects of a pipeline integrity loss incident, while this work was done without knowledge of these works in advance. This incident group exists on the edge of the scope of this work, and as such, no further comments are made.

5.2.5. Conclusion

The key points from the risk analysis are that lots of incidents can be prevented if proper measures are taken. These measures often relate to cavern design (and all of its components like pressure management and a thorough geological survey of the area), well design and proper maintenance. The cavern and well design need to be extensively thought out during the building and design phase of a storage cavern. Another important point is that monitoring needs to be complemented by an action; monitoring in itself is not a preventive or mitigating measure.

6. Lessons learned

6.1 The current situation

To give recommendations to the Dutch industry of cavern storage, a short summary of ongoing storage and its current storage plan should be provided. N.V. Nederlandse Gasunie owns a cavern for the storage of nitrogen in Heiligerlee, Groningen. This cavern lies in domal salts at a depth of 1016-1510m. There are few published incidents in the Netherlands, although there has been one incident in this storage location. Among a capacity increase, a minor leakage[15] along the well of this storage cavern resulted in a review of the storage plan[16] in 2019. It shows that maximum daily pressure cycling and minimum/maximum pressures are redefined. The maximum daily pressure difference is an increase or decrease of 10 bar, and the minimum pressure is 70 bar. The maximum pressure is defined at 147 bar. This pressure management was built in as a safety precaution, where higher minimum pressure is a counter to creep and subsequent subsidence, and a lower maximum pressure acts as a barrier to leakage. The advice of the State Supervision of Mines[14] is that the storage in Heiligerlee is effective, but that it is important to start thinking of the method of abandoning early, as this abandonment is complicated by five brine production caverns at a distance of 250m. As mentioned in the cavern instability chapter, thermal stress due to cyclic loading can result in incidents; the nitrogen storage plan shows that N.V. Nederlandse Gasunie has used thermodynamic modelling to ensure that pressure management is adequate in staying within the operational pressure constraints.

EnergyStock BV, a daughter company of N.V. Nederlandse Gasunie, has 6 caverns for the storage of natural gas, in Zuidwending, Groningen. These caverns are situated in domal salt and lie at depths of 500-1600m. A storage plan[17] of 2017 shows that pressure management is detailed, similar to the nitrogen storage cavern. The maximum daily pressure cycling is 10 bar, and the minimum/maximum pressures differ per cavern. The advice of State Supervision of Mines[15] on this storage plan indicates that the described pressure management is adequate, the margin for safety is sufficient. The supervisor also advised the storage plan to include that abandonment plans need to be submitted two years prior to the end of the life cycle.

The 2 Marssteden storage caverns in Enschede, Overijssel, store diesel for freight, in bedded salts at a depth of 400-500m. These caverns are owned by Nobian and Argos. The storage plan[18] of this site is from 2013. One of the key points were the stabilities of the five candidate cavern roofs, and they show that all five candidate caverns could have long-term stability based on two different criteria. State Supervision of Mines concludes in their advice[16] that it may be expected the caverns have long-term stability. State Supervision of Mines does suggest that Nobian delivers a yearly monitoring report on them.

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15 News article on the leakage in the nitrogen storage cavern in Heiligerlee: https://www.rtvnoord.nl/nieuws/170817/gasunie-geen-gevaar-geweest-bij-ontsnapping-stikstofgas

16 The storage plan for the Heiligerlee nitrogen storage and the advice of State Supervision on Mines on the storage plan can be found here: https://www.rvo.nl/onderwerpen/bureau-energieprojecten/lopende-projecten/gasinfrastructuur/stikstofbuffer-heiligerlee/fase-1

17 The storage plan for the Zuidwending natural gas storage caverns and the advice from State Supervision on Mines can be found here: https://www.agbzw.nl/projecten/vergunningen-capaciteitsuitbreiding

18 The storage plan and the advice from State Supervision on Mines for De Marssteden diesel storage can be found here: https://www.rvo.nl/onderwerpen/bureau-energieprojecten/afgesloten-projecten/overige-projecten/gasolieopslag-twente

6.2 Recommendations to the Dutch industry

What can we learn in the Netherlands from the published examples of storage caverns, for liquids and gases, in other countries?

Overall, based on the findings in this study, storage in the Netherlands is quite safe, and important prevention measures like pressure management are a part of the storage plans. The pressure management of the Heiligerlee nitrogen storage is detailed and provides boundaries to the pressure in the cavern. The same applies to the Zuidwending natural gas caverns. This benefits the safety of the storage caverns and possibly prevents incidents. The storage plan of De Marssteden shows that long-term stability of the diesel storages is achievable with their cavern design, which is desirable.

Some lessons can be learned from this risk analysis based on published examples of storage caverns in other countries. The discussion of this work showed that cavern design during the building and design phase of a storage cavern is one of the most important prevention measures. The local geology surrounding a cavern is of utmost importance to the stability and integrity of a cavern. There needs to be done extensive research in the pre-leaching phase of storage caverns. As shown by the storage plan for De Marssteden diesel storage, several different locations are discussed and investigated. It is important that cavern design (depth, pressure management, geology of the surrounding rock mass and others), well design (for example, a proper distance of the last casing shoe to the cavern neck, Thompson et al. 2007), and proper maintenance (regularly planned testing and sufficient funds to keep the desired quality) are investigated before incidents take place.

Another key point is that monitoring has no preventive or mitigating effects on its own. The monitoring needs to be coupled to actions; this way, appropriate action can be taken in a timely fashion and on clearly agreed-upon measures.

Finally, it should be mentioned that regulation by the government on cavern storage in the Netherlands is extensive and nationwide, and safety appears to be an important topic for all parties involved. Well regulations and previously mentioned prevention measures like double barriers in cemented casings are mandatory for all cavern storage wells.

7. Conclusions and recommendations

7.1. Inventarisation

The most important takeaway from the inventarisation is that more data on storage caverns is necessary to find statistically significant correlations between incidents and other parameters. One can make tentative assumptions; storage in domal salt is more prone to incidents than storage in bedded salts and that both shallow caverns (0-500m) and ultra-deep caverns (1500m+) are also more susceptible to incidents. Interpretations on why this is the case cannot be made with any certainty without future research.

Future work could be focussed on finding more information on the available published incidents, or perhaps, could include brine production cavern incidents (or include previous research in that area). These are similar in nature, and the causes of incidents may be similar if not identical (especially in the cavern instability and cavern integrity incident groups). Finally, this overview did not divide the different kinds of bedded salt (thin- versus thick-bedded salts), as there is insufficient data available. This may be an area of further interest.

It is recommended for a follow-up study to also include ‘theoretical’ research, modelling work, lab experiments and oil and gas wells. These may all provide further insights or strengthen the conclusions of this study.

7.2. Risk analysis

The general bow-ties per incident group give insights into the different steps of possible incidents. It is a guideline to be able to prevent or mitigate incidents. It is shown that cavern design and all its aspects are critical to the long-term safety of a storage cavern; it is recommended that this design includes extensive geological surveys and takes learnings from research on cavern parameters like the shape of the cavern. These geological surveys can help find heterogeneities in the salt body, but there is always uncertainty as these salt bodies can be quite complex. Pressure management is another important preventive measure for safety, and this is currently applied in the nitrogen and natural gas storage caverns. The thermal effects due to cyclic loading are important to note and are appended in the nitrogen storage plan of the Heiligerlee storage cavern. Finally, proper monitoring is important but needs to be coupled with actions to improve the safety of cavern storage.

Storing products in caverns can be done safely if proper precautions are taken, and research is conducted in the pre-leaching phase.

Regulations by the government for storage caverns in the Netherlands are set in place to prevent or mitigate incidents. Operators and supervisors communicate and together make an effort to minimise the occurrence of incidents. It is also important to mention that some causes are almost non-existent in the Netherlands (for example, incidents caused by or escalated by having wells with only one barrier, while most if not all storage cavern wells have double cemented casings). Cavern storage in the Netherlands is relatively safe compared to some other countries, but the recommendations above provide a good basis to ensure safe operation continues.

Future work on risk analysis of incidents in cavern storage could focus on elaborating and refining the preventive and mitigating measures. Defining these will have the ability to prevent incidents from taking place or lessen their impact.

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