Investigation of research needs regarding the storage of hydrogen gas in lined rock caverns

Prestudy for Work Package 2.3 in HYBRIT Research Program 1

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Summary

The objective of HYBRIT RP1 is to explore and assess pathways to fossil-free energy-mining-iron-steel value chains and thereby provide a basis for industrial development activities and the necessary future transformative change in this field. A large-scale storage capacity for hydrogen gas is an important component of the proposed HYBRIT concept. Underground storage in lined rock caverns provides a reasonable option: a large-scale demonstration plant for storage of natural gas was constructed in Sweden in 2002 and has operated safely since then. Considering that this lined rock cavern facility was constructed for natural gas, the present report investigates the current research needs to allow for underground storage of hydrogen gas in such a facility. This will serve as a basis for the research in Work Package 2.3 of HYBRIT RP1.

Studying the experiences from decades of Swedish and international research and practice on the construction of underground gas storage facilities, the conclusion is that the lined rock cavern concept seems a reasonable way forward. In terms of rock engineering research, there are currently no critical research issues; however, a development of a previously proposed risk-based design framework for lined rock caverns may further strengthen the ability to manage risks related to underground gas storage facilities. The report identifies several potential research questions on this topic to be further studied: development of a risk-based design approach using subset simulation, the optimization potential of the concrete thickness in the lining, and the effect of spatial variation of rock mass properties on a location's suitability for the storage facility.

Additionally, the report identifies the potential effect of hydrogen embrittlement on the steel lining as a critical research issue to ensure safe storage of hydrogen gas in lined rock caverns. However, as this issue is not related to rock engineering, but a material issue, it will not be covered further in Work Package 2.3.

Keywords: LRC, lined rock caverns, hydrogen gas, gas storage

Sammanfattning

Syftet med HYBRIT RP1 är att undersöka och utvärdera möjliga vägar till att göra värdekedjorna för energi-gruva-järn-stål fossilfria och därigenom ge en grund för industriella utvecklingsarbeten och den framtida omställningen. En viktig del i HYBRIT-konceptet utgörs av behovet av lagring av stora volymer vätgas. Lagring i inklädda bergrum är ett möjligt alternativ: en storskalig demonstrationsanläggning för lagring av naturgas byggdes 2002 i södra Sverige och har använts sedan dess. Eftersom denna anläggning konstruerades för naturgas, är syftet med denna rapport att undersöka det nuvarande forskningsbehovet för att kunna lagra vätgas i en sådan typ av anläggning. Detta kommer att utgöra basen för det fortsatta arbetet inom delprojekt 2.3 i HYBRIT RP1.

Efter att ha studerat resultaten från svensk och internationell forskning, samt erfarenheterna från byggnation av inklädda bergrum för gaslagring, är slutsatsen att inklädda bergrum utgör ett rimligt alternativ för lagring av vätgas. Avseende bergmekanik finns det för närvarande inga kritiska frågeställningar. Däremot finns möjlighet att vidareutveckla riskbaserade dimensioneringsmetoder för inklädda bergrum, vilket kan stärka förmågan till god riskhantering vid byggnation av sådana anläggningar. Rapporten identifierar flera forskningsuppslag inom detta område att arbeta med inom delprojekt 2.3: utveckling av en riskbaserad dimensioneringsmetod med hjälp av subset-simulering, studie av optimeringspotentialen för betongliningens tjocklek, samt hur bergmassans rumsliga variation påverkar en plats lämplighet för anläggandet av ett inklätt bergrum.

Avseende materialfrågor finns dock en kritisk frågeställning för underjordisk vätgaslagring: vätgasförsprödning av stållliningen ses som ett möjligt problem och bör studeras vidare. Men eftersom detta inte är relaterat till bergmekanik kommer det inte att studeras vidare inom delprojekt 2.3.

Nyckelord: LRC, inklädda bergrum, vätgas, gaslagring

Preface

This prestudy was carried out at the Division of Soil and Rock Mechanics at KTH Royal Institute of Technology during October 2017 to February 2018. The study was initiated as a part of the Work Package 2.3 of the HYBRIT RP1 (Hydrogen Breakthrough Ironmaking Technology: Research Program 1). HYBRIT is a joint initiative of the three companies SSAB, LKAB, and Vattenfall with the aim of developing the world's first fossil-free ore-based steelmaking route. HYBRIT RP1 was initiated in July 2017. A key issue is the possibility to store large quantities of hydrogen gas to ensure continuous steel production when there is little production in renewable energy. Lined rock caverns have been put forward as the main alternative for storage of hydrogen gas. This is the main focus of Work Package 2.3.

The lined rock cavern concept has been successfully demonstrated for natural gas in Sweden through the construction of the Skallen demonstration plant in Halland. Recognising the success of the Skallen plant and the preceding decades of research, a project team and a reference group with significant previous experience from work with lined rock caverns were formed for the prestudy. The objective was to identify the current research needs to be addressed to allow for underground storage of hydrogen gas.

The project team consisted of the report authors, while the reference group consisted of Robert Sturk, Skanska; Per Tengborg, Rock Engineering Research Foundation (BeFo); Nicklas Simonsson, Vattenfall; and Bojan Stojanovic, Vattenfall. Their contributions to the project work are gratefully acknowledged.

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Stockholm, March 2018

Fredrik Johansson, Johan Spross, Davi Damasceno, Jan Johansson, and Håkan Stille

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1. Introduction

1.1. Background

HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a joint initiative of the three companies SSAB, LKAB and Vattenfall with the aim of developing the world's first fossil-free ore-based steelmaking route. In traditional steelmaking from iron ore, carbon is a decisive component required for the chemical reduction of the (oxidic) ore in the production of (metallic) iron. Hydrogen replacing carbon as reductant is the most sustainable and technically promising option for the iron and steel industry.

The objective of HYBRIT Research Program 1 (RP1) is to explore and assess pathways to fossil-free energy-mining-iron-steel value chains and thereby provide a basis for industrial development activities and future transformative change. The six work packages within the project address the central research issues associated with a transition to hydrogen and the resulting fundamental changes in energy systems, iron ore and steel-making process technologies, as well as markets and policies (Figure 1).

One of the challenges when replacing coal with hydrogen in iron and steel production is the envisaged need of a hydrogen storage facility. The storage acts as an accumulator and buffer. This enables the iron and steel production to have access to hydrogen at demand without requiring a hydrogen production equivalent to the peak demand. The other advantage is the ability to procure and store hydrogen when process demand is low and electrical production is high. In turn, it is envisaged that such facilities can enable the national electrical system to additionally dampen future fluctuations, due to a presumed increase in intermittent electrical production, e.g. wind power.

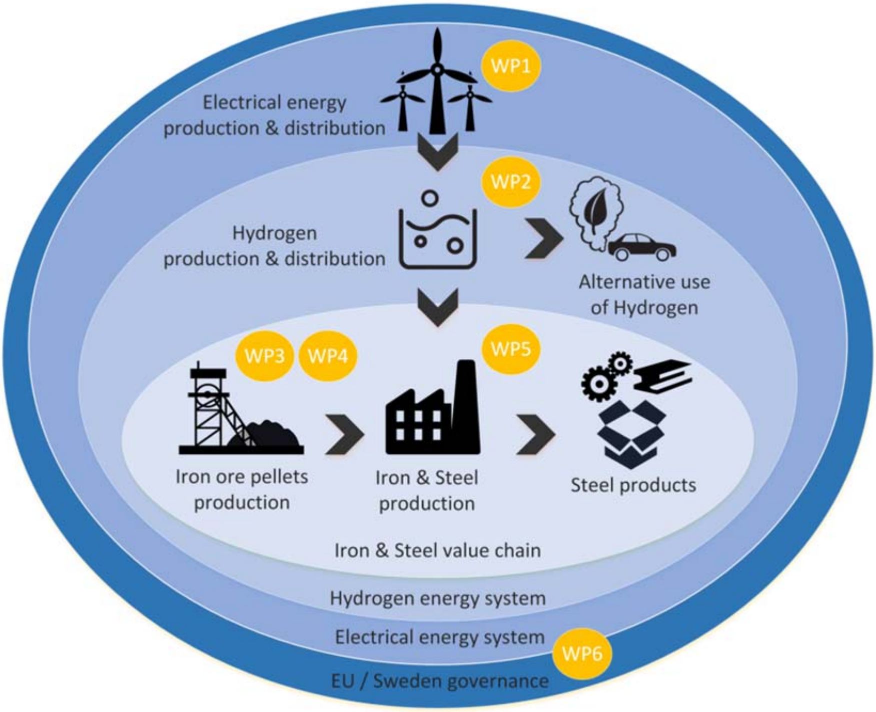


Figure 1. Schematic layout of the HYBRIT project, showing industrial process flows, work packages and domains. As can be seen, a vital step from electrical energy to iron & steel is the hydrogen production, distribution and storage. Storage is included in WP2. (© Hybrit AB, with permission)

For Swedish conditions, previous research and current practice show that underground storage in lined rock caverns (known as the LRC concept) likely is a viable option for such an energy system. A lined rock cavern currently stores natural gas at Skallen on the Swedish West coast. The development of a storage concept for hydrogen gas therefore takes its basis in the technology that was developed for the facility at Skallen; though, other storage options are investigated in another work package of the HYBRIT project.

The basic principles of the LRC concept are outlined in Figure 2. The respective components are covered in the main chapters of this report.

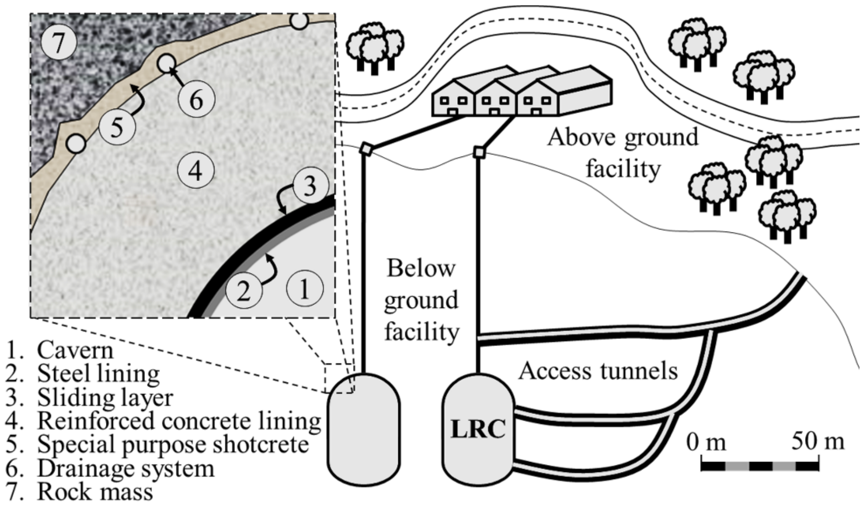


Figure 2. The components of the lined rock cavern concept for storage of gas. (Figure by authors).

1.2. Objective of the prestudy

The purpose of this prestudy is to investigate the current research needs regarding storage of hydrogen gas in lined rock caverns. The objective is to establish the most pressing rock engineering research issues that are to be addressed in the execution of WP 2.3 in HYBRIT RP1.

1.3. Outline of report

The report is outlined as follows. Chapter 2 describes the general principles of the LRC concept in light of both the external conditions that the planned use of the hydrogen storage facility implies and the current Swedish legislation that is applicable. An overview of the international state-of-the-art in underground gas storage is also presented. Chapter 3 discusses the design principles that are available for large, lined underground rock caverns, with focus on structural safety and risk management concepts. Chapter 4 identifies and discusses the current research need. Chapter 5 summarizes the main conclusions of the report.

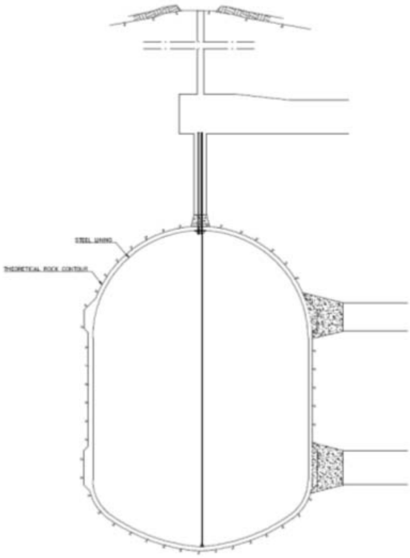
2. General principles for underground storage of hydrogen gas

2.1. External requirements on the facility

Using the Skallen facility as a baseline, the present scope of the expected external requirements on the LRC design is that the facility may need to accommodate a geometric volume in the approximate range of 50 000 – 150 000 m^3 and withstand an internal maximum pressure of at least 200 bar (20 MPa). The gas cycling frequency is expected to be less than 1 per week, if feasible, corresponding to approximately 1500–2000 storage cycles for a life-span of 30–35 years. According to tentative assessments, a design equivalent to the existing Skallen facility would approximately suffice to supply a full-scale HYBRIT steelmaking facility with hydrogen for about 50 hours. (For reference, the Skallen facility was designed for 1 cycle per month over 30 years, which adds up to close to 400 cycles in total.)

The Skallen facility is 51 m high and 35 m in diameter, giving a geometrical volume of 40,000 m^3. The rock cover is 115 m. The geometric shape is shown in Figure 3. The pressure range is 20–200 bar, giving the facility a total gas volume of 10 MNm^3. The working gas capacity is approximately 90% and the cushion gas 10%. It takes 20 days to fill the facility with gas and 10 days to withdraw (Mansson & Marion 2003).

Considering the wide target values regarding the external requirements at this point, the requirements should be interpreted as a starting point for the research project and not as technical limitations.



Total gas volume	10 MNm^3
Geometrical volume	40 000 m^3
Diameter	35 m
Height	51 m
Pressure	200 bar
Rock cover	115 m
Injection	20 days
Withdrawal	10 days

Figure 3. Vertical section and basic data of the demo plant at Skallen in south-west of Sweden. (© Johansson, 2003, with permission).

2.2. Development of the LRC concept

2.2.1. Early development

Worldwide, there are several concepts for storage of gas. The alternatives include storage in existing geological formations, such as depleted oil and gas fields; storage of liquefied gas in insulated tanks (natural gas can be stored at –163°C); and storage in lined or unlined excavated caverns in hard rock. The gas tightness of such caverns can, in principle, be ensured by several different methods, as presented in Figure 4. The methods categorized as being based on permeability control ensure gas tightness by providing sufficiently low permeability around the storage, where one option is the LRC concept. The methods categorized as being based on control by hydrodynamic containment use water pressure to prevent gas migration through the rock mass (Kjørholt 1991).

With respect to Swedish conditions, there are no suitable existing geological formations and insulated tanks are generally expensive to run, which leaves the lined alternative or any of the unlined alternatives. Out of these, the lined rock cavern (LRC) concept has been found more suitable than the unlined alternatives, as the LRC concept is more cost-effective for shallow depths. Additionally, it allows a rather large variety in the geological conditions, although the weight of the rock mass must prevent overburden uplifting (see section 3.3). The shallow location implies, however, that the tightness of the storage must be kept at all times, as the internal pressure is higher than the pressure of the formation, i.e. the rock and the groundwater are not capable of preventing the gas from escaping in case of a leak (Kovári 1993, Johansson 2003).

Control by hydrodynamic containment needs a large groundwater pressure to balance the pressurized gas; for a storage pressure of 15 MPa, the equivalent depth would be 1500 m if natural groundwater pressure is used. As a consequence, the storage volume needs to be very large, for the facility to be economical. However, underground gas storages with artificially pressurized water curtains have been successfully used in Norway as air cushion surge chambers in headrace pressure tunnels at hydropower plants. The Norwegian experience shows that a properly

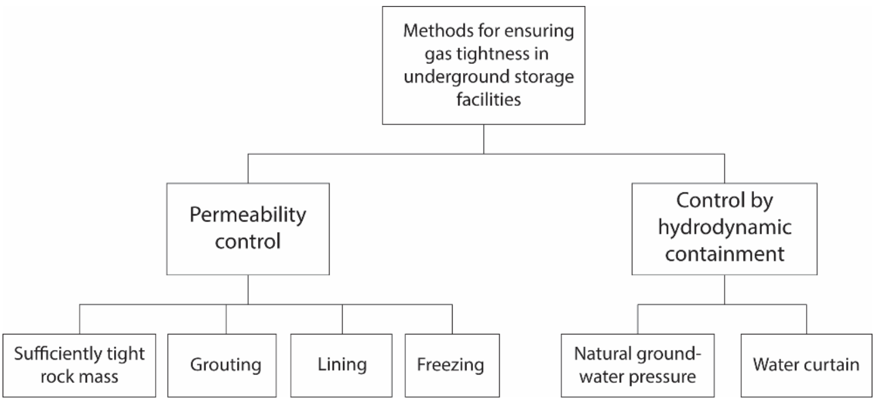


Figure 4. Methods for ensuring gas tightness in underground storage facilities. (After Kjørholt, 1991).

designed water curtain eliminated all leakage for air pressures in the tested range of 4–8 MPa (Kjørholt & Broch 1992). However, for substantially larger pressures, e.g. in the same range as the pressure in the Skallen facility, the required water pressure in the curtain would cause hydraulic fracturing because of the relatively low in-situ stress in the rock mass.

Note also that storing gas in rock caverns that previously were used for storing oil is generally not possible, because such caverns have an unfavorable shape with too large horizontal cross-sectional area. The larger the horizontal cross-sectional area, the deeper the storage facility has to be placed, considering the risk for uplift failure.

The LRC concept has to a large extent been developed in Sweden since the mid-1980s, as an effect of the introduction of natural gas in the Swedish energy system. Though, even before that, there was plenty experience in constructing underground storage facilities for oil; see e.g. Calminder & Hahn (1982). Main stakeholders in the research on natural gas storage were major Nordic energy companies and contractors. Pilot tests were conducted in Grängesberg to investigate the effectiveness of different lining concepts, evaluate the effect of different pressures and temperatures, as well as study the failure mechanism in the surrounding rock and the consequences of leakage through the lining. The results of the pilot tests were published in an extensive report by Johansson et al. (1995), as well as in several conference papers, e.g. Stille et al. (1994). A summary of the findings is presented in the following. A timeline for the development of the lined rock cavern concept is presented in Figure 5.

2.2.2. The Grängesberg pilot tests

The Grängesberg pilot tests involved three different steel–concrete lined caverns with 9 m high and 4.4 m diameter at 50 m depth in a fractured granite formation. The first cavern (Room 1) was designed with a 0.4 mm thick lining of austenitic stainless steel, but problems with the quality of the lining welding method were observed, limiting the evaluation of this cave because of leakage problems.

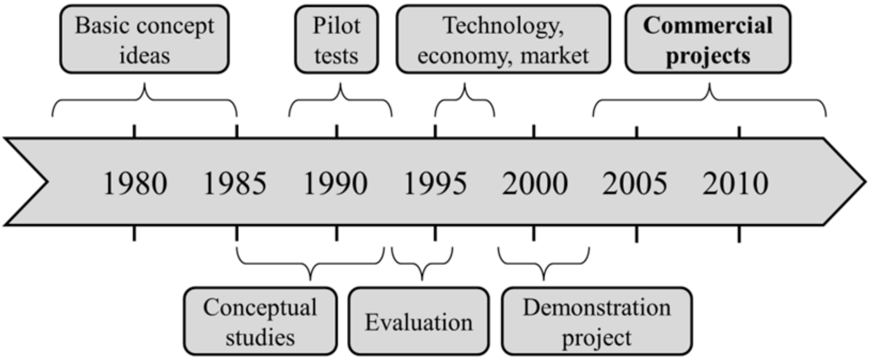


Figure 5. Timeline for the development of the lined rock cavern concept in Sweden.

The second cavern (Room 2) had a 6 mm carbon steel lining with a 0.6 m unreinforced concrete lining and an asphalt sliding interface between them. Tests in this cavern at pressures far above the in situ conditions (52 MPa) and close to the compressive strength of the concrete resulted in a maximum radial displacement of 5.65 mm in the rock mass, and fracturing of the concrete; however, the cavern functionality was not disturbed by this fracturing, because the concrete was designed mainly to transfer the compressive load to the surrounding rock.

The last cavern (Room 3) was first equipped with a lining of 10 mm thick fusion welded thermoplastic sheets installed on 0.3 m reinforced concrete (without a sliding layer). Unfortunately, the lining failed during the first water filling due to low ductility in the welds and brittle failure behavior. The thermoplastic sheets were therefore substituted by 0.5 mm stainless steel on the reinforced concrete. The maximum tested pressure in this cave was 28 MPa with 3.2 mm maximum deformation and the concrete lining stayed in very good conditions with only thin cracks being observed.

The number of cyclic loads was over 200 for Room 2 and 91 for Room 3 with a plastic strain-hardening deformation pattern; that is, the deformability of the rock mass decreased as it deformed irreversibly.

During these cyclic tests, opening and closing of rock joints were experienced.

2.2.3. The demonstration plant at Skallen

After further studies of the technical details of constructing a lined rock cavern for underground storage of natural gas, as well as the economic aspects of the project, a demonstration plant was commissioned at Skallen close to Halmstad in south-west of Sweden. The operation started in 2002 (Glamheden & Curtis 2006, Mansson et al. 2006).

2.3. General description of the LRC concept

2.3.1. Structural components

The LRC storage system consists of two parts: the surface-bound facility and the underground facility. The surface-bound facility consists of a compressor station, heating and cooling equipment, piping, valves, metering, and a control system, similarly to that of other underground gas storages. The underground facility consists of one or several storage caverns and a system of tunnels connecting the caverns with the ground surface. The caverns are excavated as vertical cylinders with rounded top and bottom (Figure 3). Typical dimensions are 35–40 m in diameter and a height of 60–100 m. Typical gas pressures ranges between 15–30 MPa (Johansson 2003).

The key element in a rock cavern for gas storage is the lining, which consists of three structural components with different purpose: a sealing layer to contain the gas in the facility, a pressure-distributing part to transfer the load from the gas to the rock mass, and, of course, the rock mass, which carries the load from the gas pressure. These structural components work together in a complex interaction as the cavern is pressurized (Johansson et al. 1995).

Having studied the behaviour of different lining concepts in the Grängesberg experiments, a working concept was developed with the following components (Figure 2), listed from the inside and outwards (Johansson et al. 1995, Johansson 2003):

- An inner steel lining, which ensures gas tightness and bridges minor cracks in the underlying concrete.
- A sliding layer in between the steel lining and the concrete, reducing the friction between these components. This layer also provides some corrosion protection to the steel and assists in sealing off the concrete surface in case of gas leaks in the lining.
- A concrete lining, which transmits the gas pressure to the rock mass, distributing the deformations in a uniform way. It is also needed to provide a smooth base for the steel lining. The concrete lining is reinforced with a welded mesh to distribute the tangential strain into many small concrete cracks.
- A layer of low strength permeable shotcrete, which protects the drainage system, allows water to seep between the rock and the casted concrete to the drains, and reduces the interlocking between the concrete lining and the rock surface.
- A drainage system, which consists of perforated drainpipes around the cavern. The purpose of the drainage system is to reduce the water pressure against the steel lining when the gas pressure in the facility is low. It is also part of the monitoring system for gas leaks. Referring to confidential project reports, Johansson (2003) states that the drainage system should not circulate water under normal conditions, but be activated if a gas leak has been indicated. This reduces the risk for chemical and biological clogging. It is also favorable from corrosion point of view to maintain stagnant conditions and avoid introducing oxygen near the steel lining.
- Surrounding rock, which carries the load from the gas pressure. The occurring deformations in the lining will mainly depend on the gas pressure, the deformation modulus of the rock mass, the rock mass strength, and the size and shape of the cavern. Additionally, the deformations may also be affected by the presence of joints and weakness zones in the rock mass and its in-situ stresses.

The structural considerations of these components are further discussed in chapter 3. Note that a US patent covers the design principle of the lining; see Johansson (2002).

2.3.2. System for detection and collection of potential gas leaks

The facility is designed to be completely gas tight during its lifetime. This is primarily ensured by a high level of quality control of the welds during construction, directed equally on testing weld strength and weld tightness. Additionally, the mechanical integrity of the lining is tested with a water pressure test before the cavern is put into operation. Thus, any leakage during operation of the facility would likely be caused by corrosion of the steel lining or fatigue, which for the storage of natural gas was deemed as possible but unlikely (see further discussions on the effect of hydrogen embrittlement on steel in section 2.5.2).

A leakage detection system is integrated into the drainage pipes, which also are used for groundwater, so should any gas leakage occur, it will be detected by this system. Any leakage will increase the pressure in the drainage system, which provides a warning signal. The leakage detection concept was tested in the pilot plant in Grängesberg and the result showed that leakage was clearly detectable (Johansson & Lindblom 1995). The leakage detection system (including several independent leak detection methods) was also successfully tested at Skallen. The design of the drainage pipe system is further discussed in section 3.6.1.

2.3.3. Design limitations related to temperature effects

Reducing the pressure of a gas leads to temperature reduction of the gas; however, the cavern walls must not be exposed to temperatures below 0 °C, because freezing may damage the concrete lining, if it is saturated by water. For the Skallen plant, full ground water saturation of the concrete lining was expected within 5–10 years of operation. This means that restrictions must be put on the gas withdrawal rate to avoid temperatures below zero, to avoid frost heave and internal frost damage in the concrete.

The LRC concept developed in Sweden also includes a circulation heating and cooling system that can control the temperature in the cavern. The main purpose is to increase the effective working gas volume; see further details on this heating system in the US patent by Hall (2002) (for which GDF Suez and E.ON Sverige AB currently are assignees). However, the temperature can, if needed, be controlled through the operation procedure only.

2.4. Rock mass – properties and behaviour

In this report, we assume that the rock mass is a jointed hard crystalline rock mass. This type of rock can be exemplified with the Scandinavian granite or gneiss of the very old Baltic Shield, which covers most parts of Sweden; the main exceptions are the sedimentary rocks of Skåne, Öland, Gotland, and the Scandinavian mountain range, which generally are softer and weaker. The jointed hard crystalline rock of the Baltic Shield is more favourable to the LRC concept than sedimentary rock types. In fact, locations with such hard crystalline rock are generally feasible for an LRC facility; the better rock mass quality, the higher gas pressure can be used. Though, detailed analyses with respect to local heterogeneities in the rock mass and anisotropic in situ stresses are always required before the feasibility of a location can be evaluated.

The excavation of a large rock cavern will cause deformation to the rock mass because of the surrounding gravitational (vertical) and tectonic (horizontal) stresses. On a large scale, the deformations both during excavation and operation are expected to behave analogously to the rock mechanical concept known as the convergence–confinement method (the ground reaction curve), which describes how the rock mass deformation around the opening depends on the counter-pressure from, for example, support measures. The analysis of such structural interaction is well described in many textbooks; see e.g. Palmström & Stille (2010). Affecting parameters on the deformation pattern of a highly pressurized cavern are the rock mass deformation modulus, the rock mass strength, the in situ stress situation, the cavern shape, and the pressure of the stored gas (Johansson 2003).

In addition to the large-scale analysis, the effect of local heterogeneities in the rock mass (e.g. rock joints) needs to be considered in the design of the storage facility. The reason is that such local effects may strain the lining in addition to the large-scale deformations. Thus, the design of the facility needs to consider both the general deformation pattern of the rock mass and the effect of local heterogeneities in the rock mass on the behaviour of the lining. In particular, largely anisotropic horizontal stress conditions are unfavourable for the LRC concept, as isotropic conditions provide the facility with a uniform prestressing of the rock wall that is favourable in the pressurising of the facility. In addition, largely anisotropic horizontal stresses may also make excavation more difficult. The effect of anisotropy on the LRC concept is discussed in detail in Johansson (2003).

2.5. Hydrogen gas – properties and behavior

2.5.1. Hydrogen gas compared to other gases

While hydrogen gas is a promising renewable and clean energy, it requires specific safety considerations for its storage. Hydrogen is a gas in ambient conditions and it is the lightest known molecule in the universe; therefore, the tightness of the storage needs to be ensured. It is undetectable by human senses (colourless, odourless and tasteless) and sulphur or another odorant compound cannot be added, as in safety demands for natural gas, given the drastic difference in the densities of the different gases. On the other hand, hydrogen rises at almost 20 m/s (in fact, it is 14 times lighter than air and 8 times lighter than natural gas); this buoyancy effect is a safety advantage for rapid dispersion in an open environment. The accumulation of hydrogen in a closed environment may cause asphyxiation, even though it is not poisonous. The flammable concentration of hydrogen varies within a wide range, from 4 to 75%, against 5 to 15% of the natural gas; thus, the operational area should be free of heat flames and sparks. Hydrogen has an optimum combustion at 29% concentration and its minimum ignition energy is very low, 0.02 mJ, compared to natural gas, 0.29 mJ. On the other hand, hydrogen carries less energy per volume than methane, achieveing 2.5 vs. 8.0 GJ/m^3 at 20 MPa and 10.5 vs. 32.0 GJ/m^3 at 80 MPa (Makridis 2016).

Makridis (2016) summarizes how hydrogen behaves differently than most other gases and that classical gas theory may not be applicable. One example can be observed during the decompression of hydrogen gas to atmospheric pressure. For most other gases, with the exception of helium and neon, the gas cools down as a result of expansion; however, hydrogen gas heats up. This behaviour is named the Joule-Thomson effect and is quantified by a top limit inversion temperature, for which gases change from cooling down to heating up at expansion. For instance, at atmospheric pressure, the hydrogen inversion temperature is about 202 K (–71 °C) while for the air it is above 700 K (427 °C); that is, hydrogen gas needs to be cooled down below –71 °C to behave like most other gases. This effect has been studied by several authors; e.g. McCarty et al. (1981), Maytal & Shavit (1997), Woolley et al. (1948), and Johnston et al. (1946).

The well-known ideal gas assumption is often used for simplicity in thermodynamic analyses of gases: $PV = nRT$, where P is the gas pressure, V is the gas volume, n is the amount of substance (in mole), R is the universal gas constant, T is the gas temperature. However, for a real gas, the compressibility factor, Z, should also be taken into account, such that $PV = ZnRT$. Thus, Z is given by the ratio

$$Z = \frac{PV}{nRT} = \frac{PM_\mathrm{m}}{\rho RT}, \tag{1}$$

where ρ is the density of the gas, and M_m is the molecular weight of the gas. (Consequently, $Z = 1$ for the ideal gas assumption.)

Maslan & Littman (1953) present compressibility factor charts for hydrogen gas. The closer the gas is to phase change, by changes in

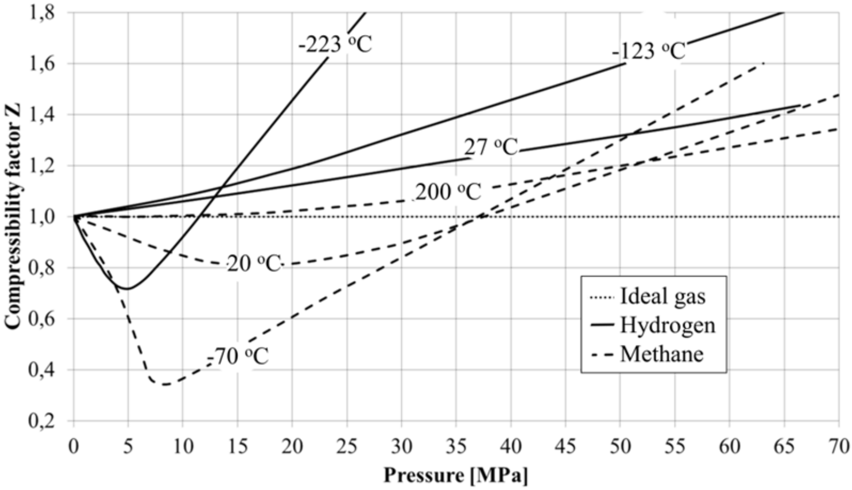


Figure 6. Change in compressibility factor (*Z*) with pressure (*P*) for ideal gas, natural gas (CH_4) and hydrogen gas (H_2) in different isotherms.

pressure and temperature, the more *Z* deviates from the ideal gas behaviour. Figure 6 shows the change in compressibility factor with respect to pressure for the ideal gas, natural gas, and hydrogen gas at different isotherms. It can be observed that below 35 MPa and at atmospheric temperatures (20–27°C), the *Z* of hydrogen is always greater than 1, while methane has a *Z* less than 1. Therefore, as the thermodynamic relationship of real gases shows that the density of the gas is inversely proportional to *Z*, it can be expected that the density of hydrogen gas will be less than the density of the natural gas for the same temperature and pressure. The effect on the storage capacity of a rock cavern is that the stored amount of hydrogen gas would be less than the stored amount of natural gas in terms of Nm^3, given that temperature and pressure is the same in the storage facility.

Figure 7 shows a comparison of the density of hydrogen gas and methane for different pressures and isotherms. Clearly, stored hydrogen gas will have a much smaller density than methane for the same pressure and temperature.

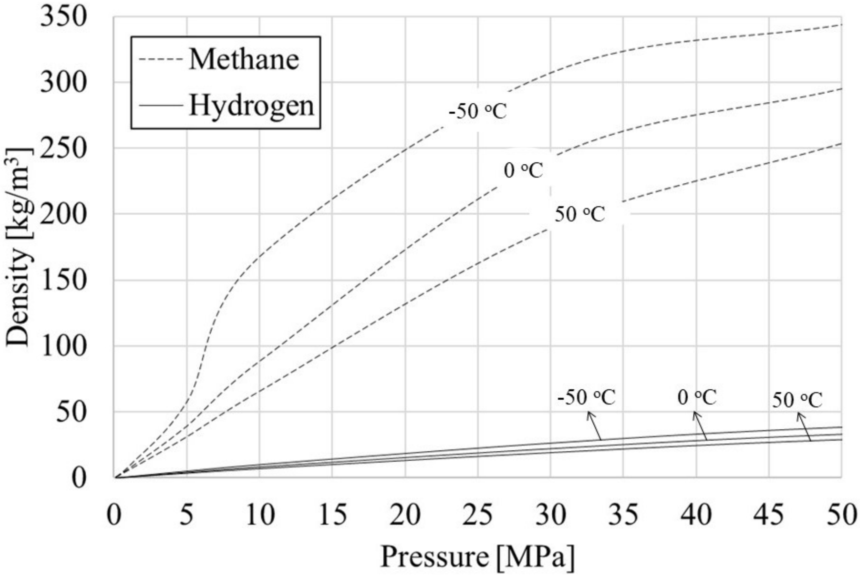


Figure 7. Density variation of methane and hydrogen gas for varying pressure and isotherms.

2.5.2. Technical aspects to consider for the storage system

The behavior of the steel lining is a crucial aspect of the facility, as it provides the barrier against gas leakage. For natural gas, a relatively thick, welded steel lining made of low-alloyed ductile carbon steel with moderate yield strength was considered the most favorable option, based on the Grängesberg pilot tests (see section 2.2.2). The substantial thickness also allowed the steel lining to act as a formwork for the casting of the concrete between the steel and the rock.

Hydrogen, however, differs from natural gas in the ability to chemically react with steel, as hydrogen under some circumstances may cause the degradation phenomenon known as hydrogen embrittlement. Hydrogen atoms may promote localized plastic processes and enhance crack propagation in the steel (Zheng et al. 2012). It is therefore critical to assess the potential effect of any chemical reaction between the hydrogen and the steel lining, as degradation caused by hydrogen embrittlement may reduce the life length of the lining. According to Kanezaki et al. (2008), hydrogen embrittlement is expected to affect for example tensile strength, ductility, and crack growth under static loading. Generally, it is believed that austenitic stainless steel is less susceptible to hydrogen embrittlement; therefore, steel with the austenitic crystalline structure is believed to be a better candidate for hydrogen fuel cell applications. However, hydrogen embrittlement may occur also for austenitic steel. The performed research shows that hydrogen makes the fracture process more complex; in fact, Zheng et al. (2012) regard hydrogen embrittlement to be “one of the most controversial issues of all fracture related phenomena up to now”.

Mechanical tests have proven crucial to be able to select construction materials that have good compatibility with hydrogen. Therefore, to support the needs of the hydrogen community, the Sandia National laboratories have issued a report (San Marchi & Somerday 2012) containing an extensive technical reference of hydrogen compatibility with various materials. Additional references on materials testing are also available in Zheng et al. (2012).

2.6. Legal issues

This section does not intend to provide an exhaustive cover of the applicable Swedish laws, rules, and regulations for underground storage of gas, but an overview of issues that may be relevant for further investigation.

From a legal point of view, underground storage of hydrogen gas in lined rock caverns is in Sweden governed by several laws. They can be divided into two categories: the construction of the underground cavern and the handling of the explosive gas.

Regarding the construction, the underground facility must be planned, design, and constructed in accordance with the laws that govern any type of civil engineering structure. This includes a ruling [*miljödom*] from the Environmental court regarding any potential effects on the environment, a building permit [*bygglov*], and a design that satisfies the society's structural safety requirements in the Ordinance for planning and building [*Plan- och byggförordningen*]. A concession in accordance with the Act on Some Pipelines (1978:160) [*Lag om vissa rörledningar*] may also be required.

Regarding the handling of explosive gas, the relevant laws are the Flammables and Explosives Act (2010:1011) and the Flammables and Explosives Ordinance (2010:1075), which deal with the import and handling of flammable and explosive goods. The aim of the legislations is to prevent and limit loss of life, injury, and damage to environment and property as a result of fire or explosion. The Flammables and Explosives Act also permits the Swedish Civil Contingencies Agency (MSB) to issue detailed rules on this matter. The Swedish Work Environment Authority's Rules for pressure-carrying devices (AFS 2016:1) [*Arbetsmiljöverkets föreskrifter om tryckbärande anordningar*] does not cover "devices for underground storage that are intended to contain and/or control the gas pressure", according to its paragraph 2§h.

Currently, the MSB rule SÄIFS 2000:4 – Rules and general advice regarding tanks, domes, rock caverns, and pipelines for flammable gas [*Föreskrifter och allmänna råd om cisterner, gasklockor, bergrum och rörledningar för brandfarlig gas*] is applicable to storage of hydrogen gas in lined rock caverns. SÄIFS 2000:4 does not, however, provide detailed rules; rather, it states requirements such as "Rock caverns that contain air shall be put into operation in a safe manner" and "A contingency action plan for emergency situations during filling shall be developed". Additionally, MSB's rules on explosion hazardous environment in management of flammable gases and liquids [*Statens räddningsverks föreskrifter om explosionsfarlig miljö vid hantering av brandfarliga gaser och vätskor, SRVFS 2004:7*] may also be applicable. A separate MSB handbook is available for these rules [*MSB Handbok om tillstånd till hantering av brandfarliga gaser och vätskor*].

Note that new rules currently are under development; though, the new rules will not explicitly cover rock caverns, because such facilities were not expected to be commonly built in the foreseeable future. Though, in the case of application for a permit for such a facility, the old rules (SÄIFS 2000:4) will likely be used for the rock cavern in this special case, according to Lars Synnerholm at MSB (2017, personal communication). Any external gas-related parts of the energy system (e.g. pipelines, etc.) will however be governed by the applicable parts of the new rules, once they have been issued.

Permitting public authority for handling of flammable gas is the board that the local municipal authority (*kommun*) has appointed for this purpose. In many municipalities, this is the local Emergency Services (*Räddningstjänsten*). Because of the large scale of the project, the permitting authority may seek consultation from MSB or other public authorities in reviewing the application (Lars Synnerholm, 2017, personal communication).

Additionally, Sweden has implemented the Seveso II directive (96/82/EG) as the Act on preventive and limiting measures in case of serious chemical accidents (1999:381) [*Lagen om åtgärder för att förebygga och begränsa följderna av allvarliga kemikaliolyckor*]. This implies that the facility requires a comprehensive safety report including a plan for contingency actions and an emergency preparedness plan to be submitted to the County board (*Länsstyrelsen*).

Regarding the operation of the facility, the Swedish Work Environment Authority's new Rules on use and control of pressurised devices (AFS 2017:3) [*Arbetsmiljöverkets föreskrifter om användning och kontroll av trycksatta anordningar*] may be applicable, as underground storage facilities are not explicitly exempted.

2.7. State-of-the-art in underground storage of gas

2.7.1. Overview

As discussed in section 2.2, a concept for storing natural gas in lined rock caverns has been developed in Sweden. However, to the authors' knowledge, this concept has not previously been studied or tested for storage of hydrogen gas. This literature review therefore covers studies both on the use of lined rock caverns for other gases and on experiences from alternative storage methods for hydrogen gas.

Rutqvist et al. (2012) discuss a Japanese experiment for rock caverns lined with concrete and synthetic rubber seal that showed acceptable compressed air leakage for operational pressures of 4–8 MPa (cf. the Skallen facility with pressure up to 20 MPa). Also, other LRC experiments have been conducted in Korea as stated by Tunsakul et al. (2017); however, these reports are not available in English. Regarding Compressed Air Energy Storage (CAES), only two projects are under operation today and they are related to unlined salt rock formations. One of these storage facilities was built in 1978 in Huntorf, Germany, with storage volume of 310000 m^3 (Crotogino et al. 2001, Raju & Kumar Khaitan 2012) and the other facility is in operation in McIntosh, USA, since 1991 with storage of 500000 m^3 (de Biasi 2009).

2.7.2. Development in structural analysis methodology for gas storage

In terms of methods for structural analysis of underground storage of pressurized gases, there has been some development during the last decades, despite high investment costs and extensive laboratory experiments. Additionally, numerical simulation tools are often used along with field observations in order to overcome practical barriers.

Numerical design tools for general rock mechanic applications have been well defined by Jing & Hudson (2002) and Jing (2003); though since then, there has been a significant development of numerical methods such as the Finite Element Analysis and the Discrete Element Analysis toward efficient handling of complex three-dimensional thermo-hydro-mechanical (THM) simulations. For modelling of underground gas storage facilities, researchers have used different methods and they are briefly covered in the following.

Xia et al. (2015) derived a simplified analytical solution for temperature and pressure variations for thermodynamic analysis of CAES systems. Another solution for CAES coupled THM analysis of jointed hard rock was derived by Zhuang et al. (2014). Probabilistic method combined with numerical approximation was used by Park et al. (2013) to design an LRC in South Korea to resist high internal gas pressure.

Park et al. (2012) proposed a two-dimensional numerical simulations including coupled thermodynamic, multiphase fluid flow and heat transport analysis that have investigated the LRC concept for CAES with respect to gas leakage and energy-balance disregarding geomechanical changes. Their results showed that a cavern at 100 meters depth and operational pressure varying from 5 to 8 MPa achieves acceptable air leakage for concrete lining with permeability 10^{-18} m^2. The energy-balance study showed that the energy loss in a daily pressure cycle depends on the air pressure and heat loss to the surrounding media.

Rutqvist et al. (2012) used a thermomechanical two-dimensional CAES model to compare an LRC that has a low permeability concrete lining to an LRC with an impermeable thin lining. Fracture patterns were estimated from results of strain and permeability; however, the model was rather simplified disregarding mechanical interaction with and within the lining, rock fractures and drainage zone, as well as the use of a coarse numerical mesh. They concluded that the mass loss from using a low permeability concrete is acceptable for CAES and a tight lining may be more important to contain explosive fuels. In another study performed by the same group (Kim et al. 2013), they used geophysical surveying to characterize the excavation damaged zone (EDZ) and numerical thermodynamic and geomechanical modelling to evaluate the EDZ influence on the storage geomechanical stability.

Glamheden & Curtis (2006) report on how they used the FLAC code for the numerical simulation of the Skallen facility. They aimed to analyse the rock mass response to the excavation and pressurization of the cavern in two different geometries: one horizontal profile and another vertical profile of the storage. However, the conclusion was that the two-dimensional assumption was unrealistic for the cylindrical storage and that three-dimensional models are necessary.

Other two-dimensional numerical analyses were conducted by Kim et al. (2012, 2013) and Rutqvist et al. (2012) with the linking of two established codes (TOUGH-FLAC) applied to CAES in a LRC. Zhuang et al. (2014) presented numerical models with a coupled THM analysis for unlined caverns that could represent better the physical processes involved in the LRC concept; however, several simplifications and assumptions were necessary due to the computational complexity of the problem.

2.7.3. Other storage concepts for hydrogen gas

Züttel (2003) presented a review on hydrogen storage methods. Among all hydrogen storage concepts, the most commonly used is the compressed gas cylinder at surface level. The cylinder must stand pressures in the order of 20 MPa; therefore, its material composition should have very high tensile strength, low density and be inert to hydrogen.

Storing compressed gas in cylinders involves severe safety concerns due to the highly flammable characteristic of the hydrogen gas and high operational pressures. The gas is compressed using piston-type compressors and the work required for that is high due to the temperature change. The method is well established, but high gas pressures are generally required, considering the relatively low hydrogen gas density.

Higher volumetric densities of 70.8 kg/m^3 are achieved for liquid hydrogen at atmospheric pressures (compared to <40 kg/m^3 for the compressed gas at 80 MPa of pressure); however, the hydrogen temperature must then be decreased and maintained below its critical temperature of –252 °C. Constant heat leakage from the cryogenic tank narrows down the usage of this method to cases in which the hydrogen is consumed after a low storage period, such as for aerospace applications.

Other methods are the storage of hydrogen by surface interaction within carbon nanotubes (which is known as physisorption or physical adsorption) and within the molecular structure of metal and complex hydrides. In addition, hydrogen can be stored in the molecule of water (H_2O) and released by chemical reaction with sodium (Na); however, although these are established technologies, they still require development for industrial application (Züttel 2003). Other concepts are currently under development for the hydrogen storage on the molecular level (Rosi et al. 2003, Schmitt et al. 2006, Duriska et al. 2009).

Although compressed gas tanks have been the most popular method of storing hydrogen, the cost for large-scale storage would be substantial. Geologic storage of hydrogen gas in salt caverns has been proposed as a cheaper and sufficiently safe solution. The impermeable characteristic of salt caverns makes them excellent for storing gas; however, these formations are not available in most geographical locations.

Currently, two salt caverns are being used for this purpose in Texas, USA, (580000 m^3; Leighty, 2008) and three small ones in Teeside, UK (150000 m^3 each; Crotogino and Huebner, 2008; Panfilov et al., 2006). Hydrogen gas can also be stored in other types of geological storages rather than salt caverns, e.g. as 50-60% H_2 town gas (Fasanino & Molinard 1989, Panfilov et al. 2006) and helium have been stored successfully in aquifers (Tade 1967). Large-scale salt caverns related to gas fields and aquifers have been used as hydrogen storage in Turkey (Ozarslan 2012).

According to Lord et al. (2011), the popularity of LRC is expected to increase with increasing demand for gas storage worldwide and due to its versatility in implementation. Lord (2009) and Lord et al. (2010, 2011, 2014) conducted robust economic and deliverability studies for large-scale storage of hydrogen comparing salt caverns, depleted hydrocarbon reservoirs, aquifers and hard rock caverns. They developed the Hydrogen Geological Storage Model (H2GSM) simulator, which is used to analyse the cost per kg of hydrogen stored for the geological storages in USA. The results in Lord et al. (2014) showed that depleted hydrocarbon reservoirs and aquifers are more attractive economically (US\$1.23–1.29 /kg H_2). It was observed that the location of a given city with respect to geological storage formations had significant influence on the estimated hydrogen cost because of storage volume and transportation logistics. The current analysis did not account for the possibility of increasing the number of cavern cycling per year and that would make the salt cavern the most economic option (currently estimated as US\$1.61/kgH_2). Lined hard rock caverns, on the other hand, are generally able to be cycled multiple times per year and that would decrease the calculated levelized cost of US$2.77/kg$H_2$ for the storage; however, this decrease was not estimated. Lord et al. (2014) suggested that an update of this simulation could include additional parameters such as dehydration units and steel liner costs. Furthermore, it was proposed to consider lined caverns in soft rock for future studies, as they would be easier and cheaper to excavate, while they could be operated in a similar fashion to salt caverns.

3. Design principles for pressurised caverns and gas-tight linings

3.1. Chapter overview

With the structural components as described in section 2.3.1, a lined rock cavern for gas storage has three main aspects that need to be considered in the design work. These main aspects are discussed in this chapter: establishment of sufficient depth below the ground surface to avoid large-scale uplift failure (section 3.3); design of temporary support to be installed during the excavation of the cavern (section 3.4); and design of the gas-tight and pressure-distributing lining (section 3.5).

Additional key aspects in the design work concern management of groundwater and gas leakage (section 3.6), the use of a risk-based design approach (section 3.7), and applied risk management procedures (section 3.8).

3.2. Failure modes of the storage facility

In principle, the depth below ground surface of the cavern may affect the structural integrity of the storage facility in three ways, according to Johansson (2003):

1. Global failure of the rock mass, caused by too large uplift pressure from the stored gas, so that it exceeds the vertical resisting forces of the overburden.
2. Rupture of the steel lining caused by too large, one-time deformation of the surrounding rock mass, as it is loaded by the gas pressure.

3. Low-cycle fatigue of the steel lining for caverns located at such depth where the influence of the free ground surface will enlarge the strain range in the steel lining.

As discussed by Johansson (2003), these failure modes could be considered to be different stages of the same phenomenon. The global failure of the rock mass (failure mode 1) must therefore have been preceded by a rapid increase of the lining strain (failure mode 2 and 3). How to select a sufficient depth with respect to uplift is further discussed in section 3.3.

In addition to the first three failure modes, Johansson (2003) also states that even at sufficient depth, structural failure may also occur under the following two circumstances.

4. Low cycle fatigue of the steel lining for caverns located deep enough to avoid the influence of the free ground surface.
5. Local failure of the steel lining because of some structural weakness. Causes can be a local weakness in the rock mass, the concrete, the welds, or possibly pipe lead-throughs. Corrosion may also be a causative factor.

It should be noted that structural failure here is defined as something that causes a measurable gas leak such that the facility is no longer sufficiently safe or economically justifiable to operate. The reason is that the LRC concept is very robust, so that failure in one structural component not necessarily implies failure of the gas tight lining and subsequent gas leakage.

3.3. Large-scale failure of the facility caused by uplift

Referring to the global failure of the rock mass, caused by too large uplift pressure from the stored gas that exceeds the vertical resisting forces of the overburden, some simplified analytical methods are available to assess the resisting forces (Johansson et al. 1995). One of them considers the resistance as the weight of a rigid upside-down rock mass cone, where the cone tip has been cut off where the cross-sectional diameter equals that of the storage facility. An overview of some simplified models for ground uplift is presented in Figure 8: the log-spiral model, which is based on pullout tests of soil anchors; the rigid cone model; and the straight failure-plane-geometry model, as compiled in Tunsakul et al. (2017).

In addition to the analytical methods discussed above, it is also possible to perform numerical analyses to assess the resistance against uplift. In these analyses the pressure in the rock cavern can be increased until a complete plastic state of the rock mass above the cavern is reached. At this stage, the deformations rapidly increase for small increases of pressure in the cavern.

Johansson (2003) reports that a general methodology to assess the safety against uplift was developed for the demo plant in Skallen and presented in a confidential project report. The general recommendation was that the cavern should be placed deep enough to make the influence from the ground surface on the structural behaviour negligible.

3.4. Failure modes in the rock during excavation

3.4.1. General considerations

In addition to the failure modes of the facility, the general failure modes of rock masses are relevant to analyse in the design of the facility

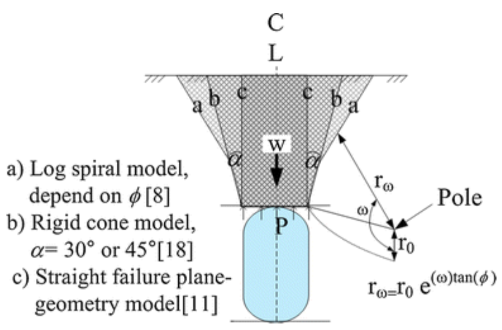


Figure 8. Different models for ground uplift evaluation above the silo-shaped pressurized storage in the past. (© Tunsakul et al., 2017, with permission from Springer).

to enable a stable cavern before the lining is installed. Such failure modes are described in most basic textbooks on rock mechanics, to which we refer for further details; see e.g. Palmström & Stille (2010).

In jointed hard crystalline rock, the most common failure mode is block instability. The strike and dip of the joints of the rock mass create blocks of different shape and volume. Depending on the stress state surrounding the cavern and the characteristics of the rock joints in terms of frictional resistance, different degree of support is required. The support usually consists of rock bolts combined with shotcrete, where rock bolts are used to secure larger block volumes while the shotcrete stabilizes potential loose block between the rock bolts.

In Sweden, the initial stresses in the rock mass are rather high, especially the horizontal ones. For example, at a depth of 100 m, horizontal stresses in the order of 10–15 MPa are common, while the vertical stresses are roughly around 3 MPa. Due to the shape of the cavern, its excavation results in stress concentrations near its boundary. Thus, it is necessary to analyse the expected stresses and strains in the rock mass around the cavern and compare them against the strength of the rock mass. If local overstressing of the rock mass occurs, it can result in need for additional support. In rock mass of very good quality the strength could be sufficient, but other types of failure modes related to the strength of the intact rock, such as spalling, might be necessary to consider. Spalling implies that thin fragments of rock with time detach from the boundary of the cavern. Other potential instability problems related to high stresses in competent rock include rock burst, where rock blocks with high velocity are pushed out of the cavern wall due to high stress conditions in the rock mass. If conditions for spalling or rock bursts exist, this has to be accounted for in the design of the rock support.

The relation between horizontal and vertical initial stresses together with the diameter of the cavern also governs the height of the compressive arch that keeps the roof of the cavern stable. In the case of a low horizontal/vertical initial stress ratio, the height of the compressive arch might exceed the arch of the cavern roof, resulting in unstable volumes of rock mass in need of support. Another potential failure mode concerning the arching stability of the cavern roof is sliding along rock fractures, which occurs when the direction of the compressive arch in the rock mass is directed at an angle near parallel to the rock fracture. Analyses are therefore needed to verify that the arching stability of the roof is sufficient; if not, adequate support is needed.

The aforementioned failure modes imply that information is needed on the initial stress state in the rock mass, the cavern shape, the orientation of the rock fractures and their frictional resistance, together with the rock mechanical parameters describing the strength and deformation characteristics of the rock mass, in order to perform a design of the necessary rock support needed to stabilize the cavern. However, the rock support only needs to be designed for the time period until the lining is installed; thus, there are no long-term requirements.

3.4.2. Experiences from the Skallen storage facility

Glamheden & Curtis (2006) report that the rock support at the Skallen facility was designed with the Q-system (Barton et al. 1974), although the design was verified with numerical modelling. The cupola was supported by fibre-reinforced shotcrete and systematic bolting. The cavern walls were first covered in unreinforced shotcrete, to which fibre-reinforced shotcrete and systematic bolting were added. The bolts aimed to prevent large slab failures caused by the dominant north–south vertical joint set. Glamheden & Curtis (2006) state that the amount of support was considered conservative with respect to the present rock mass quality; however, considering the potential impact of large-scale failures and the considerable wall height, which limited the access to the upper walls, the support effort was deemed reasonable.

A possible construction sequence of a lined rock cavern for gas storage in a hard crystalline Scandinavian rock mass is also described in Glamheden & Curtis (2006). An informative video clip is also available on Youtube (Johansson 2012). We only provide a very brief outline of the procedure in the following.

All excavation is made with conventional drilling and blasting. The excavation sequence is presented in Figure 9.

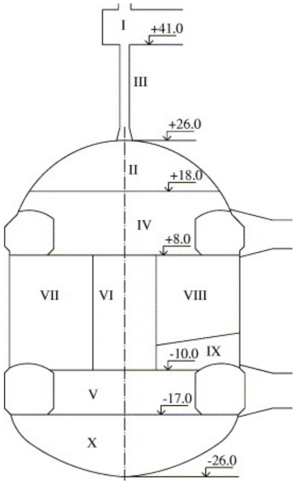


Figure 9: Vertical section of the cavern showing the steps and levels in the excavation sequence at Skallen. Ground surface on level +135 m. (Reprinted from Glamheden and Curtis, 2006, with permission from Elsevier).

First, access tunnels were excavated to three levels in the facility. Starting at the top (I), a pilot hole for the vertical shaft to the ground surface was bored. Then, the cavern was excavated, advancing in two spirals along the edges from level +8 m up to the top of the cupola (II and Figure 10), then excavating from the upper level to the lower level, using a central shaft (VI) for loading and hauling out the rock (Figure 11). Lastly, the bottom was excavated (X).

At Skallen, the lining was constructed by using the steel layer as a formwork for the casting of the concrete. This implies that the steel lining has to be thick enough to carry its own weight before the concrete lining has been casted.

The experience from the construction of the demonstration plant Skallen also shows that the constructability needs to be carefully assessed, as the steel welds need to be inspected from both sides to ensure gas tightness and the concrete reinforcement must be possible to put in place between the rock wall and the steel plates in an efficient manner. Using

Figure 10. Excavation of the cupola at Skallen, equivalent to step II in Figure 9. Photo: Storengy (ENGIE) and E.ON, with permission.

Figure 11. Downward excavation from the upper level at Skallen, equivalent to step VII and VIII in Figure 9. The rock was hauled out through a central shaft. The drainage system is clearly visible on the naked rock walls, before it was covered with shotcrete (section 3.6.1). Photo: Storengy (ENGIE) and E.ON, with permission.

additional space provided by work niches in the rock wall at one level and then hoisting the structure upward step-by-step allowed efficient assembly without having space for workers all around the cavern walls (Figure 12).

3.5. Failure modes of the cavern wall lining

3.5.1. Low cycle fatigue of the steel lining

The internal gas pressure in the storage causes an expansion of the cavern due to deformations in the rock mass. The principle behaviour is illustrated in Figure 13.

Depending on the internal pressure, the stress situation in the surrounding rock mass close to the cavern boundary can be divided into: an elastic state with compressive stresses in the rock mass (up to an

Figure 12. Work niche to allow for assembly of the steel plates and concrete reinforcement at Skallen. Photo: Storengy (ENGIE) and E.ON, with permission.

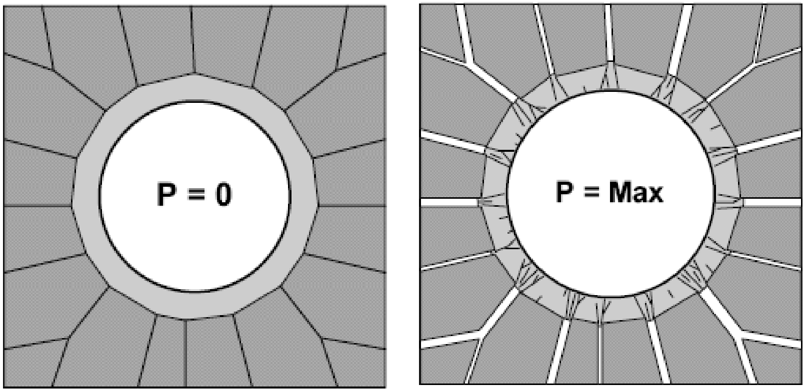


Figure 13. Illustration of the principle behavior due to a pressurization of the cavern: as the pressure increases, rock joints start to open up (© Johansson, 2003, with permission).

internal pressure equal to two times the initial stresses in the rock mass), an elastic state with tangential tensile stresses in the rock mass, a plastic state with radial compressive stresses equal to the uniaxial compressive strength of the rock mass. The different stages are illustrated in Figure 14.

As previously described in chapter 2.4, the deformations and strains in the rock mass are analyzed according to the principles of the ground reaction curve concept and is mainly a function of the rock mass

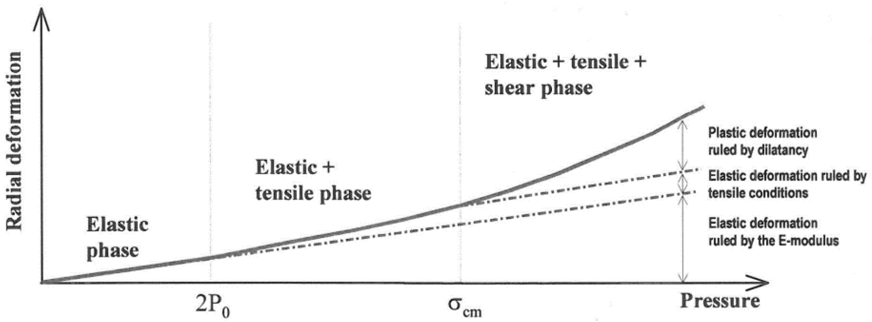


Figure 14. Principle of elasto-plastic stress states of the rock mass (© Johansson, 2003, with permission).

modulus, rock mass strength, initial stresses in the rock mass, the cavern shape and the internal pressure in the storage.

The tangential deformation in the rock mass will mostly be due to opening and shearing of existing joints in the rock mass. These local strains will generate cracks in the concrete lining concentrated to the opening of the rock joints. If the concrete lining is unreinforced, there will be few but large cracks, which influence the strain in the steel lining negatively. In order to make the crack pattern more evenly distributed reinforcement should preferable be installed in the concrete lining, located in the outer parts of it (towards the steel lining).

The cracking of the concrete will cause a tangential strain in the steel lining. How this strain is distributed depends to a large extent on the friction coefficient of the sliding layer. If there no friction at all between the steel and the concrete, the stress in the steel lining will, in principle, be evenly distributed and proportional to the tangential strain. Under such conditions the stress in the steel lining will be governed by global the factors mentioned above (i.e. rock mass modulus etc.). However, if the friction is high, concentrations of high stresses will occur at the locations of the cracks while they will be as lowest in the middle between two cracks. The principle is illustrated in Figure 15.

Based on chosen reinforcement, concrete quality and thickness of the concrete lining, together with the expected opening of the rock joints and their spacing, the average concrete crack spacing can be calculated. From this, the average crack width can be determined.

Once the average crack width is known together with the friction of the sliding layer, limit equilibrium in the horizontal direction derived from a piece of the steel-lining makes it possible to calculate the maximum strain over the crack; see Johansson (2003) for an account of the principles.

In order to analyse the effect of the sliding layer, its frictional resistance has to be known. It is also necessary that it could function properly under the varying temperatures and pressures that will exist in the cavern during the operation of the facility. Another important design aspect is also to ensure long-term durability and that it can handle the cyclic loading it will be exposed to.

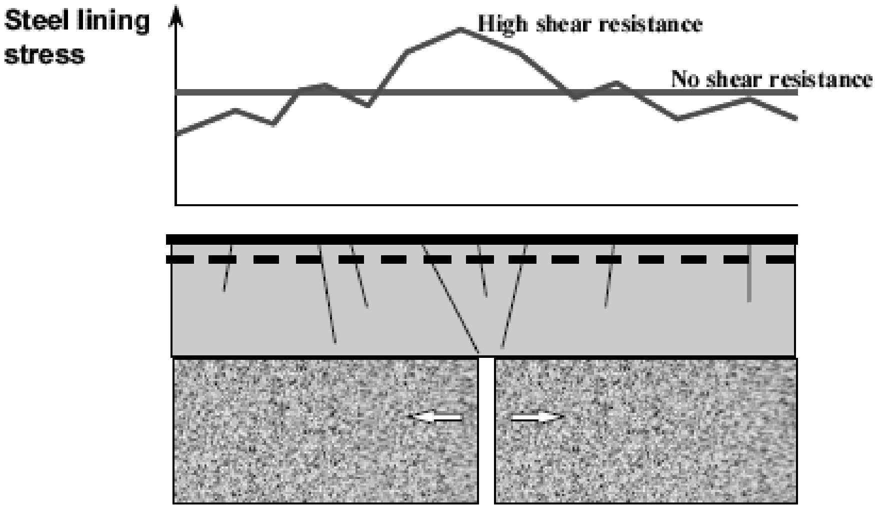


Figure 15. Illustration of the influence from friction between the concrete- and steel lining (© Johansson, 2003, with permission).

Since the storage will be filled and emptied a large number of times during its operational lifetime, the maximum strain in the lining has to be controlled with respect to fatigue. According to Johansson (2003), the material for the steel lining should be a high quality grade, fully killed carbon steel with high ductility, excellent weldability and impact properties. The yield strength should be in the range of 300 to 400 MPa.

With respect to fatigue, two different types of behavior can be distinguished depending on the strain range: (1) ϵ_y < strain range < $2\epsilon_y$ and (2) strain range $>2\epsilon_y$ (where ϵ_y is the yield strain).

If the strain range is of the first type, it yields in tension during the first loading cycle. During unloading, the tension is relaxed and at some point changes to compression. However, the whole unloading is elastic and the yield limit is not reached in the compressional stage. During the next load cycles, the steel will work elasticly in the whole strain range. The principle is illustrated in Figure 16a. This means that it will be an elastic fatigue situation with a large number of cycles (high-cycle fatigue) until failure occurs.

If the strain range is larger than two times the yield limit, the steel will yield in both tension and compression in the first cycle. In the following load cycles, yielding will also take place in each of the cycles. The principle is illustrated in Figure 16b. In this type of situation, the fatigue limit is significantly smaller (low-cycle fatigue).

As an example, the fatigue limit was investigated within the Skallen storage project based on tensile testing on a steel (S355J2G3) with a thickness of 12 mm. Based on this data, an ϵ-N diagram was constructed based on Manson's universal slopes equation (Jergéus 1982, Dieter 1988, Rask & Sunnersjö 1992), see Figure 17.

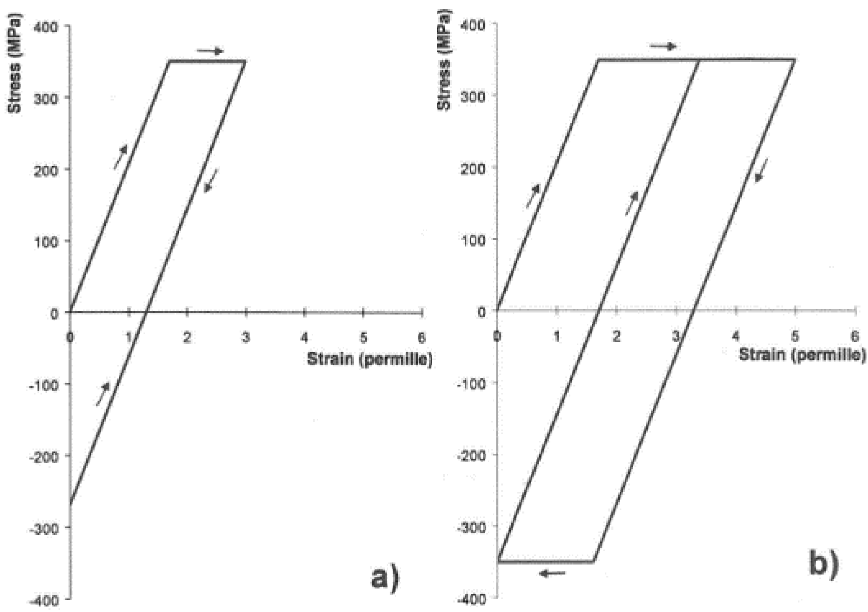


Figure 16. Illustration of steel behavior for two different strain ranges for steel with yield limit 355 MPa with a) Strain range 3‰ and b) Strain range 5‰ (© Johansson, 2003, after Rask and Sunnersjö, 1992, with permission).

In the curve, it can be observed that the fatigue limit is approximately 10 000 cycles at a strain of 5‰ and 100 000 cycles at a strain of 3‰. In addition, when the fatigue limit is analysed, it has to be considered that the LRC cavern has a biaxial stress state, meaning that the strain in both directions along the steel has to be accounted for in the design. It should be noted that the curve in Figure 17 does not include the effects from welds. If the effects from welds are included, the curve will be different (Johansson 2003).

In the calculations performed on the Skallen facility by Fredriksson & Persson (2000), as reported in Johansson (2003), it was found that for a cavern pressure of 20 MPa and initial stresses in the rock mass equal to 5 MPa, the maximum strain was approximately 1.25‰. This strain corresponds to a fatigue limit larger than 1 000 000 cycles. However, as previously discussed, the strain in the steel lining depends on several factors and is a design question that has to be taken seriously and analyzed for each specific case.

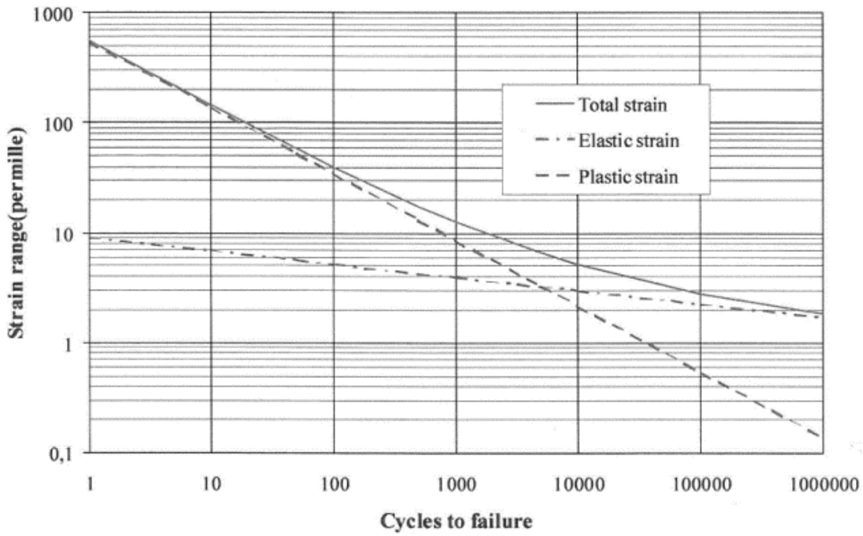


Figure 17. Fatigue diagram based on Manson’s universal slopes equation and data from a tensile test on steel S355J2G3 (© Johansson, 2003, with permission).

3.5.2. Local failure of the steel lining due to structural weakness

In the methodology described in the previous subchapter, the general assumptions are that the rock mass is a homogeneous isotropic material; however, spatial variations of the properties or the influence from large weakness zones can imply that local parts of the cavern experience larger deformations than other parts. As a consequence, it is important to have knowledge not only on the average properties but also on the variation of the mechanical properties. This is particularly important if the scale of fluctuation of the properties is close to the size of the cavern, since this can imply local additional straining of the steel lining.

Other possible causes for failure due to structural weakness could be if the concrete is of an uneven quality, resulting in spatially varying mechanical properties. This has to be controlled through comprehensive quality assurance programs at site, making sure that the concrete is of sufficient quality during the casting process.

Another important aspect, which could cause failure, is if the welds are not properly performed. Therefore, all welds should be thoroughly checked as a part of the quality assurance program.

Any pipe lead-throughs into the cavern or access roads into the chamber are also potential points of weaknesses and has to be designed accordingly.

3.6. Groundwater management and gas leakage detection

3.6.1. The drainage system

The purpose of the drainage pipes is multiple. The drainage system is used to drain groundwater during construction and to avoid the groundwater pressure from damaging the lining when the gas pressure in the cavern is low. The system is also used as a safety system with the ability to detect, collect, and evacuate leaking gas. Should any leakage of gas occur from the cavern, it will be collected in the grid of drainage pipes and safely vented at the ground surface. The drainage system is described in detail in Johansson & Lindblom (1995). The main components are:

- a rhombic pattern grid of sub-vertical perforated drainage pipes covering the complete cavern wall with 1–2 m spacing,
- two ring-shaped horizontal gas collector pipes (one at the top and one at the bottom of the wall), which collect the gas from the drainage pipes, and
- several large gas evacuation pipes, leading any leaking gas toward the ground surface from the horizontal collector pipes.

Under normal conditions, the drainage system will be filled with water to prevent chemically or biologically induced clogging and to prevent oxygen for corrosion of steel lining. The drainage system needs to be protected during the constructions phase, e.g. during the pouring of the concrete. The technical solution for the Skallen plant was to cover the drainage system in heavy geotextile and spray a special low-strength and permeable shotcrete on top (Figure 18). This design concept is part of a US patent: see Johansson (2002) for further details.

3.6.2. Pre-grouting of the rock mass

Although the LRC concept implies an impermeable steel lining (which not only prevents gas from escaping from the cavern, but also prevents groundwater from entering), pre-grouting of the rock mass may need to be considered if the inflow to the excavation is expected to be substantial.

Flowing or dripping water during concrete casting and welding of the steel lining will affect the construction process and quality negatively. Additionally, the acceptable groundwater inflow to the excavation from an environmental point of view will be governed by the environmental permit issued by the Environmental Court.

3.7. Advantages of using a risk-based design approach

For the construction of the Skallen demo plant, considerable effort was spent on assessing the involved risks in the project. The risks associated

Figure 18. Installation of the drainage system at Skallen. Photo: Storengy (ENGIE) and E.ON, with permission.

with the construction and operation of an underground storage for gas concern both the overall structural safety of the facility and the effects of gas leakage. As detailed in section 2.6, a number of laws and other regulations ensure that the safety of the facility is satisfactory. Notably, as a general rule, these laws and regulations aim to manage the involved risk, which can be seen as the combination of likelihood and consequences; the larger the consequences of an event are, the lower the acceptable probability of the event is. This principle is valid both for most modern structural design codes and for the regulations on management of chemicals in the Seveso II directive. For example, the Eurocodes for design of structures suggest acceptable failure probabilities in the range of 10^{-5}–10^{-7}, depending on the magnitude of the consequence of failure; though, the respective nation may prescribe other levels (CEN 2002).

Following this principle – to correspond the structural safety level toward a specified risk level – implies that it will be favorable to adopt a risk-based design approach, which directly addresses the risk associated with structural failure and gas leak. Using a risk-based design approach also circumvents the issue that no specific guidelines on the structural safety of underground gas storage facilities are available currently. Additionally, the great natural variability of rock mass properties gives risk-based design approaches an advantage over traditional deterministic design approaches, as highlighted in Johansson et al. (2016). Using a risk-based design approach to satisfy the structural safety requirements makes it also easier to link the structural safety aspects to all other safety-related issues that need to be considered in the overall safety assessment, which is part of satisfying the Seveso II directive. Thereby, a more stringent risk management can be achieved for the construction and operation of the facility.

3.8. Risk management of design, construction and operation

As discussed in the previous section 3.7, the construction and operation of the underground gas storage facility will carry risks that need to be managed. For this context, risk management is an established term in ISO 31000 (ISO 2009) for the coordinated activities that direct and control an organization with regard to the associated risks.

From a general perspective, the management of risks in a project can be seen as a part of the overall project management. In the context of underground gas storage facilities, the relevant risks may concern for example the structural safety, workers' safety during construction, environmental impact of the construction, economic aspects of the project, the handling of the hydrogen gas, the possibility of gas leakage, etc. Clearly, the scope is huge; therefore, a structured approach to manage all relevant risks is necessary to ensure sufficient quality in the project. The aforementioned ISO standard 31000 provides a general framework for structured risk management. Its applicability to the geotechnical aspects of civil engineering works has recently been studied (Spross et al.

2017, Spross et al. 2015) and the Swedish Geotechnical Society has adopted a general methodology for this purpose (SGF 2017).

Given the complexity of the underground gas storage facility, a structured and carefully executed risk management is essential to the project. Application of the risk-based design approach, which is discussed in section 3.7, may contribute to facilitate high quality in the management of both the design-related risks. However, the scope of the risk management is clearly much larger and substantial effort must consequently be put into this work. For example, an essential part of the construction of an LRC facility is extensive and thorough quality control of all structural components and their interaction both with the rock mass and with each other. As discussed by Stille (2017), rock engineering projects require a dual approach to quality assurance: in addition to *doing things right*, which is the focus of traditional quality systems for manufacturing processes, the rock engineer must also ensure that *the right things* are done (with respect to the geological conditions at the site). For a project such as a lined rock cavern for gas storage, quality assurance during construction becomes extremely important, because of the extreme difficulties in correcting errors after completion.

4. Discussion

4.1. General

Due to the geological conditions in the Scandinavian bedrock, the most favorable solution for storing large quantities of hydrogen gas (50 000–100 000 m^3) is through the LRC concept. Today, only one such type of facility exists in the world: the Skallen facility in the south west of Sweden, which stores natural gas. The successful construction and operation of the plant show that this type of storage is possible to construct. However, the main problem in storing hydrogen gas in a steel-lined rock cavern subjected to high pressure compared to natural gas is the possible embrittlement of the steel caused by the hydrogen gas. According to the Swedish steel manufacturer Sandvik, this problem is most likely possible to solve, although it requires careful testing of both the steel and the welds of the steel before a proper steel type can be chosen. However, the issue of choosing a proper steel type for an LRC facility for hydrogen is not within the scope of WP 2.3, but will be a key question to solve before a storage facility can be constructed within the HYBRIT project. Additionally, the degradation process of the sliding layer between the steel and concrete in the lining may require further studies, in particular for longer life lengths and higher gas pressures than applied in the design of the Skallen plant.

The fact that the LRC concept has been developed and proven successful means that it today does not exist any critical research question that needs to be solved before a storage facility can be built, except for the hydrogen embrittlement and degradation of the sliding layer. However, the design and construction of an LRC facility in the rock mass is a complex engineering task, which requires a good understanding on how the different components interact and with what uncertainties they are associated.

In order to fulfill the legal requirements in the design, such as the Seveso directive and the Eurocodes, design with risk-based methods is preferable. Even though a risk-based design methodology was used in the design of the Skallen facility, the experience and knowledge of using risk-based methods in design is still limited. This is generally the case for rock engineering problems and in particular for LRC-storages. Further development of these methods would therefore be beneficial for the LRC concept. The use of such methods would also enable an optimization of the design with respect to the present uncertainties. A logical way forward within WP 2.3 would therefore be to further develop the use of risk-based methods in the design and construction of an LRC facility for hydrogen in order to achieve a safe, economic, and environmentally sustainable storage.

4.2. Potential research questions for WP 2.3

4.2.1. Application of subset simulation for risk-based design

The LRC concept consists of several components where the rock mass acts as load-carrying medium. The deformations caused by the gas pressure will follow a behavior similar to the behavior when excavating a circular tunnel in an isotropic rock mass, according to the principles of the ground reaction curve (Hoek & Brown 1980). However, due to the cavern geometry, the analytical solutions for the two-dimensional problem of an infinite tunnel is not suitable to use for the analysis of stresses and strains in the rock mass and the lining. Instead, three-dimensional numerical analyses are needed in the assessment of global stresses and strains. When risk-based methods are used in the design together with numerical calculations, the assessment of the probability of failure requires a large number of computations, unless specific search algorithms are used for more efficient sampling around the design point. Subset simulation, which is based on a Markov-chain Monte Carlo algorithm, is one example; see e.g. Au & Wang (2014). With this method, the location of the design point is located with an iterative search algorithm and the sampling of the parameters around this point is weighted with respect to their probability of occurrence, leading to a more efficient Monte Carlo simulation.

Approximate techniques can also be used, such as the point estimate method or the modified point estimate method (Langford & Diederichs 2013); however, the accuracy of this technique is questionable, especially for complex limit states with low probabilities of failure.

A potential research question is therefore the implementation of subset simulation together with numerical analysis, in order to reduce the necessary calculation time and improve the accuracy of the numerical analyses used to assess the structural safety.

4.2.2. Optimization of concrete thickness in the lining

When the cavern is pressurized, tensile stresses tangential to the cavern will develop at a certain internal pressure. At which pressure this occur depends on the prevailing tangential compressive stresses around the cavern due to the initial stresses in the rock mass. These tensile stresses open up existing fractures in the rock mass. Such fractures constitute potential areas with high local strains in the impermeable lining. To reduce these local strains, a reinforced concrete lining together with a sliding layer between steel and concrete is used. In the Skallen facility, the thickness of the concrete layer was not optimized from a structural perspective, but mainly chosen with respect to practical reasons. The space between the rock mass and the steel liner should allow for welding and non–destructive testing of the steel, to pour the concrete, and to install reinforcement mesh, etc. (Johansson 2003).

Detailed analysis of the minimum required thickness would therefore constitute a potential research question within WP 2.3, with respect to the ability of the lining to reduce local strain effects caused by the opening of rock fractures. This optimization of the concrete thickness should preferably be performed using a risk-based approach combined with numerical methods.

4.2.3. Effect of spatial variation of rock mass properties on location suitability

The spatial variation of the rock mass properties could significantly influence the occurring strain in the rock close to the wall and in the lining. Depending on allowable strain limits in the steel, the shape of the cavern, and the in-situ stress conditions, the spatial variation of the surrounding rock mass properties may influence the design. Today, analysis of stresses and strains in the rock mass are usually made assuming a homogeneous and isotropic rock mass.

How a spatial variation due to different scale of fluctuations of the rock mass properties influences the cavern behavior is of interest, because it is not only the average properties that govern the cavern behavior, but also their spatial distribution, especially if the scale of fluctuation is relatively large compared to the cavern size. Another important aspect is also the presence of weakness zones, which are relatively frequently occurring in the rock mass. The effect of the spatial variation in the rock mass on the cavern wall may affect how close the cavern can be located to different types of identified weakness zones. These topics are worth further research, since they constitute important input in the selection of suitable cavern locations.

4.3. Additional important research questions and design issues

In the course of the work with this report, a number of additional research questions related to underground storage of hydrogen gas have been recognized. Although they may be worth further investigation, or even be critical to the design, we have not deemed it reasonable to cover them in WP 2.3 for various reasons, which are discussed in each subsection. They are therefore listed here separately.

4.3.1. Hydrogen embrittlement of the steel lining

As discussed in section 2.4 and 4.1, the effect of hydrogen gas on steel properties, which is known as hydrogen embrittlement, is a critical issue to study and solve for the design of an LRC facility for hydrogen gas. The selection of a suitable steel type is, however, a metallurgic issue rather than a rock engineering issue. We suggest that the potential effect of hydrogen embrittlement is studied separately.

4.3.2. Long-term behavior of the sliding layer

A specially developed sliding layer was used in the Skallen facility to even out shear stresses in the interface between steel and concrete. The layer was 6 mm thick and consisted of polymer-modified bitumen with textile reinforcement in between. The surface of the layer, which was applied against the concrete, was covered in sand and the layer was applied on epoxy-primed steel. Several shear tests were performed on the layer under different temperatures and the normal stress ranged up to 25 MPa. The shear stress was found to be dependent on both normal pressure and shear resistance. It may be possible that cyclic loading with time gradually decrease the ability of the layer to reduce shear stresses. However, no test was performed on the long-term behavior of the sliding layer with respect to cyclic loading at high pressure. Additional testing under cyclic loading at different temperatures would therefore be of interest to further increase the understanding of the characteristics of the sliding layer over time. However, similarly to hydrogen embrittlement, this is also an issue related to selection of manufactured construction materials and should therefore be studied separately.

4.3.3. Case study of the application of risk management frameworks

Although high-quality and substantial risk management will be a necessity in the design and construction of the storage facility, we see no critical need for further development of the available risk management methods. Well-established risk management procedures are already available through the ISO 31000 standard and application guidelines for geotechnical aspects of construction work have been published. However, there are few publicly available high-quality case studies on the practical application of such risk management frameworks; in fact, for rock engineering structures, there is none, to our knowledge. Therefore, we believe that a case study of the design and execution of the planned underground gas storage facility from a risk management perspective would be of high value. However, as this is not a theoretical study to enable the construction of the facility, but a report of the experience from the actual work, we believe that such a study is out of the scope of WP 2.3.

4.3.4. Control of temperature variation in the cavern

Due to the cyclic filling and emptying of the storage during commercial operation, the temperature in the cavern will vary. Very high temperatures may be harmful for the sliding layer. Temperatures below 0 °C could freeze the groundwater causing damage to the concrete lining. Restriction of the operation during gas injection and withdrawal is necessary to avoid too high or too low temperatures. How to control the temperature in the cavern is an important question; see also the US patent by Hall (2002).

4.3.5. Gas behavior in the rock mass and design of gas detection system

In principle, there are two options to manage a possible gas leakage in the design of the cavern: design the drainage and gas detection system with respect to a “worst case” leakage scenario or only design the drainage system with respect to the water leakage during the construction phase of the cavern.

In the design for a “worst case” gas leakage scenario, it is necessary that the leakage drainage and detection system is properly designed in order to be able to collect and transfer the gas to specific locations on the surface. The dimensions and spacing of this system is mainly dependent on gas pressure and the expected size of the crack in the steel lining.

If the system has insufficient dimensions, which for example is the case if the leakage system only has been designed for water leakage during the construction phase, hydrogen gas may leak into the rock mass. If the cavern is situated relatively shallowly, the distribution of gas in the rock fractures could result in jacking (uplift of the rock mass due to pressurized rock fractures) and uncontrolled leakage to the surface. How gas is transmitted in a rock mass has been studied by a number of researchers, see e.g. Kjørholt (1991), but further research on this topic with respect to hydrogen gas and the LRC concept may be of interest; however, such a study would need to start off on a rather basic research level and the expected outcome over 4 years is not believed to contribute as much to the advances of the HYBRIT project, as the studies listed in section 4.2.

5. Conclusions

The most suitable way of storing large quantities of hydrogen gas in Sweden is concluded to be the use of lined rock caverns (LRC). The LRC concept has been proven successful through the construction and operation of the Skallen demonstration plant. No critical research questions exist today for the construction of such facility with the exception of the issue concerning hydrogen embrittlement of the steel lining. Even though this question will not be covered within WP 2.3, it is a key question that needs to be solved before the storage can be designed and constructed.

In the design of an LRC facility, the use of risk-based methods is preferable. However, the experience of using such methods in rock engineering in general – and for lined rock caverns in particular – is limited. Future research questions within WP 2.3 are therefore suggested to further develop the use of risk-based methods in the design and construction of the LRC-concept. Within this context, several potential research questions has been identified, which mainly focus on the use of numerical methods in combination with risk-based design methods in rock engineering:

- Implementation of subset simulation together with numerical analysis to reduce the necessary calculation time and improve the accuracy of the numerical analyses with respect to reliability.
- Optimization of the concrete lining thickness with respect to the ability of the lining to reduce local strain effects caused by the opening of rock fractures.
- Influence from spatial variation due to different scale of fluctuations of the rock mass properties and from possible weakness zones in the rock mass on the cavern behavior.

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