REPORT ON MATERIAL QUALIFICATION INCLUDING GUIDELINES FOR MATERIAL SELECTION/DEVELOPMENT

- DELIVERABLE D6.1 -

DESIGN STUDY FOR THE
EUROPEAN UNDERGROUND
RESEARCH **I**NFRASTRUCTURE
RELATED TO ADVANCED ADIABATIC
COMPRESSED **A**IR ENERGY **S**TORAGE

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Abstract: The information for defining a proper storage solution for a large CAES facility is reported and analysed. The different storage possibilities are compared and the initial optimal solution for the RICAS2020 project defined. In addition, initial numerical simulation of the storage is reported.

VERSION	DATE	REASON OF CHANGE
1	01/11/2016	Initial version of the report
2	13/12/2016	Final version

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1 Executive Summary

Various activities have been carried out to assess the feasibility and the initial requirement for building the storage system of an Adiabatic Compressed Energy Storage System (A-CAES) in soft rock. RICAS2020 project focuses on the development of a CAES system with a storage independent on the available geological formation. Under this condition, the only feasible solution is represented by the use of a cavern/tunnel in rock formation. The main information and required parameters for the storage cavern in rock are analysed and reported in the following taking the RICAS2020 conditions into account.

The report contains furthermore an evaluation of the initial location requirement as well as the possible lining material and structural solution. For the RICAS2020 project, the most promising design for the storage is represented by a segmented liner. The possible candidate materials for each part of the structure components are here reported and analysed.

2 Introduction

2.1 Purpose of the Deliverable

This deliverable describes the general principle behind the A-CAES system, providing a general introduction and information about the already installed system and pilot plants around the world. The different solutions previously tested are reported and compared to evaluate the optimal design solution for the specific application of RICAS2020.

The defined design for A-CAES solution is then analysed and verified by mean of numerical simulation using the state of the art numerical tools. An initial set of lining material for the caverns and their related combination has been numerically tested under the real in service condition that will be experienced in the cavern.

2.2 Scope of the Deliverable

The deliver will provide:

- Introduction to the CAES system
- Previous CAES systems built and tested
- Literature review for the design of the cavern storage system
- Definition of the initial cavern design for specific RICAS condition
- Simulation methodology
- Simulation of the specific design of the RICAS storage system
- Initial set of possible lining material and combination to be used

2.3 Related Documents

The Deliverable is related to the overall RICAS2020 design concept (D2.1) and to the numerical simulations of the underground structures (D4.1).

3 General description of CAES system

3.1 General introduction about CAES

The society today is highly depending on electric power. Almost all of our modern conveniences are electrically powered. In the last years, the massive use of renewable electric production system has generated a challenge for the worldwide electric grid where the produced energy (especially from renewable sources) is generally not in phase with the peak demand from the population. This leads to a necessity to develop large electric storage system that can accumulate electric power and supply it during the peak request periods.

The CAES plant is the answer to this problem. CAES is a low cost technology for storing large quantities of electrical energy in the form of compressed air. Air is compressed in a storage unit when electric energy overproduction is available, and by the inverse process, is reintroduced in the grid when required in the high demand periods. CAES represent a system that is capable of storing large amount of electric power at very low price. Several other technologies previously investigated (flywheels and ultra-capacitor) are not cost effective and technological valid solutions for load shifting situation and renewable production system support (e.g. wind farm) [1, 2].

Recently new emerging battery technology system seems to represent a valid alternative to CAES, but the typical system capacities and storage size are generally smaller and with an initial much higher cost. In addition, the problem related to the low cycle life of battery system, together with the environmental impact at the end of the life, make batteries not a suitable solution for storing large quantity of electric energy. These represent a more valid solution for overcoming short load peak supplier more than long time constant power output.

The only comparable solution to a CAES system, capable of delivering several hours of electric power output, is represented by pumped hydroelectric storage (PHS) [3-6]. These systems are highly efficient and have been used for long time with a valuable field experience built over the years. However, these solutions can be implemented only in specific locations where water reservoirs are available at different elevations. This highly reduces the possible location where PHS system can be positioned. In addition, large PHS plants have a drastic environmental impact due to the drastic changes required to the surroundings with a very strong opposition from local communities.

CAES systems instead represent a valid solution with a very limited environmental impact and high flexibility compared to PHS. High-pressure air can be stored in surface piping, but for large-scale applications, developing a storage reservoir in an underground geologic formation such as solution mined salt, saline aquifer, abandoned mine, or mined hard rock are typically more cost effective. A comparison of the estimated cost for the different storage solutions is reported in Table 1. It is evident that the CAES system represents the most economical solution for storing large electric power.

Table 1: Capital Costs for Energy Storage Options [1, 7]

Technology	Capital cost capacity ($/kW)	Capital Cost Energy ($/kWh)	Hours of Storage	Total Capital cost ($/kW)
CAES (300MW)	580	1.75	40	650
PHS (1000MW)	600	37.5	10	975
Sodium Sulfur Battery (10MW)	1720-1860	180-210	6-9	3100-3400
Vanadiun Redox Battery (10MW)	2410-2550	240-340	5-8	4300-4500

3.2 General CAES working principles

In a classic CAES system (see Figure 1), during the charging phase, off-peak production electricity is used to compress air using an electric motor connected to a multi stage compressor. The compressed air is stored in an ad-hoc location (tank, cavern or any other media) and, through the inverse process during the discharging phase, electric energy is produced by the use of a classic gas turbine connected with a generator. The process has a round efficiency of approximately 50%.

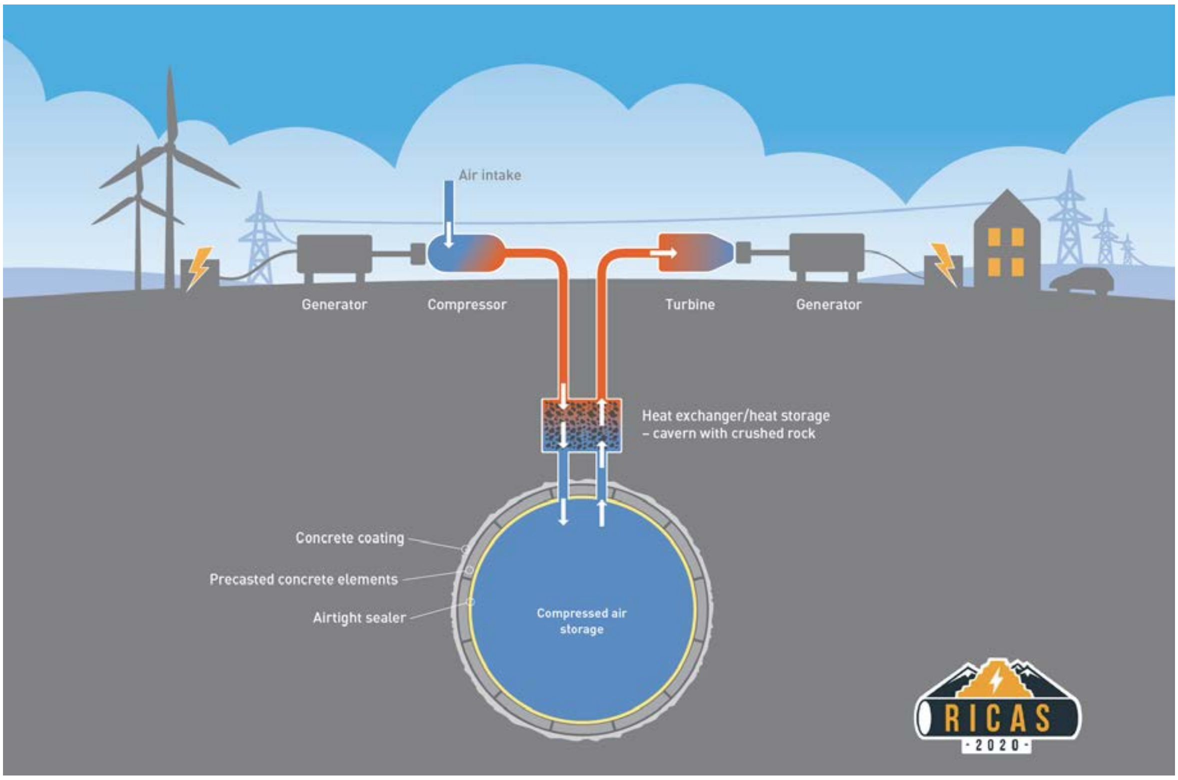

Figure 1: CAES basic working principle

The major component of a CAES system includes (see Figure 2):

- A *motor* connected to the compressor transform the electric energy in mechanical power to activate the compressor (charging phase)
- A *generator* connected turbine transform the mechanical work of the turbine into electric power during the discharging phase. Generally the motor and generator functions are carried out by the same unit

- *Compressor train* made of a multi stage compressor is used to compress the air in the storage. This is generally coupled with intercooler to reduce the required power during the compression cycle. In addition an aftercooler is also generally used to reduce the fluid temperature and consequently the required storage volume (for the same power)
- An *expander train* consisting of high and low pressure turbines
- *Combustors* are generally required with conventional CAES system between the different turbine stages to compensate the temperature reduction during the discharging phase. This generally uses fossil fuel to produced air at elevated temperature that is then mix to the main airstream.
- *Control system and Auxiliary system* to operate the plant
- *Storage system*: Underground or above ground compressed air storage reservoir

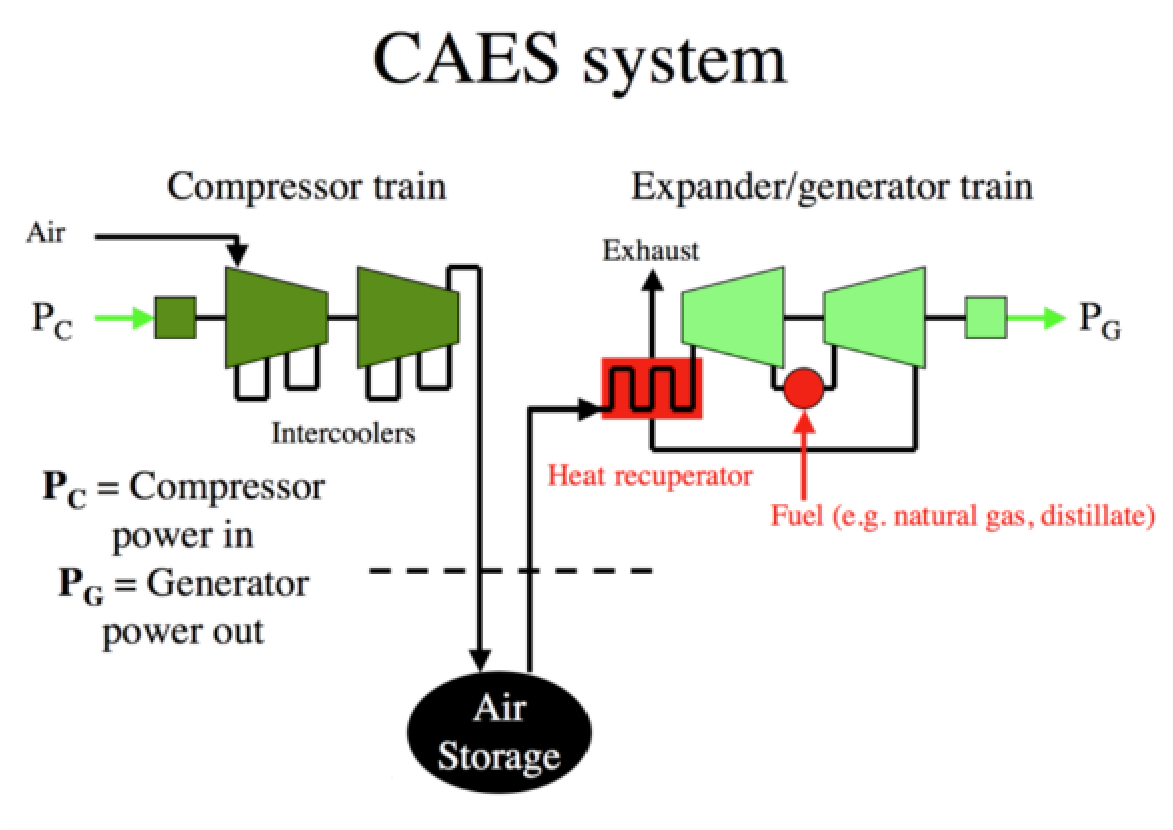

Figure 2: CAES system from [8]

3.3 Compression and expansion phases

The CAES technology is not new; it was initially developed in the early 70th under the pressure of economic and political needs. These systems were developed based on conventional gas turbines used for energy production, with the difference that the compression and the expansion operations occur independently and at different time. For CAES, the compression power is supplied separately and the full output of the turbine can be used to generate electricity during expansion. Conventional gas turbines, however use typically two thirds of the output power from the expansion stage to run the compressor.

The working cycle of a CAES is divided in two main phases:

- *Compression or charging phase*: During this phase, the electricity is used to run a series of compressors that inject air in the storage reservoir. The compressors increase the storage pressure. The compressors are coupled with intercoolers and an aftercooler to reduce the temperature of the injected air. This allows to increase the compression efficiency, to reduce the storage volume requirement and to minimize the thermal stress on the storage volume walls.
- *Expansion or discharging phase*: During the expansion phase, the air is withdrawn from the storage and mixed with hot air generated from combustion or stored heat during the compression phase. The mixed air is then expanded in multi stages turbine. The turbine is directly connected with the generator (motor during the compression phase) and the electric energy is regenerated.

3.4 Conventional CAES and A-CAES systems

The current existing CAES system is massively using hot air generated by combustion of natural gas to increase the air temperature between the different stages of the turbine during the expansion phase. This highly reduces the system round efficiency. The injection of hot air is mainly done for two reasons:

- Expanding air at the wall temperature of the reservoir (25C to 40C), would necessitate higher airflow in order to achieve the same turbine output;
- The low temperatures at the turbine outlet due to the gas expansion, would pose a significant risk of icing for the blades with potential damage.

Conventional compressed air storage plants are inefficient, and it is counterintuitive that they should require an input of fossil fuel in addition to the electricity they use to compress. The main input of energy is in the form of the electricity that is used to compress the air. However, some of this energy is lost afterwards, either by intentional cooling or by dissipating into the walls of the storage cavern. Pressure is maintained throughout the storage process, but combustion is required to restore the lost thermal energy.

3.4.1 A-CAES

In contrast with conventional power plants, which must convert stored energy into useful work, storage energy plants as CAES, do not need to generate a net output of work. The combusted fuel is only required to overcome the turbine functioning behaviour and to compensate for the large portion of the thermal energy loss by the air during storage through the wall. If thermal energy generated during compression is properly stored, fuel consumption would be not required with consequent improvement of the total system efficiency.

Adiabatic Compressed Air Energy Storage (A-CAES) are the solution to this problem (see Figure 3). In this system, the heat generated during compression phase is stored in a specific thermal storage, generally referred as TES (Thermal Energy Storage). This thermal energy is then reused in the expansion phase to heat the air entering the turbine by the use of a specific heat exchange.

Thermal store is a technical challenge to overcome. Because of the extremely high temperature difference between the thermal energy store and the surrounding environment, preventing heat dissipation is a significant challenge. This is specifically addressed by the RICAS2020 in WP3. More details to be found in their specific reports.

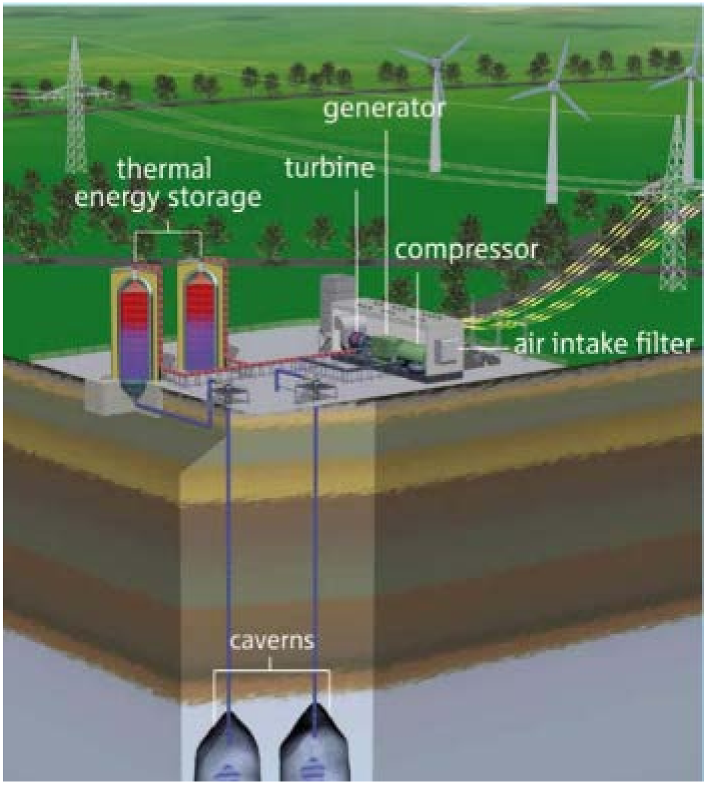

Figure 3: A-CAES typical layout and main components from Adele project.

3.5 Current storage solutions

One of the main components of the CAES system is represented by the storage for the compressed air. This represents a quite challenging component that can highly affect the total economic feasibility of the CAES plant. Three different solutions are currently available for storing pressurized air for a large CAES power plant: *Hard Rock, Salt Formation and Porous Rock.*

3.5.1 Hard rock

A large cavern in hard rock is one of the possible options for locating the storage of a CAES facility. However, this can represent quite an expensive solution due to the high excavation cost in hard rock formation. The cost for mining new cavern can be in the order of $30/kWh produced according to [8]. However the use of abandon mine, easily available in central Europe, can drastically reduce the cost up to $10/kWh produced [1, 9, 10].

Methodologies have been developed in the past for evaluating the rock stability, leakage and energy loss in hard rock installation for CAES facilities [11-13]. Several system have been developed [14]. In Japan, two pilot plants have been developed in hard rock formation with concrete lining: a 2 MW test system using a concrete-lined tunnel in the former Sunagaawa Coal Mine and a hydraulic confinement test performed in a tunnel in the former Kamioka mine [1].

If abandon mines can be utilized, this storing solution can represent a very promising option for large CAES plants.

3.5.2 Salt formation

Currently the only two functional CAES facilities in the world use solution-mined cavities in salt domes as their storage reservoirs. These solutions are the most easy and cheap to develop and build. In situ leaching process can provide a suitable solution for develop large storage volumes at low cost. According to the available estimation typical capital cost for these solution is in the order of \$2.00/kWh produced [8]. However, these storage solutions require the availability of salt dome and fresh water for the leaching process in addition to an adequate location for the damped resulted brine. Despite the challenges with such solutions , the elasto-plastic properties of salt storage provide a very limited risk of air leakage providing an very favourable solution for CAES installations [15, 16]. Salt formations however have the drawback of shrinking over time reducing the available volume. This is an important aspect that needs to be considered during the design.

Salt formations are generally available in the form of bedded and dimal formations; both of these can be used for CAES applications. However, salt beds are generally more challenging to use when large storage volume are required. These are generally small and present generally impurities that can affect the structural integrity of the installation [17]. On the other end, salt dome formations are instead generally larger with a better ratio between width and height (tall and narrow formation).

Salt formations are available in Europe, however their location is not homogeneous spread between the different countries (see Figure 4). This represent a challenge when CAES plant wants to be located in region with limited or even no availability of such formations. Other solutions are required in these situations.

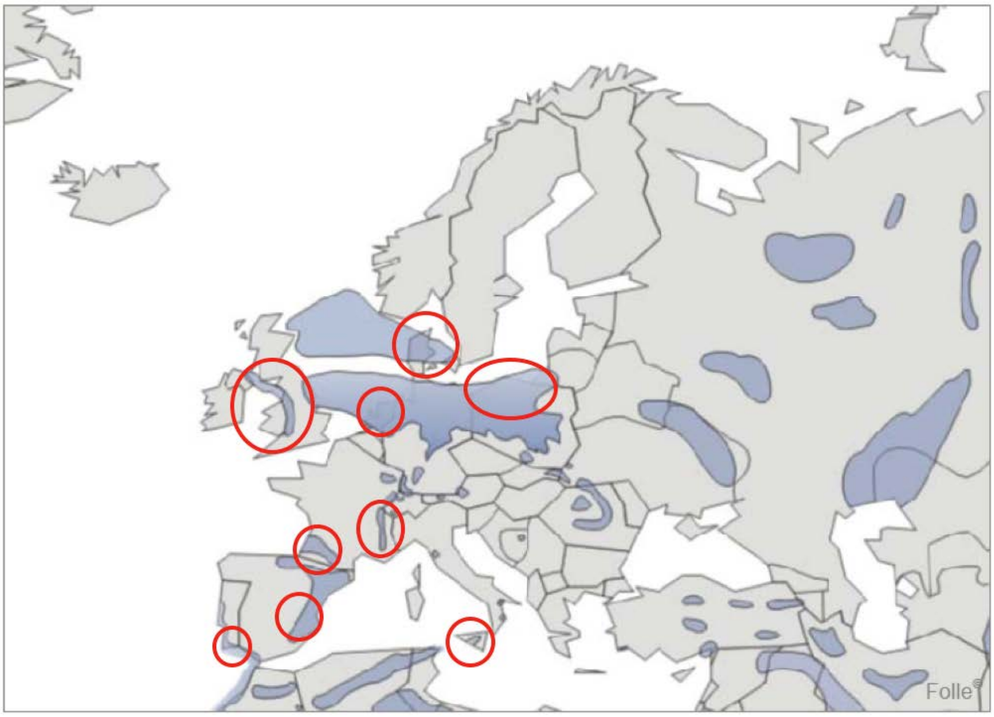

Figure 4: In blue, salt dome formations and in red circles, wind farm distribution in Europe. From [18]

3.5.3 *Porous Rock*

Another possible solution for storing compressed air for a CAES facility is to use porous rock formation (such as empty oil reservoir underneath a tight cover). The air can be stored in the rock porosity mixed with the available liquid. This represent the most valuable economical solution with an estimated development cost of ~$0.11/kWh [1].

However, despite the favourable cost potential, the use of such solution for a CAES power plant requires large field evaluation of the geological condition to assess the real capability of the defined location. This can lead to a drastic increase of the development cost. In addition, even if the geological survey shows favourable conditions, this can present anyway challenges and possible failure. An example is the 25 MW porous rock-based CAES test facility operated for several years in Sesta, Italy. In this case, a geological event disturbed the defined site leading to the closure of the facility [1]. Another example is the CAES plant in porous rock reservoir planned in Dallas Centre, Iowa. In this case, even if the initial investigations showed favourable geological conditions, further field investigations demonstrated the impossibility to reach the required airflow for a large CAES facility leading to the complete stop of the project (more details in the following sections).

3.6 Storage geological requirements

The definition of the storage location is one of the main aspects during the design of a CAES power plant. The high pressure involved in the storage facility (generally from 50 to 70 Bar), requires the definition of a proper location and related geological formation capable to host the system.

All the installed or planned CAES facilities around the world, have been generally located in deep cavern in hard rock formation or salt dome. According to [19], several different aspect should be considered when defining the optimal location of a CAES facility according to the type of storage that need to be used:

- *Rock cavern*: crucial parameters for these installations are the rock mass strength, permeability, stability depth and thickness. Important is the evaluation of the uniaxial compressive strength (UCS) of the hosting formation together with the evaluation of discontinuities and air water permeability. In addition, the depth from the ground surface is also crucial for determining the maximum allowed pressure (in case of not lined solution – more details in the following sections). According to [19], for unlined cavern, 30m thick rock with UCS in the range of 70 -138MPa, conductivity less than $2x10^{-6}$cm/s and a depth between 400-600 m represent the favourable conditions. However, these minimum requirements are evaluated when applying storage in hard rock with no support or lining solution. If other containment methods are used, even lower rock quality can represent a suitable solution. In this case a proper confinement method would be required.
- *Salt cavern*: the main parameters in this case are related to the cavern depth (top of the cavern up to the ground level). In addition, crucial are also the formation thickness and its quality. According to [19], depth of 900m and minimum roof cover or 91m are recommended for using salt formation for CAES facilities.
- *Porous rock*: important criteria for water and gas bearing porous-media sites are anticlinal structure, impermeable cap rock, appropriate depth, permeability, porosity, noncorrosive fluid, and mineral chemistry.

3.7 Storage operation conditions

Several different storage operation conditions can be defined for a CAES plant. This can highly affect the behaviour of the system.

3.7.1 Constant storage volume

The most common and currently used in all the built and planned facilities storing operation method is based on a constant volume. This means that the storage volume is fixed by the reservoir size and, during the CAES operation, the storage pressure varies over a fixed range. This operation mode offer to two different possibilities to the design of the CAES machineries:

- *Variable inlet pressure*: the inlet of the high pressure (hp) turbine can vary during the expansion phase according to the reduction of the storage pressure
- *Constant inlet pressure*: the inlet pressure of the hp turbine is kept constant by throttling the air pressure with a specific regulator. The pressure variation in the cavern does not affect the inlet pressure of the turbine.

The constant inlet pressure option is the one currently used in the two functional CAES facility. This solution, even allowing air loss due to the throttling operation, allows higher turbine efficiency (turbine optimized for a specific inlet condition). The Huntorf CAES plant is designed to throttle the cavern air to 46 bar at the hp turbine inlet (with caverns operating between 48 to 66 bar) and the McIntosh system throttles the incoming air to 45 bar (operating between 45 and 74 bar).

3.7.2 Variable storage volume

The other available solution for storage operation is to use a constant pressure and variable volume of the storage system. This can be obtained by using a head of water applied by an aboveground reservoir (see Figure 5). The storage presents a combination of pressurized air and water. The air storage volume is constantly varying its total volume during the charging and discharging phases by varying the water volume (constant water pressure).

This represents the optimal solution from the total system efficiency due to the reduced losses. However, this solution required the additional requirement of large water reservoir and need special attention to manage possible flow instabilities of the water shaft such as the so called "champagne effect" [20]. The use of constant-pressure CAES operation is primarily limited to systems with reservoirs mined from hard rock.

This solution has never been used and can represent a challenge due to the required water availability and possible problems related to the "champagne effect".

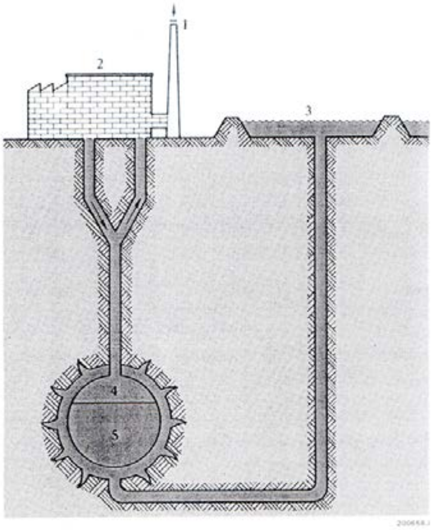

Figure 5: Constant pressure CAES reservoir with compensating water column. (1) Exhaust (2) CAES Plant (3) Surface Pond (4) Stored Air (5) Water Column [21]

3.8 Storage required volume

One of the main parameter for design a large CAES facility is the evaluation of the required storage volume according to the desired output total energy. This can be evaluated as the generated electric power for unit volume of storage: E_{Gen}/V_s.

The electric output of a turbine (E_{Gen}) can be calculated as:

$$E_{Gen} = \eta_M \eta_g \int_0^t \dot{m}_t w_{CvToT} \, dt$$

The integral represent the mechanical work generated during the expansion of the air in a turbine and:

- w_{CvTot}: total mechanical work per mass unit
- $\dot{m}_t$: air mass flow rate
- t: time of discharge phase of the cycle
- η_m: mechanical efficiency of a the turbine
- η_g: Electric generator efficiency

The complete mathematical evaluation of the energy output for unit volume is available in [8] and not reported here.

In Figure 6, the energy storage density for the three possible storage operation conditions (constant storage pressure, variable storage pressure and variable storage pressure with throttling valve) is reported as function of the reservoir initial pressure and ratio [22]. The use of constant cavern pressure with compensated volume seems to be the optimal solution providing the higher energy density. According to the evaluation reported in [22], the use of this storage technique could have reduced the required storage volume in the Huntorf CAES plants (more details later) of approximately 72%. However, due to the previously reported limitation related to the unpracticality of this solution, only the variable storage pressure solution can be considered valid and feasible.

For variable pressure storage, it is evident as the energy density increases linearly with the increase of the initial storage pressure (Ps2) and the pressure variation ratio (for the cases of variable storage pressure). However, these two factors are highly limited by other considerations:

- *Storage pressure*: this is limited by the cavern/storage structural properties to sustain high mechanical load. The use of a lined solution with the addition of reinforced concrete support can provide the required structural stiffness to support higher pressure that what currently used (see next section with the details of the available CAES facilities)
- *Pressure variation ratio*: this parameter represents the ratio between the initial (Ps2) and final (Ps1) pressure in the storage during the discharging phase. This value is highly influence by two factors. A too low final pressure (Ps1) can produce problem on the turbomachinery with the impossibility of correct function of the system (with and without the throttling valve). In addition, large pressure variation during the discharge phase, can highly influence the internal storage temperature with consequent effect on its structural integrity.

According to the previous reported consideration, it is evident that the evaluation of the working parameters of the CAES system is crucial and requires an iteration/compromise between turbomachinery and storage requirements.

In addition, for the case 3 when pressure throttling is used to ensure constant pressure inlet to the turbine, the induced energy loss are very limited. In particular, the throttling losses are small when large initial pressure (Ps2>60Bar) are used (as the case of all the existing CAES facilities). However this system operation method present several benefit as operation simplification and higher turbine efficiency that can mitigate the loss of efficiency induced by the trothing. This can then represent the optimal solution even if slightly larger storage volume is required.

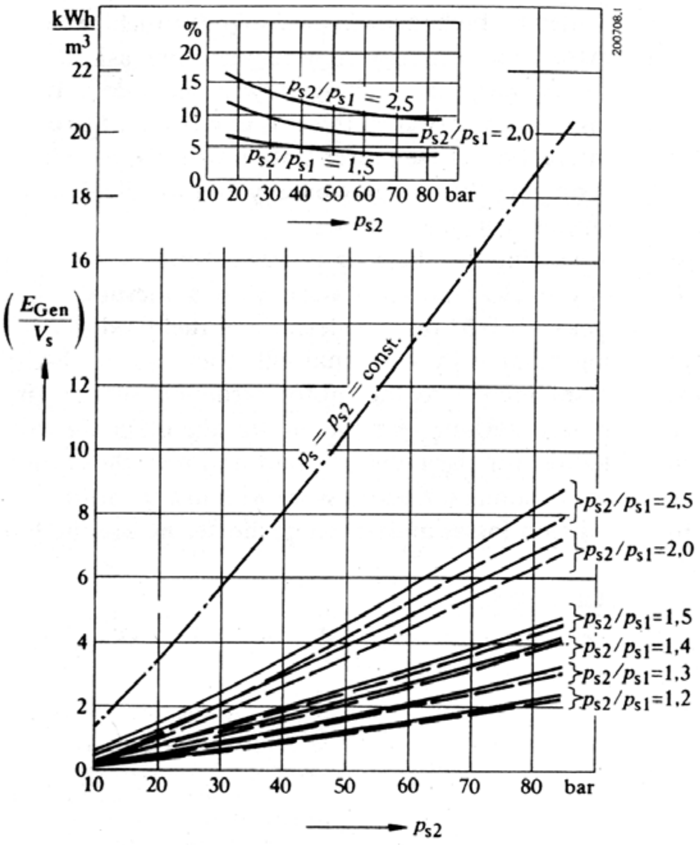

Fig. – Determining the size of the reservoir

E_{Gen} = Generator energy
V_s = Storage volume
p_{s2} = Upper storage pressure
p_{s1} = Lower storage pressure

–·–·–·– = Reservoir, case 1
——— = Reservoir, case 2
– – – – = Reservoir, case 3
T_{EHD} = 825 °K, T_{END} = 1100 °K

Figure 6: Energy produced for unit value for different storage operation conditions: Case 1 - constant pressure, Case 2 - variable pressure; Case 3 - variable pressure and constant turbine inlet pressure (using throttling valve). Graph from [22]

According to the available data reported in [1] [23], typical value for the energy density (E_{Gen}/V_S) are in the range of 2-4kWh/m^3 for the current existing CAES installations (Huntorf - pS2/pS1=1.38, pS2=66 bar, EGEN/VS=3.74). New CAES design, as the Adele CAES plan (more detail in the following sections), can lead to higher energy density on the range of 6-9 kWh/m^3 due to the higher operative pressure and larger pressure ratio (Ps2/Ps1=2.0, Ps2=110 bar, EG_{en}/V_S=8.44)

4 CAES facilities around the world

Following a list of the CAES facility built or proposed around the world.

4.1 Huntorf CAES plant

Location:	Bremen, Germany
Completion date:	1978
Power	290 MW
Duration at full power	3 hours
Depth of cavern	650-800 m
Caverns	Two underground salt caverns with total of 310,000 m^3
Operation pressures	48 - 66 bar
Expanders	Stage 1: 46 to 11 bar Stage 2: 11 bar to 1 bar

The Huntorf CAES plant has been the first world CAES facility. It was completed in 1978 near Bremen, Germany. The plant has a total power of 290 MW for 3 hours. It was designed and built by ABB to provide black-start services[1] to nuclear units near the North Sea and to overcome peak power requirement with low energy cost. It has been operating for almost four decades as peak shaving unit to compensate other (hydroelectric) storage facilities. According to the available data, starting reliability for this unit is reported to be 99%.

The storage system of the CAES plant consists of two separate salt caverns (310,000 m^3 in total) designed to operate in a pressure range between 48 and 66 bar. The only registered problem with the storage system was related to the air from the salt caverns that were found to generate oxidation upstream of the gas turbine during the first year of operation. This problem was solved by the replacing of the bore pipelines from metal to fiberglass reinforced plastic (FRP). Because the turbine expanders are sensitive to salt in the combustion air, special measures were taken to ensure acceptable conditions were met at the turbine inlet as well [24].

The compression and expansion phase of the cycle draw 108 and 417 kg/s of air respectively. The first turbine stage expands air from 46 to 11 bar. Gas turbine technology was, at the time of the installation, not capable of this pressure range, steam turbine technology was used for the high-pressure (hp) expansion stage. In order to ensure proper cooling and to overcome the increase in the heat transfer coefficient at elevated pressure and temperature, the hp turbine inlet temperature was held to only 550° C compared to 825° C for the lp turbine (typical for a gas turbine without blade cooling). In addition, the lower inlet temperature facilitate the daily turbine start-ups of the facility [21]

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[1] Black start refers to the ability of a plant to start up during a complete grid outage. Because nuclear power stations require some power to resume operation, the Huntorf CAES plant was built in part to provide this start up power.

Even if the plant could have been able to operate at a lower heat rate using heat recuperates (to recover exhaust heat from the lp turbine for preheating the gas entering the hp turbine), this addition was omitted in order to minimize system start up time [25, 26].

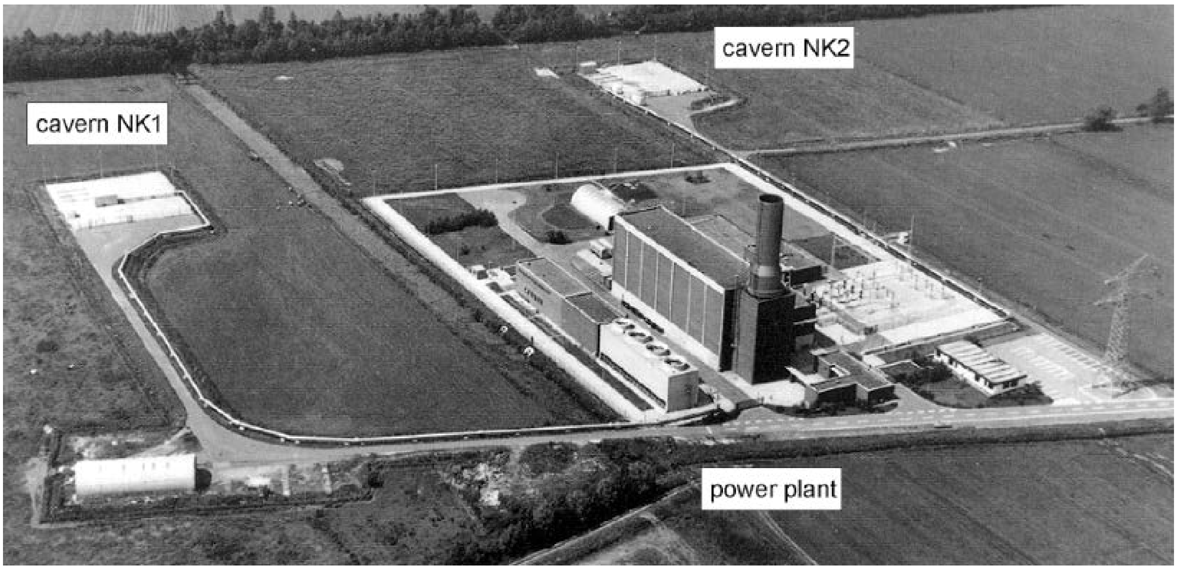

Figure 7: Aerial view of the Huntorf CAES plant

4.2 McIntosh

Location:	Alabama, USA
Completion date:	1991
Power	110 MW
Duration at full power	26 hours
Depth of cavern	305 m
Caverns	single salt cavern total volume of 540,000 m^3
Operation pressures	45 - 74 bar

McIntosh power plant in Alabama has been the first CAES facility in the United States. This was built by Alabama Electric Cooperative on the McIntosh salt dome in southwestern Alabama and has been in operation since 1991. It was design for a total power output of 110MW generation for 26 hours. Differently than the Huntorf CAES plant, it used a single salt cavern with operative pressure between 45 and 74 bars. The project has similitudes with the Huntorf plant such as the inlet temperatures, pressures, etc. However, this CAES includes heat recuperators that reduces fuel consumption by approximately 22% at full load output and features a dual-fuel combustor capable of burning two different fuel oil in addition to natural gas [1]. This allows a drastic increase of the total plant efficiency compared to Huntorf CAES plant.

The plant experienced significant problems in the initial operation phase. These were solved through modifications of the high pressure combustor mounting position and a redesign of the low pressure combustor [26].

These changes enabled the McIntosh plant, over 25 years of operation, to achieve 91.2% and 92.1% average starting reliabilities as well as 96.8% and 99.5% average running reliability for the generation cycle and compression cycle respectively [27].

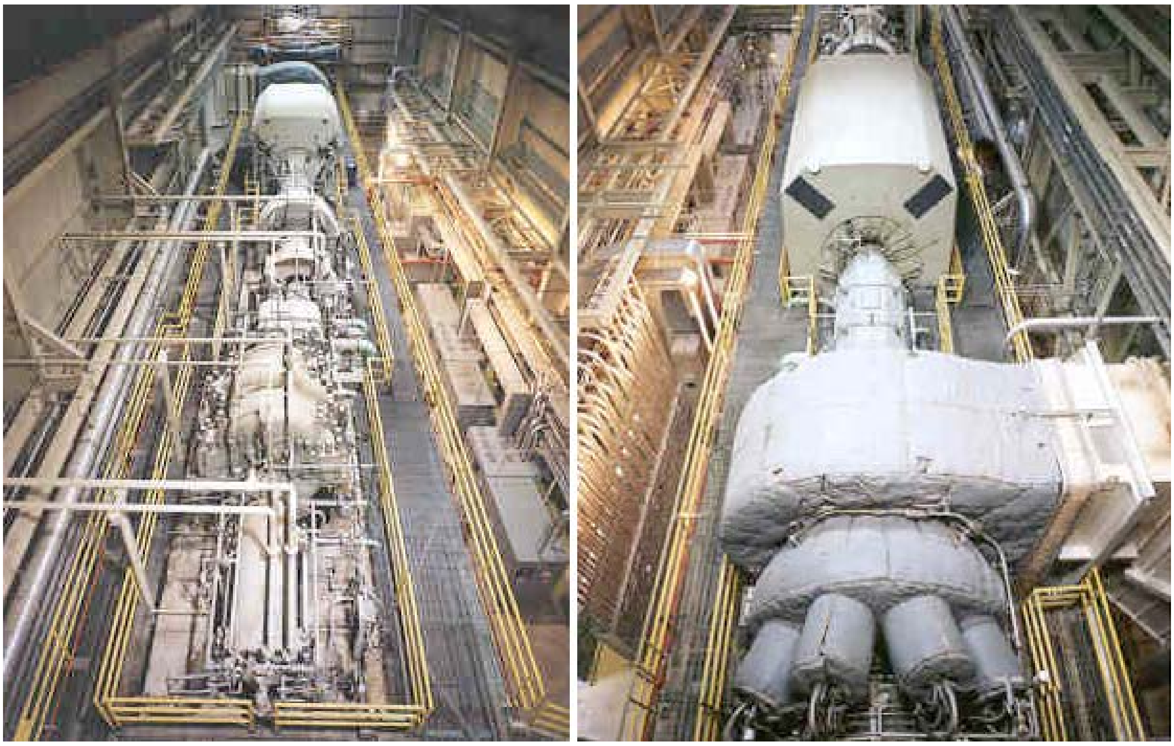

Figure 8: McIntosh CAES system compressor train (left) and combustion turbine (right)

4.3 Norton (proposed - currently in hold)

Location:	Norton, Ohio, USA
Power	800 to 2700 MW
Caverns	limestone mine of 9,600,000 m^3
Operation pressures	55 - 110 bar
Year:	2001-2006

The project aimed to convert an old limestone mine in Norton (Ohio) into a storage system of a large CAES plant ranging from 800MW to 2700MW (9 x 300MW). The total planned storage volume was 9.6M m^3 designed to operate between 55 and 110 bars without the use of any lining on the rocks. After the approval and the initial design, the project was terminated due to the low energy price with the consequent low economical value of such large installation.

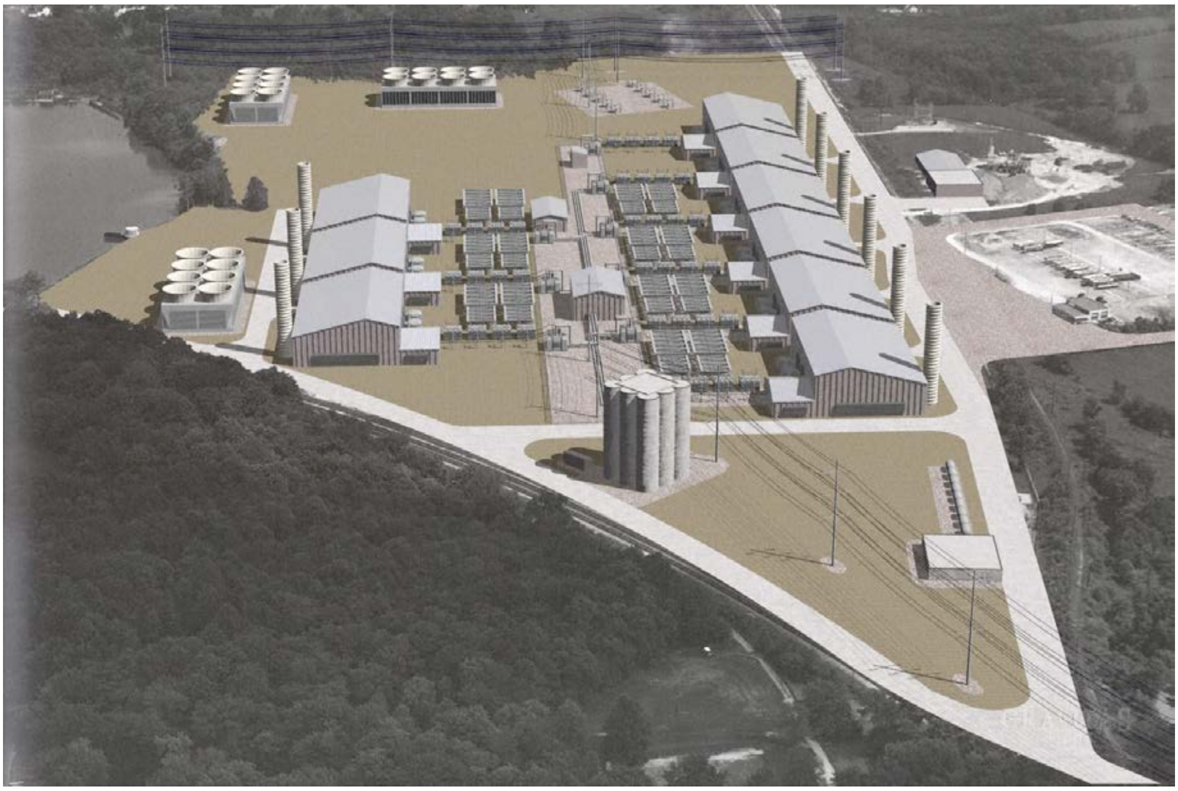

Figure 9: A rendering of the proposed 2700 MW CAES plant based on an abandoned limestone mine in Norton, OH

4.4 Iowa Storage Energy Park (proposed)

Location:	Dallas Center, Iowa USA
Power	270 MW
Caverns	Aquifer porous rocks
Year	2006-2009

The Iowa Association of Municipal Utilities (IAMU) aimed to develop a large CAES facility using aquifer porous rocks as storage in Dallas Center, Iowa. The original plan was to couple the CAES directly with a wind farm.

The Iowa Stored Energy Park was formally announced in December 2006. The CAES facility was planned to occupy 40 acres located within 30 miles of Des Moines, Iowa and use a 900m deep anticline in a porous sandstone formation to store wind energy. This was the third location studied after an initial screening of more than 20 geologic structures in the state. Initial studies of the chosen formation verified it has adequate size, depth and caprock structure to support CAES operation. Unfortunately, further and more accurate evaluation showed that the defined location presented too low air permeability for achieving the required airflow for a CAES facility. This stopped the project that has never been realized.

4.5 Seneca Lake (proposed)

Location:	Watkins Glen, NY, USA
Power	135-210 MW
Duration at full power	50 hours
Depth of cavern	830 m
Caverns	salt cavern
Operation pressures	50 - 100 bar

The project was never realized. After the initial design, further geological and thermodynamic analysis showed that the pressure variation between the charging and discharging phase would induce a temperature variation on the cavern wall from 60C to 15C. This could highly affect the structural integrity of the salt cavern. To avoid this, the lower pressure value should have been increase to 80 Bars. This would have affect to total power capacity of the plant making not more economical feasible.

4.6 Dakota Salts (proposed)

Location:	Williston Basin, southeast of Beulah, North Dakota, USA
Power	390 MW
Duration at full power	50 hours

No further details are available for this project

4.7 ADELE (proposed)

Location:	Sachsen-Anhalt, Germany
Power	360 MW
Duration at full power	5 hours
Caverns	salt cavern
Year	2014

The Adele project has been the first to propose a design based on A-CAES system aiming to a total cycle efficiency higher that 70% using a large heat storage and salt cavern. The project has been under development for several years where the detailed and optimized design of the plant has been carried out.

Unfortunately, the project is currently in hold due to the low energy price that the European market is currently facing.

4.8 Alacaes (testing facility currently under construction)

Location:	Switzerland
Cavern	Abandon mine

Airlight has been developing an innovative A-CAES system concept, including the thermal energy storage. An initial small scale test facility is currently under construction in the Swiss alps. Due to the commercial and proprietary nature of the used solutions, no more information is available.

5 Literature review of relevant publications on conventional and A-CAES system

5.1 Introduction

This section provides a brief review of the available literature and previous project on compressed gas technology.

5.2 Literature review

Kim, H.M., Lettry, Y., Park, D., Ryu, D.W., Choi, B.H., and Song, W.K. (2012) ***Potential and evolution of compressed air energy storage: Energy and exergy analysis [28].***

The paper provides an in situ permeability measurement system tested in the available pilot CAES facility. The accuracy of the measurement was demonstrated in low permeability concrete and rock mass.

Abstract: Energy storage systems are increasingly gaining importance with regard to their role in achieving load levelling, especially for matching intermittent sources of renewable energy with customer demand, as well as for storing excess nuclear or thermal power during the daily cycle. Compressed air energy storage (CAES), with its high reliability, economic feasibility, and low environmental impact, is a promising method for large-scale energy storage. Although there are only two large-scale CAES plants in existence, recently, a number of CAES projects have been initiated around the world, and some innovative concepts of CAES have been proposed. Existing CAES plants have some disadvantages such as energy loss due to dissipation of heat of compression, use of fossil fuels, and dependence on geological formations. This paper reviews the main drawbacks of the existing CAES systems and presents some innovative concepts of CAES, such as adiabatic CAES, isothermal CAES, micro-CAES combined with air-cycle heating and cooling, and constant-pressure CAES combined with pumped hydro storage that can address such problems and widen the scope of CAES applications, by energy and exergy analyses. These analyses greatly help us to understand the characteristics of each CAES system and compare different CAES systems.

Kim, H.M., Rutqvist, J., Ryu, D.W., Choi, B.H., Sunwoo, C., and Song, W.K. (2012) ***Exploring the concept of compressed air energy storage (CAES) in lined rock caverns at shallow depth: A modeling study of air tightness and energy balance [29].***

The paper describes a complete methodology for modelling and simulating CAES system in shallow location with lined cavern. Leakage rate are accounted and their influence on the total system efficiency reported. The thermal conditions of the cavern are also investigated showing the temperature variation induced by the charging/discharging cycles. The paper focuses also on shallow cavern construction and conclude that low depth construction of new caverns can, under specific condition, be more economical compared to deep location. The numerical methodology here developed included thermodynamic, multiphase flow and heat transport. This is applied to the specific CAES condition using lined cavern. The different model variables, as permeability, water saturation of the surrounding rocks, capillary pressure, liner thickness and cavern depth are here analysed and their influence on the system functionality evaluated.

Abstract: This paper presents a numerical modeling study of coupled thermodynamic, multiphase fluid flow and heat transport associated with underground compressed air energy storage (CAES) in lined rock caverns. Specifically, we explored the concept of using concrete lined caverns at a relatively shallow depth for which constructing and operation costs may be reduced if air tightness and stability can be assured. Our analysis showed that the key parameter to assure long-term air tightness in such a system was the permeability of both the concrete lining and the surrounding rock. The analysis also indicated that a concrete lining with a permeability of less than 1 ×10−18 m2 would result in an acceptable air leakage rate of less than 1%, with the operation pressure range between 5 and 8 MPa at a depth of 100 m. It was further noted that capillary retention properties and the initial liquid saturation of the lining were very important. Indeed, air leakage could be effectively prevented when the air-entry pressure of the concrete lining is higher than the operation air pressure and when the lining is kept at relatively high moisture content. Our subsequent energy-balance analysis demonstrated that the energy loss for a daily compression and decompression cycle is governed by the air-pressure loss, as well as heat loss by conduction to the concrete liner and surrounding rock. For a sufficiently tight system, i.e., for a concrete permeability of less than 1 ×10−18 m2, heat loss by heat conduction tends to become proportionally more important. However, the energy loss by heat conduction can be minimized by keeping the air-injection temperature of compressed air closer to the ambient temperature of the underground storage cavern. In such a case, almost all the heat loss during compression is gained back during subsequent decompression. Finally, our numerical simulation study showed that CAES in shallow rock caverns is feasible from a leakage and energy efficiency viewpoint. Our numerical approach and energy analysis will next be applied in designing and evaluating the performance of a planned full-scale pilot test of the proposed underground CAES concept.

Kushnir, R., Dayan, A., and Ullmann, A. (2012) ***Temperature and pressure variations within compressed air energy storage caverns [30].***

This paper presents a combined numerical analytical model including temperature and pressure variation on the CAES cavern surface. The paper concludes that the thermal effusivity (square root of the product of the material's thermal conductivity and its volumetric heat capacity) is a crucial parameter that needs to be accounted during the cavern design.

Abstract: In the present work, the thermodynamic response of underground cavern reservoirs to charge/discharge cycles of compressed air energy storage (CAES) plants was studied. During a CAES plant operation, the cyclical air injection and withdrawal produce temperature and pressure fluctuations within the storage cavern. Predictions of these fluctuations are required for proper cavern design and for the selection of appropriate turbo-machinery. Based on the mass and energy conservation equations, numerical and approximate analytical solutions were derived for the air cavern temperature and pressure variations. Sensitivity analyses were conducted to identify the dominant parameters that affect the storage temperature and pressure fluctuations and the required storage volume. The heat transfer at the cavern walls was found to highly affect the air temperature and pressure variations as compared to adiabatic conditions. In essence, heat transfer reduces the temperature and pressure fluctuations during cavern charge and discharge and effectively leads to a higher storage capacity. Additionally, for realistic conditions, in each cycle, few percents of the injected energy are lost by conduction into the rocks. The principal thermal property that governs the heat transfer process is the rock effusivity. To reduce the required storage volume preference must be given to sites of rocks that have the largest thermal effusivity. Lower injected air temperatures also reduce the required storage volume, but increase the cooling costs. The injected temperature can also be used to control the cycle temperature extreme limits. It is evident from the results that the storage pressure ratio has a dominant effect on the required storage volume and should preferably range between 1.2 and 1.8.

Rutqvist, J., Kim, H.M., Ryu, D.W., Synn, J.H., and Song, W.K. (2012). ***Modeling of coupled thermodynamic and geomechanical performance of underground compressed air energy storage in lined rock caverns [31]***

An innovative simulation approach is here presented coupling TOUGH2D and FLAC3D including thermal and geotechnics load. The methodology is applied to simulate the behaviour of lined CAES storage cavern at shallow dept. The paper evaluates the effect of cyclical pressure variation (including relative temperature variation) from 5 to 8 MPa. The effect of the liner configuration are evaluated. The effect of the liner damage was also evaluated showing not significant impact on the global system efficiency.

Abstract: Coupled nonisothermal, multiphase fluid flow and geomechanical numerical modeling is conducted with TOUGH-FLAC, a simulator based on the multiphase flow and heat transport simulator TOUGH2 and the geomechanical simulator FLAC3D, to study the complex thermodynamic and geomechanical performance of underground compressed air energy storage (CAES) in concrete-lined rock caverns. The analysis focuses on CAES in lined caverns at relatively shallow depth (e.g., 100 m depth) in which a typical operational pressure of 5 to 8 MPa is significantly higher than both ambient fluid pressure and in situ stress. Two different lining options are analyzed, both with a 50 cm thick low permeability concrete lining, but in one case with an internal synthetic seal such as steel or rubber. Thermodynamic analysis showed that 96.7% of the energy injected during compression could be recovered during subsequent decompression, while 3.3% of the energy was lost by heat conduction to the surrounding media. Geomechanical analysis showed that tensile effective stresses as high as 8 MPa could develop in the lining as a result of the air pressure exerted on the inner surface of the lining, whereas thermal stresses were relatively smaller and compressive. With the option of an internal synthetic seal, the maximum effective tensile stress was reduced from 8 to 5 MPa, but was still in substantial tension. One simulation in which the tensile tangential stresses resulted in radial cracks and air leakage though the lining was performed. This air leakage, however, was minor (about 0.16% of the air mass loss from one daily compression) in terms of operational efficiency, and did not significantly impact the overall energy balance of the system.

Shidahara, T., Oyama, T., and Nakagawa, K. (1993). ***The hydrogeology of granitic rocks in deep boreholes used for compressed air storage [32]***

This paper focus on the evaluation of the hydrological condition of the CAES pilot facility built in Japan. The sealing of the cavern is achieved by using favourable groundwater conditions. Favourable geological conditions in hard rock were here used.

Abstract: The compressed air energy storage (CAES) is a much-awaited new system for load levelling power supply. An economical system must be developed, preventing leakage of stored air (with pressures of more than 20 atm) using groundwater pressure surrounding an unlined cavern in hard rock. The air tightness of the rock around the cavern must be confirmed. In this study, the hydrogeology of the test site was examined prior to field air tightness tests in the borehole. The results indicate that, when evaluating the hydrogeology of the test site related to the air tightness of rocks, it is necessary to understand the geological structure and fracture characteristics of the site. This is done by means of a field survey, investigations and tests in and between the boreholes, and the examination of the distribution of permeability and pore water pressures.

Shidahara, T., Oyama, T., Nakagawa, K., Kaneko, K., and Nozaki, A. (2000). ***Geotechnical evaluation of a conglomerate for compressed air energy storage: the influence of the sedimentary cycle and filling minerals in the rock matrix [33]***

Innovative methods were used for the evaluation of the rock mineralogy for the location of the CAES storage system. A relation between the hydrogeological properties, crucial for the achievement of the required sealing characteristic, and the grain size and filling mineral in the rock is here reported. The importance of a proper rock evaluation for the definition of the CAES cavern location is reported.

Abstract: It is necessary for the rock mass that surrounds the excavated storage cavern to maintain its mechanical and hydrological properties in order to keep the stability and air tightness of the storage caverns of the operating compressed air energy storage (CAES) system. A case study for the CAES, which included drilling a borehole of 600 m in depth, was carried out on the Paleogene sedimentary rock that consisted mainly of conglomerate in northeast Kyushu, Japan. Elastic wave velocity corresponds to the sedimentary facies and the mineralogy in the rock matrix that are controlled by the sedimentary cycle. The mechanical properties can be inferred from physical properties such as elastic wave velocity.

Hydrological properties such as permeability coefficient and pore water pressure are affected by the grain size distribution and the filling minerals in the rock matrix that are controlled by the sedimentary cycle. Carbonaceous shale and sandstone with abundant filling mineral (calcite), which are distributed at the top of the sedimentary cycle, are inferred to be impervious. It is assumed that the groundwater flow is divided into two zones based on the vertical change of pore water pressure and one of these zones overlies the impervious layers and the other underlies the impervious layers. Finally we concluded that sedimentological and mineralogical studies were required to evaluate the mechanical and hydrological properties of stratified sedimentary rocks. We propose a procedure for the geotechnical evaluation of sedimentary rocks that surround the CAES cavern.

Kim H-M, Rutqvist J, Kim H, Park D, Ryu D-W and Park E-S.: ***Failure Monitoring and Leakage Detection for Underground Storage of Compressed Air Energy in Lined Rock Caverns [34]***

The paper reports an innovative method for the detection of leakage in a lined shallow CAES storage cavern. Metal liner is used as liner material together with supporting concrete. The detection leakage is based on in service strain measurement of the inner face of the cavern. Simulation tools have been used to calibrate and verify the method.

Abstract: Underground compressed air energy storage (CAES) in lined rock caverns

(LRCs) provides a promising solution for storing energy on a large scale. One of the essential issues facing underground CAES implementation is the risk of air leakage from the storage caverns. Compressed air may leak through an initial defect in the inner containment liner, such as imperfect welds and construction joints, or through structurally damaged points of the liner during CAES operation for repeated compression and decompression cycles. Detection of the air leakage and identification of the leakage location around the underground storage cavern are required. In this study, we analyzed the displacement (or strain) monitoring method to detect the mechanical failure of liners that provides major pathways of air leakage using a previously developed numerical technique simulating the coupled thermodynamic and geomechanical behavior of underground CAES in LRCs. We analyzed the use of pressure monitoring to detect air leakage and characterize the leakage location. From the simulation results, we demonstrated that tangential strain monitoring at the inner face of sealing liners could enable one to detect failure. We also demonstrated that the use of the cross-correlation method between pressure history data measured at various sensors could identify the air leak location. These results may help in the overall design of a monitoring and alarm system for the successful implementation and operation of CAES in LRCs.

Kim H-M, Rutqvist J, Jeong J-H, Choi B-H, Ryu D-W and Song W-K (2013). ***Characterizing Excavation Damaged Zone and Stability of Pressurized Lined Rock Caverns for Underground Compressed Air Energy Storage [35]***

The effect of the damage zone in the rock induced by the cavern excavation is here analysed. Experimental measurements were carried out in the CAES pilot plan in Korea. The measurements were done by using a combined wave velocity and permeability evaluation. In addition, numerical simulation were carried out to evaluate the influence of the Excavation Damage Zone (EDZ) on the CAES performance was numerically evaluated. The results showed that concrete lining in combination with hard rock could be a possible solution for hosting storage system for CAES.

Abstract: In this paper, we investigate the influence of the excavation damaged zone (EDZ) on the geomechanical performance of compressed air energy storage (CAES) in lined rock caverns. We conducted a detailed characterization of the EDZ in rock caverns that have been excavated for a Korean pilot test program on CAES in (concrete) lined rock caverns at shallow depth. The EDZ was characterized by measurements of P- and S-wave velocities and permeability across the EDZ and into undisturbed host rock. Moreover, we constructed an in situ concrete lining model and conducted permeability measurements in boreholes penetrating the concrete, through the EDZ and into the undisturbed host rock. Using the site-specific conditions and the results of the EDZ characterization, we carried out a model simulation to investigate the influence of the EDZ on the CAES performance, in particular related to geomechanical responses and stability. We used a modeling approach including coupled thermodynamic multiphase flow and geomechanics, which was proven to be useful in previous generic CAES studies. Our modeling results showed that the potential for inducing tensile fractures and air leakage through the concrete lining could be substantially reduced if the EDZ around the cavern could be minimized. Moreover, the results showed that the most favorable design for reducing the potential for tensile failure in the lining would be a relatively compliant concrete lining with a tight inner seal, and a relatively stiff (uncompliant) host rock with a minimized EDZ. Because EDZ compliance depends on its compressibility (or modulus) and thickness, care should be taken during drill and blast operations to minimize the damage to the cavern walls.

Perazzelli P and Anagnostou G.: ***Design issues for compressed air energy storage in sealed underground cavities [36]***

Shallow cavern are here investigated as possible solution for the air storage in CAES facilities. Hard rock with internal metal liner are here investigated. Advance numerical simulation by using FEM method, is here successfully used for the evaluation of the stress acting in the surrounding rock mass. The simulations showed that: uplift failure of the rock mass is necessary but not sufficient condition for assessing the feasibility of the storage system, stiff rock are required for providing the required support to the lining system. Buckling and fatigue failure of the metal liner can happen in case of soft rock.

Abstract: Compressed air energy storage (CAES) systems represent a new technology for storing very large amount of energy. A peculiarity of the systems is that gas must be stored under a high pressure (p = 10–30 MPa). A lined rock cavern (LRC) in the form of a tunnel or shaft can be used within this pressure range. The rock mass surrounding the opening resists the internal pressure and the lining ensures gas tightness. The present paper investigates the key aspects of technical feasibility of shallow LRC tunnels or shafts under a wide range of geotechnical conditions. Results show that the safety with respect to uplift failure of the rock mass is a necessary but not a sufficient condition for assessing feasibility. The deformation of the rock mass should also be kept sufficiently small to preserve the integrity of the lining and, especially, its tightness. If the rock is not sufficiently stiff, buckling or fatigue failure of the steel lining becomes more decisive when evaluating the feasible operating air pressure. The design of the concrete plug that seals the compressed air stored in the container is another demanding task. Numerical analyses indicate that in most cases, the stability of the rock mass under the plug loading is not a decisive factor for plug design.

Nishimoto Y, Tobase T, Hori M and Sawada T. ***In-situ Chamber Tests For Underground Compressed-air Storage Facilities [37]***

This paper report the experience of first CAES pilot plan in Japan. An innovative sealing method based on precast reinforced concrete segments coupled with special designed joining system is reported. The in situ measurements are reported and explained. The test were conducted with a storage pressure of 82Bar. After the initial test, problem with the join design between the precast segments was discover.

Abstract: Significant efforts are being made in Japan to study power generation systems using Compressed-Air Energy Storage Gas Turbines (CAES-G/T). Split-lining structure was applied for the airtight lining of the underground compressed air storage cavern, to assure the safety and economic efficiency of pressurized air storage under the various geological conditions. In-situ tests were performed in actual caverns, to verify the design of split lining structure in practice. This paper sums up the in-situ test procedures and results and compares the theoretical analysis with the measurement data for the tested structures.

Hori M, Goda Y and Onishi H.. ***Mechanical Behaviour of Surrounding Rock Mass And New Lining Structure of Air-tight Pressure Cavern [38].***

This paper reports the experience of second CAES pilot plan in Japan. This presented a new design of the segmented lining solution with: precast concrete segments, new join design and internal rubber sealing. The test facility was built and operated for a total period of six month with successful results. The feasibility of the proposed design was demonstrated and verified.

Abstract: The split-lining structure was newly developed for the air-tight lining of the underground compressed air storage cavern. This structure consists of separated reinforced concrete (RC) segments and air-tight membrane._ It is most important for the Compressed Air Energy Storage Gas Turbine (CAES-G/T) system to develop the economical lining. In order to verify the applicability of split-lining structure, CAES-G/T pilot plant was constructed and operated for 6 months. We confirmed the practical usefulness and safety of this system through the operation. This paper presents the mechanical behaviour of surrounding rock mass and the lining structure observed through the operation of CAES-G/T pilot plant.

Terashita, Fumihiro, et al. ***Airtight butyl rubber under high pressures in the storage tank of CAES-G/T system power plant [39].***

Different rubber and polymeric materials are tested and compared as possible lining solutions for providing the required air tightness in a CAES storage cavern. Experimental gas permeability tests were performed. Butyl rubber was demonstrated to be the optimal solution compared to the other tested materials: CSM (Chlorosulfonated Polyethylene), PVC (Polyvinyl chloride), EVA (Ethylene vinyl acetate), EPDM (Ethylene-Propylene Diene Monomer), CR (Chloroprene).

Abstract: The compressed air up to the maximum pressure of 8 MPa is stored in the storage facility of the Compressed Air Energy Storage Gas Turbine (CAES-G/T). The interior of the storage facility is covered by air-tight sheets to prevent a leak of this compressed air. Electricity by a power-generating system using such a facility is the first of its kind in the world. So, we have examined the materials of the airtight sheet and found that polymeric materials were suitable. Then, a normal pressure gas permeation test was done on several synthetic resins and rubbers. Butyl rubber (IIR) was found to show the smallest gas permeability. Moreover, a high-pressure gas permeation test was done on IIR and natural rubber (NR). The permeability of IIR at 10 MPa was estimated, and it was clear that IIR was a suitable air-tight material for CAES-G/T.

Report: ***Commercial potential of natural gas storage in lined rock caverns (LRC) FINAL [40]***

This report prepared by Sofregaz (U.S) and LRC (Sweden) for the U.S. Department of Energy describes and deeply analysed the different aspect of introducing natural gas storage in lined rock cavern. The different aspects and specifically the cavern related problems are here investigated and reported. The crucial uplift requirements for the cavern depth are described. A detailed cost evaluation of the different solution is reported together with a detailed review of the possible design solutions.

The report concern natural gas storage, with the requirements of higher pressure, low temperature and low number of charging/discharging cycles compared to classical CAES systems. However, several of the design solution can be adapt and used for the evaluation of the CAES system part of the RICAS project.

Abstract: The geologic conditions in many regions of the United States will not permit the development of economical high-deliverability gas storage in salt caverns. These regions include the entire Eastern Seaboard; several northern states, notably Minnesota and Wisconsin; many of the Rocky Mountain States; and most of the Pacific Northwest. In late 1997, the United States Department of Energy (USDOE) Federal Energy Technology Center engaged Sofregaz US to investigate the commercialization potential of natural gas storage in Lined Rock Caverns (LRC). Sofregaz US teamed with Gaz de France and Sydkraft, who had formed a consortium, called LRC, to perform the study for the USDOE. Underground storage of natural gas is generally achieved in depleted oil and gas fields, aquifers, and solution-mined salt caverns. These storage technologies require specific geologic conditions. Unlined rock caverns have been used for decades to store hydrocarbons - mostly liquids such as crude oil, butane, and propane. The maximum operating pressure in unlined rock caverns is limited, since the host rock is never entirely impervious. The LRC technology allows a significant increase in the maximum operating pressure over the unlined storage cavern concept, since the gas in storage is completely contained with an impervious liner. The LRC technology has been under development in Sweden by Sydkraft since 1987. The development process has included extensive technical studies, laboratory testing, field tests, and most recently includes a storage facility being constructed in southern Sweden (Skallen). The LRC development effort has shown that the concept is technically and economically viable. The Skallen storage facility will have a rock cover of 115 meters (375 feet), a storage volume of 40,000 cubic meters (250,000 petroleum barrels), and a maximum operating pressure of 20 MPa (2,900 psi). There is a potential for commercialization of the LRC technology in the United States. Two regions were studied in some detail - the Northeast and the Southeast. The investment cost for an LRC facility in the Northeast is approximately$182 million and$343 million for a 2.6-billion cubic foot (bcf) working gas facility and a 5.2-bcf working gas storage facility, respectively. The relatively high investment cost is a strong function of the cost of labor in the Northeast. The labor union-related rules and requirements in the Northeast result in much higher underground construction costs than might result in Sweden, for example. The LRC technology gas storage service is compared to other alternative technologies. The LRC technology gas storage service was found to be competitive with other alternative technologies for a variety of market scenarios

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Succar, Samir, and Robert H. Williams. ***I Compressed air energy storage: theory, resources, and applications for wind power [8].***

This report summarized the main information for the application of CAES system to level up the unstable energy production from Wind Park. This report highlights these aspects of baseload wind/CAES systems and focuses on the technical and geologic requirements for deployment of combined Wind Park/CAES systems, with special attention to relevant geologies in wind-rich regions of North America.

Luo X, Wang J. ***Overview of Current Development in Compressed Air Energy Storage Technology [41]***

A complete overview of the CAES technology including a detailed description of the current and future CAES plants in reported. The estimated cost for kW/h is also reported as function of the different possible storage solutions.

Abstract: With the rapid growth in electricity demand, it has been recognized that Electrical Energy Storage (EES) can bring numerous benefits to power system operation and energy management. Alongside Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES) is one of the commercialized EES technologies in large-scale available. Furthermore, the new advances in adiabatic CAES integrated with renewable energy power generation can provide a promising approach to achieving low-carbon targets. The small-scale CAES facilities are also attracting attention for more flexible power system applications. This paper will present an overview of different types of multi-scale CAES, including their working principles, current development, typical technical and economic characteristics, existing facilities, application potentials, challenges and issues associated with the future development of CAES.

Mehta BR and Spencer D. ***Siting compressed-air energy plants.*** *Tunnelling and Underground Space Technology*. 1988; 3: 295-9.[41]

This paper report a methodology to evaluate and asses the optimal location for CAES storage placement mainly focusing on the geological rock conditions. This is reported according to the selected storage type: hard rock, salt formation or porous media.

Abstract: Compressed-air energy storage (CAES) is a modular, environmentally acceptable, and fast-responding energy storage technology. A 290-MW plant has been operating in West Germany for ten years, and a 25-MW plant was commissioned in Italy in 1986. Alabama Electric Cooperative, Inc., and the Electric Power Research Institute (EPRI) plan to build and operate the first U.S. plant (110 MW) by 1991. Despite the technical success and attractive economics of CAES, many utilities are concerned about the viability of storing air underground. Many of the concerns can be resolved by using the vast experience of the natural gas and petroleum industries in underground gas and oil storage. This paper summarizes EPRI research aimed at resolving generic air storage issues and helping utilities evaluate air storage media at their respective sites.

Budt M, Wolf D, Span R and Yan J. ***A review on compressed air energy storage: Basic principles, past milestones and recent developments [42]***

A complete and update review of the CAES system build, panned and discontinued project is here reported. The different technical solution are compared.

Abstract: Over the past decades a variety of different approaches to realize Compressed Air Energy Storage (CAES) have been undertaken. This article gives an overview of present and past approaches by classifying and comparing CAES processes. This classification and comparison is substantiated by a broad historical background on how CAES has evolved over time from its very beginning until its most recent advancements. A broad review on the variety of CAES concepts and compressed air storage (CAS) options is given, evaluating their individual strengths and weaknesses. The concept of exergy is applied to CAES in order to enhance the fundamental understanding of CAES. Furthermore, the importance of accurate fluid property data for the calculation and design of CAES processes is discussed. In a final outlook upcoming R&D challenges are addressed.

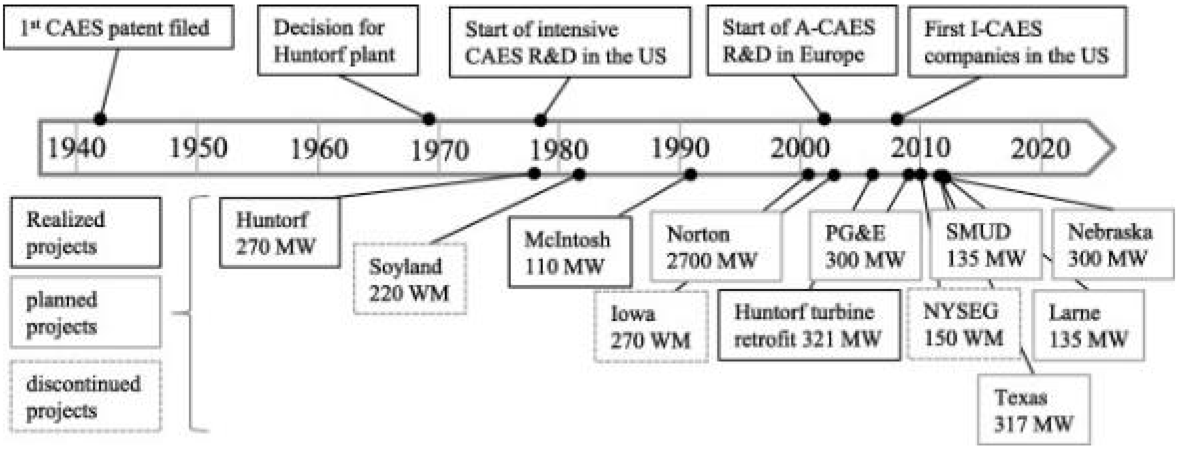

Figure 10: Timeline of CAES R&D and industrial efforts [42]

REPORT: Schulte, R.H., Critelli, Jr., N., Holst, K., and Huff, G. Sandia National Laboratories. *Lessons from Iowa: Development of a 270 megawatt compressed air energy storage project in Midwest Independent System Operator [43].*

The report provides a complete study of the never built CAES project in Iowa. The Iowa Stored Energy Park was planned to have a 270 MW CAES facility and to use porous rock formation to store compressed air. The project was terminated because of unfavorable geologic conditions. The study was commissioned by the DOE Energy Storage Systems Program and contains valuable and insightful information on the project, project design, and lessons learned. The project never past the geological investigations; however, many insights go beyond this part of the design.

REPORT: Sirius Minerals, Dakota Salts. *Compressed air energy storage feasibility in north Dakota.*

This report, developed by Dakota Salt with collaborators Electric Power Research Institute (EPRI) and Schlumberger Water Services (SWS), provides crucial insights into the importance of the underground works – in this case, the underground cavern was viewed as the most important aspect of the project proceeding surface facility design. The study suggests that the economics of the project is a crucial aspect for a CAES facility.

6 RICAS2020 initial design

6.1 Introduction

RICAS2020 project is aiming to develop an innovative A-CAES facility that could be located wherever required with no geological limitations. The main idea behind the project is to develop a location independent CAES plant of limited size that can be located in the proximity of the energy production plants, like wind farm and large photovoltaic installations. In this case, the CAES would be used for storing the surplus energy during the peak production and give it back during the electric peak demand (generally not happening at the same time).

The RICAS project aim is to develop two different power plant sizes:

- A **small scale A-CAES pilot** testing facility
- A **full scale A-CAES** power plant facility

6.2 Small scale A-CAES pilot facility

The small scale A-CAES will be developed as a pilot plant to evaluate the practical feasibility of the developed solution within the RICAS project. This testing facility will present a total power output of 5kWh for 3h. The planned pressure range will be from 30 to 36 Bar. According to the main goal of RICAS2020, this will be located in an already available set of tunnels in a test facility available in Austria.

6.2.1 Facility location

RICAS2020 will be located as an extension of the independent research infrastructure “Research@ZaB” in Eisenerz, Austria (Figure 11), which is financed by the Austrian government and designed as a European underground research, training and test-facility[2].

Eisenerz is a mining town in the Austrian state of Styria, 200 km N-E of Vienna. Population is 4,290 inhabitants (01.01.2016). It is situated in the deep Erzbach Valley, dominated on the east by the Pfaffenstein (1871 m), on the west by the Kaiserschild (2084 m), and on the south by the Erzberg (1465 m). Erzberg represents the largest iron ore reserves in Austria. The Erzberg mine produces around 2,800,000 tonnes of iron ore per year.

The local geology presents Sauberger limestone and Blassenecker porphyroid. Limestone is a sedimentary rock composed primarily of calcium carbonate ($CaCO_3$); porphyroid is a volcanic rock with a texture characterized by large crystals set in a finer groundmass. The properties of Sauberger limestone and Blassenecker porphyroid are listed in Table 2. This indicates a rock formation with low compressive strength compared to classic hard rock formation.

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[2] http://zab.unileoben.ac.at/en/

The definition of this location for the small-scale facility of the RICAS project, represent the most challenging condition for storing compressed air for a CAES plant. The definition of suitable design for the specific location can be then easily transferred to any other location.

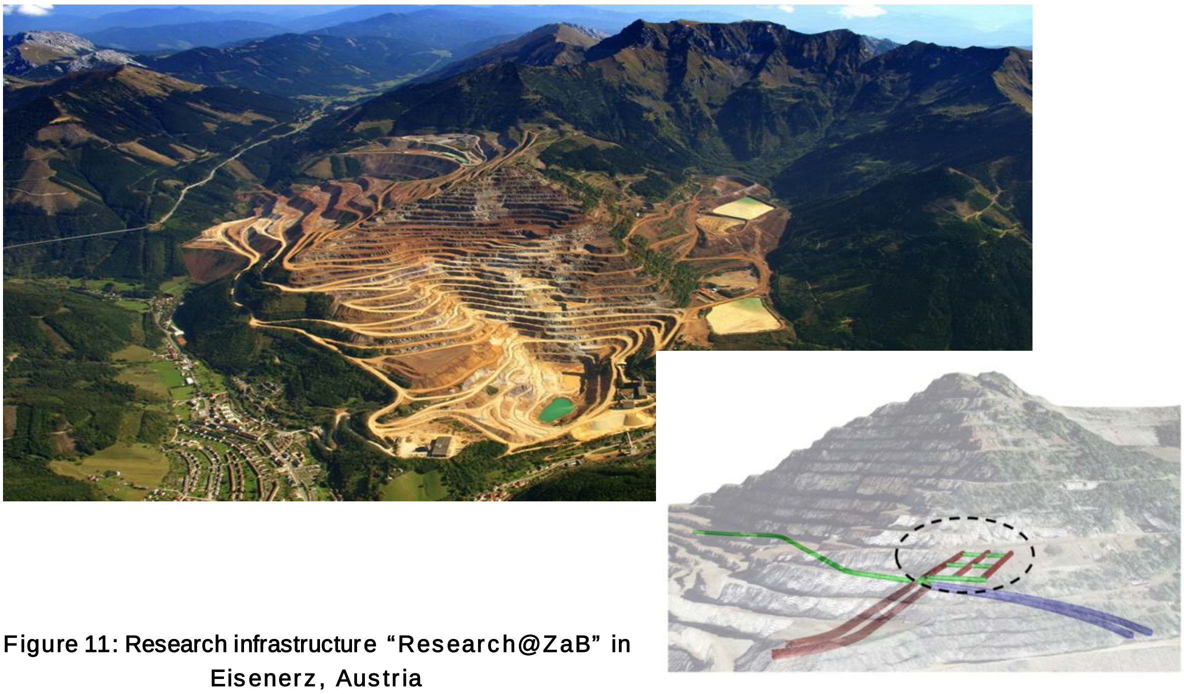


Figure 11: Research infrastructure "Research@ZaB" in Eisenerz, Austria

Table 2: Rock parameters for the location of the RICAS2020 test facility

Parameter	Value
Young's modulus	$6{,}55 \cdot 10^9$ Pa
Poisson's ratio	0,19
Cohesion	$8 \cdot 10^6$ Pa
Friction angle	31°
Specific weight	27000 N/m3
Compressive strength	$17 \cdot 10^6$ Pa
Horizontal/vertical stress relation	0,23

6.2.2 Storage volume

According to the required power output and the diagram reported in Figure 6, it is possible to calculate the total required storage volume as:

$$Power = 5MW\ for\ 3h = 15 \times 10^3 kWh$$

$$Pressure\ range = 30\ to\ 36\ Bar \qquad \frac{P2}{P1} = \frac{36}{30} = 1{,}2$$

$$\frac{E_{Gen}}{V_s} = 1\frac{kWh}{m^3}$$

The required storage volume needs to be $\boldsymbol{V_s = 15 \times 10^3\ m^3}$.

6.3 Full scale A-CAES facility

A full-scale A-CAES power plant will be developed and investigated within the RICAS2020 project. It will be design for a total power output of 100kWh for 8h. The planned pressure range will be from 67 to 48 Bar. No more details are currently available for the specific installation.

6.3.1 Storage volume

According to the diagram reported in Figure 6, it is possible to calculate that:

$$Power = 100MW\ for\ 8h = 800 \times 10^3 kWh$$

$$Pressure\ range = 48\ to\ 67 \qquad \frac{P2}{P1} = \frac{67}{48} = 1.4$$

$$\frac{E_{Gen}}{V_s} = 3.2\frac{kWh}{m^3}$$

The required storage volume needs to be $\boldsymbol{V_s = 250 \times 10^3\ m^3}$.

7 Crucial consideration for storing compressed air in RICAS2020 project

RICAS2020 project focuses on the development of a CAES system with a storage independent on the available geological formation. Under this condition, the only feasible solution is represented by the use of a cavern/tunnel in rock formation. The main information and required parameters for the storage cavern in rock are analysed and reported in the following taking the RICAS2020 conditions into account.

7.1 Containment methods in hard rock formation

The storage of pressurized air in hard rock formation as tunnels or caverns can be achieved mainly in two different way:

- Sealing using a lining (lined cavern)
- Hydrodynamic sealing (unlined cavern)

The lined cavern has the advantage of being feasible even with shallow rock cover compared to the unlined solution. For this solution, the load generated by the internal pressure is supported by the rock, while the air tightens is provided by the liner solution.

Hydrodynamic sealing relays on the principle that the water pressure around the cavern increases proportional to the cavern depth. If the cavern is placed at a consistent depth, a positive head gradient exists in all directions towards the cavern, causing a continuous penetration of ground water into the chamber preventing the leakage of the contained gas through the rock fissures. In this case, the cavern depth is calculated as a function of the internal air pressure and the hight of the ground water table over the cavern. The maximum allowed pressure for unlined cavern however cannot be more than 70-100 Bar due to the technical and economical limitations of excavating deeper caverns. However in case of absence of the required ground water level, artificial pressurized water infiltration can be achieved using water curtains.

Even if the hydrodynamic containment could be a feasible solution for CAES installation, this will require large depth and the necessity of underground installation. RICAS is aiming to install a CAES storage also in mountains where hydrodynamic containment cannot be realized. For this reason, only lined solution will be here considered.

7.2 Lining solutions

For the specific application in CAES storage system, the classic definition of lining does not include any structural reinforcement/support. This is taken care of by rock bolts and support shotcrete that ensure the cavern stability. The lining solution is only intended for preventing the air leakage and it is not going to support any load induced by the internal pressure (strain will be induced on the liner due to the rock movement).

7.2.1 Liner solutions for LNG storage

Common techniques are already available for storing LNG gas at high pressure and low temperatures [44] in hard rock formations. This solution consists of (see Figure 12):

1. **Steel liner** (carbon steel): gas tightness; no pressure absorbing function. It is able to bridge minor cracks
2. **Sliding layer**: placed between the steel liner and the concrete to reduce friction during the sliding and as corrosion protection
3. **Concrete lining**: transfer the gas pressure force to the surrounding rocks
4. **Welded mesh reinforcement** in the concrete lining to distribute the tangential strain in many small cracks
5. **Low strength permeable concrete**: protect the drainage system
6. **Drainage system**: perforated drainpipes (to reduce pressure to the vessel in case of low internal pressure)
7. **Rock mass**: support the gas pressure force acting as load carrying elements

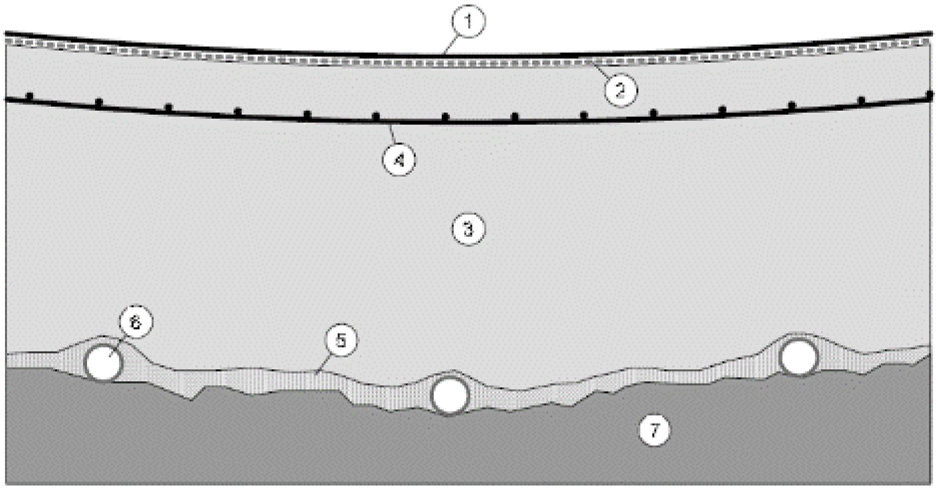


Figure 12: Typical lining + reinforcement configuration used for LNG storage from [44]

This lining solution has proven feasible for demanding conditions with pressure higher than the usual experienced in the CAES system (≈200Bar compared to the maximum ≈70Bar of a classic CAES). However, this solution presents two main limitations: construction costs and fatigue damage. The necessity to assemble a gas tight steel tank in cavern/tunnel is highly expensive due to the labour and material costs. In addition, the presence of the steel liner could generate fatigue problems due to the daily cycles to which a CAES facility is generally subjected. This is not a real problem for a LNG storage system, where the typical charging/discharging cycle is one or maximum twice per year [40]. A more suitable solution for CAES system would be to replace the steel liner with a synthetic membrane. A synthetic membrane has never been used in the LNG storage system due to the possible softening of plastic material when exposed to some of the condensate dissolved in the natural gas [45]. However, this solution can be implemented in a CAES facility where air is compressed and environmental ageing should be not affecting the liner.

7.2.2 Lining solutions from tunnelling applications

The tunnelling industry has been using lining solution since many years to waterproof the installation from water ingress from the rock mass. Even if for different purposes, these methods can also be used for air sealing the tunnel from the internal air pressure as for the CAES systems. Three main waterproofing technologies are currently used (see Figure 13):

- **SSL - Single Shell Lining**: Sprayed concrete single shell linings (SSL) have been built for decades, e.g. for the construction of water tunnels, caverns, and transportation tunnels. It is a permanent sprayed concrete lining consisting of a single layer or several layers placed at different times, without a waterproofing membrane. The main design issues of SSL are related to the structural interaction between primary (outer) lining and secondary (inner) lining, which are usually built at different times and thus submitted to different stresses and strains, as well as to water tightness of the sprayed concrete lining.

  This lining technology does not suit for CAES storage system. The only concrete layers, with the possibility of cracks and damage during the in service operation, can induces severe air leakage affecting the performance and safety of the CAES plant.

- **DSL - Double Shell Lining:** Traditionally, the lining of tunnels and other underground structures excavated by conventional methods has been designed and built based on the double-shell lining (DSL) approach. According to this approach, initially a temporary (and low quality) sprayed concrete lining is constructed to stabilise the opening after excavation and to contain only short to medium-term loads (primary lining). Later on a permanent cast in situ concrete lining is installed to contain long-term loads, and attend the requirements of serviceability and durability (secondary lining). Water tightness is achieved by the installation of a waterproof sheet membrane between primary and secondary linings, which acts additionally as a separation / sliding layer, reducing the potential of shrinkage cracking on the secondary lining. Under some project conditions, e.g. deep tunnels with anticipated high water pressure and required fully drained conditions, the DSL approach is the only possible approach to build the underground structure. During the last two decades, significant progress was made in concrete technology (mix-design), with advanced admixtures (e.g. water reduction, alkali-free accelerators), as well as in the application of sprayed concrete, with sophisticated spraying robots, and in waterproofing of tunnel linings (spray applied membranes). All these factors have enabled designers to use sprayed concrete linings increasingly for long term service life. This lining technology, even if suitable for CAES storage system, has the disadvantage of relaying only on the waterproofing membrane as main air sealing barrier. Any damage to the membrane will generate air leakage with the consequent possible damage of the complete system.

- **CSL - Composite Shell Lining:** Composite shell lining (CSL) systems are based on the single shell lining approach and consist of two concrete linings, which are usually installed at different stages, with a double-bonded spray-applied waterproofing membrane embedded between them. The secondary (inner) lining may consist of sprayed concrete (often fibre reinforced) or cast in-situ concrete. Both concrete and waterproofing membrane are vital functional parts of this system. The f embedded double-bonded spray-applied waterproofing membrane is located in between the primary and secondary linings.

  After application the membrane adheres to the primary lining and starts developing its bonding strength and curing. When curing of the membrane has finished, a secondary concrete lining (sprayed or cast insitu concrete) or a protective concrete layer can be installed against the membrane. After installation of the secondary lining / protective layer onto the cured membrane, bonding between the two layers develops and provides additional safety to the composite lining system. This liner technology present the benefit that only an aligned crack (passing through the concrete, membrane and rock support) will generate air leakage. However, the mechanical load generated by the high internal pressure, combined with continue internal liner can induce a high level of tensile hoop stress with the consequent crack/damage of the internal liner.

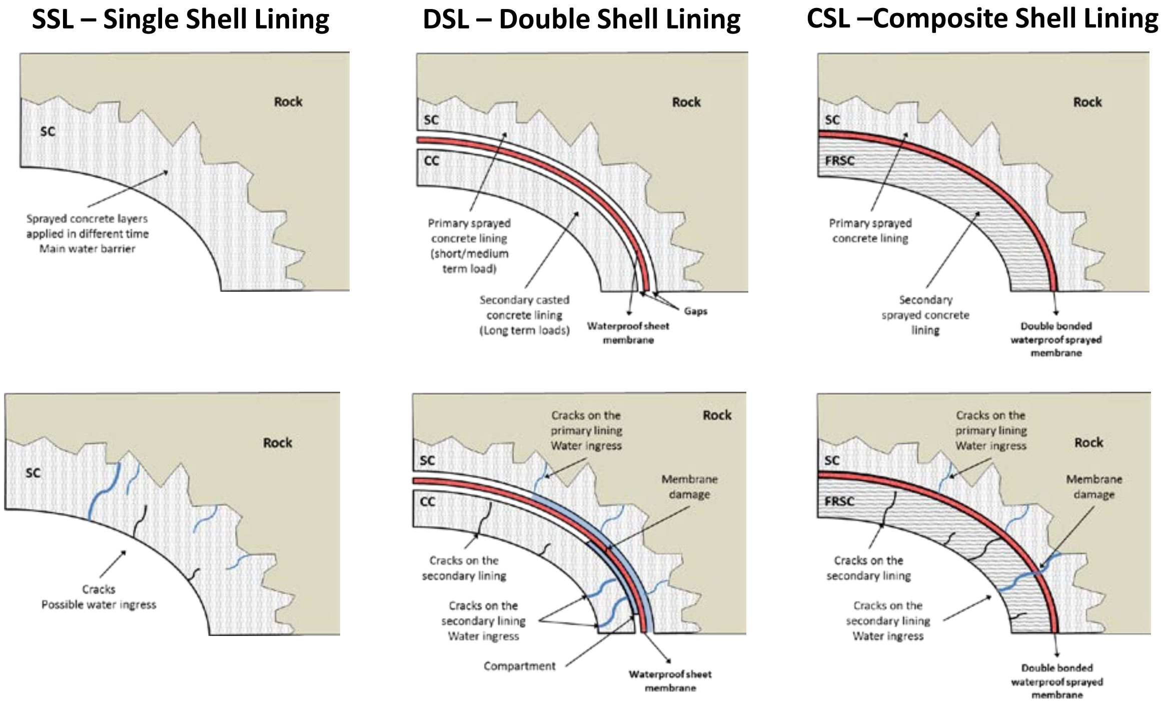


Figure 13: Liner technologies from tunnelling industry: single shell, double shell and composite shell

7.2.3 *Segmented liner design*

Another possible lining solution for CAES plant using hard rock/ tunnel has been tested in the Japanese CAES pilot plan [37]. The developed liner/structural support design was based on segmented solution using a polymeric liner in combination with precast concrete segments (see Figure 14). This represents an extension of the CSL solution used by the tunnelling industry.

The segmented design solution, by using a closed ring of precast concrete segments, in combination with a sailing material as internal liner, allowed the linier/segments to move following the rock under high internal pressure. This is beneficial with the respect to the hoop stresses acting on the tunnel liner/support system. The relative movement between the different segments allow a reduction of the hoop stress induced by the internal pressure on the liner. This can highly prevent the formation of crack and damage compared to a classic continuous liner solution. The proposed solution in Japan presented 8 precast reinforced concrete segments with a backfilling concrete layer (tunnel diameter 3.3m). Three layers of 3mm thick butyl rubber with nylon reinforcement mesh composed the internal liner. In addition, the joint between the different segments were filled with special rubber material to follow the segments opening and closing (see Figure 15).

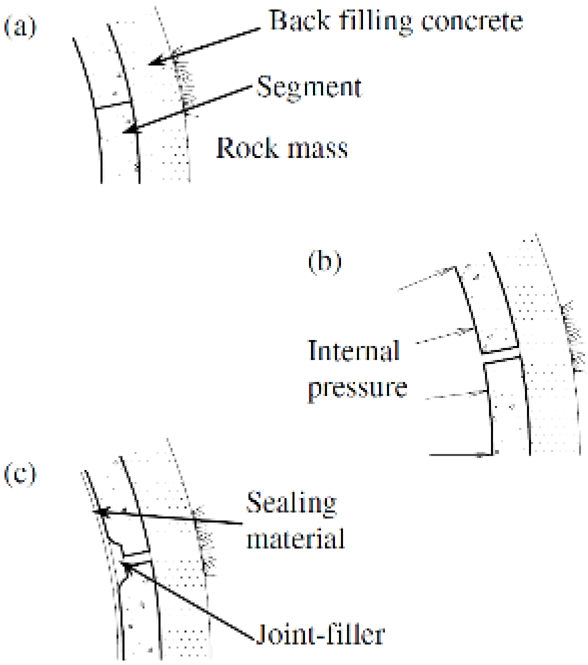
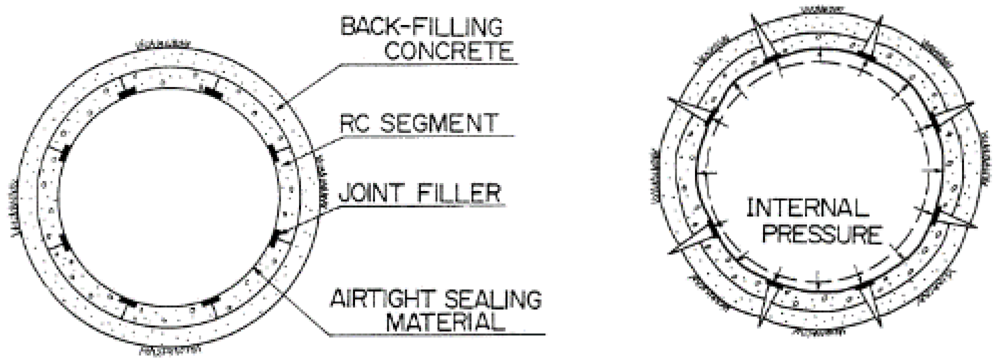


Figure 14: Basic concept of segmented liner solution

A segmented solution as used in the Japanese pilot plant, could represent the optimal solution for the RICAS project, where:

- The stiffness requirement can be provide by the precast segment. The rock quality can be compensated by the use of more stiff structural design of the tunnel.
- The air sealing function can be provided by an internal polymeric layer directly sprayed in place.



a) BEFORE INTERNAL PRESSURE

b) DURING INTERNAL PRESSURE

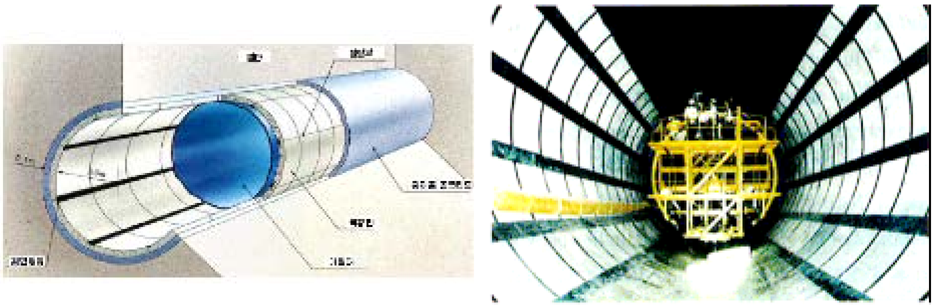


Figure 15: Japanese CAES test facility (from [37]

7.3 Cavern configuration

Several cavern configurations (shape, size and arrangement) can be used as storage for a large CAES power plant. The following consideration can be applied to both lined and unlined configurations.

7.3.1 *Chamber and shaft*

The storage of compressed air can be allocated on horizontal or vertical cavities commonly referred as chamber or shaft respectively. Both of them have their particular benefits and disadvantages.

Operational aspects: chamber requires generally a much larger surface area. In addition, in case of hydrodynamic containment, there is a large surface where the gas can get dissolved into water. This is different for shaft where the floor area is limited.

Structural aspects: Chamber, with the larger roof area compared to shafts, requires large amount of additional structural reinforcement. The roof is the most crucial area of a tunnel, due to the possible instability and possible collapse; for this reason special attention need to be place to ensure its stability. On the other hand, shaft has a very limited roof area, with less requirements of structural support. However, this is also related to the rock quality, better rock mass properties reduce the differences between chamber and shaft due to the less required structural support.

Constructional aspect: chambers follow the common construction principles used for tunnelling and mining. Drilling horizontal tunnel is quite simple and well known operation. Shaft instead, are built by sinking and are generally more time consuming and expensive compared to tunnels.

Geotechnical considerations: CAES requires solid mass rock with limited presences of discontinuities. Shaft presents the necessity of vertical axes that make really difficult to avoid large rock discontinuities. This is even more critical in sedimentary rock mass with the preferential horizontal direction of the rock structure.

From the previous considerations, it is not possible to define the optimal solution, this has to be decided according to the specific condition of the CAES plant.

7.3.2 *Shape of the cavity*

The cross section of the CAES storage is also another important parameter to consider during the design. Circular cross section can be used for both chamber and shaft. However, chamber can be constructed with other cross sections such as horseshoe shape.

Circular shape is mechanically the most suitable section to minimize stress concentrations and distribute homogenously the stresses on the cavern wall. However, if for shaft, the circular shape is the only feasible, for chambers the circular shape presents several technical challenges. The construction of a circular shape can be very expensive in addition to practical problems of accessibility. However, for chamber the optimal solution can be slightly curved floor in combination with elliptical walls and roof.

7.3.3 Volume to surface ratio

A crucial aspect, especially for a lined storage solution for CAES plant, is the aspect ratio of the storage. The volume to surface ratio of the storage can highly affect the final cost for building large storage. The higher this value, the less lining material is required. For this reason, the shape of the storage is of crucial importance when defining the CAES storage system. Obviously, a spherical cavity would represent the ideal solution. Unfortunately, the construction of a large cavity with such shape is practically impossible and needs to be discarded.

The other possible solution is represented by a toroidal shape (donut shape). However, even if this shape can be easily constructed, there are structural challenges related to the static stability of such construction under internal pressure. In such construction, the internal wall present a negative curvature with the consequent initiation of tensile load in the lining material under pressure [46]. This can easily induce crack in the shotcrete (if present). This shape could then be possible solution only if other containment methods are used.

The next possible solution is related to a classic tunnel with circular shape of diameter D and length L. It is then crucial to understand the optimal ratio between the diameter and length of the tunnel that can maximize the Volume/Surface ratio.

In this case the volume/surface can be calculated as:

$$V = \frac{D^2\pi}{4}L \quad S = \frac{2D^2\pi}{4} + D\pi L$$

$$\gamma = \frac{Volume}{Surface} = \frac{V}{S} = \frac{1}{2}\frac{L}{1+\frac{2D}{L}}$$

The optimal solution is then provided by a tunnel with D=L that is impracticable. In Figure 16 the Volume/Surface ratio and the tunnel length L are reported as function of tunnel diameter D for different total tunnel volumes. It is possible to notice that according to the total storage volume, this ratio as an optimal point for each storage size. It is important to notice, that tunnel diameter over 20m, are technically challenging to be built. However, it is clear that the tunnel diameter should be maximized, according to the available construction capabilities on order to optimize the Volume/Surface ratio.

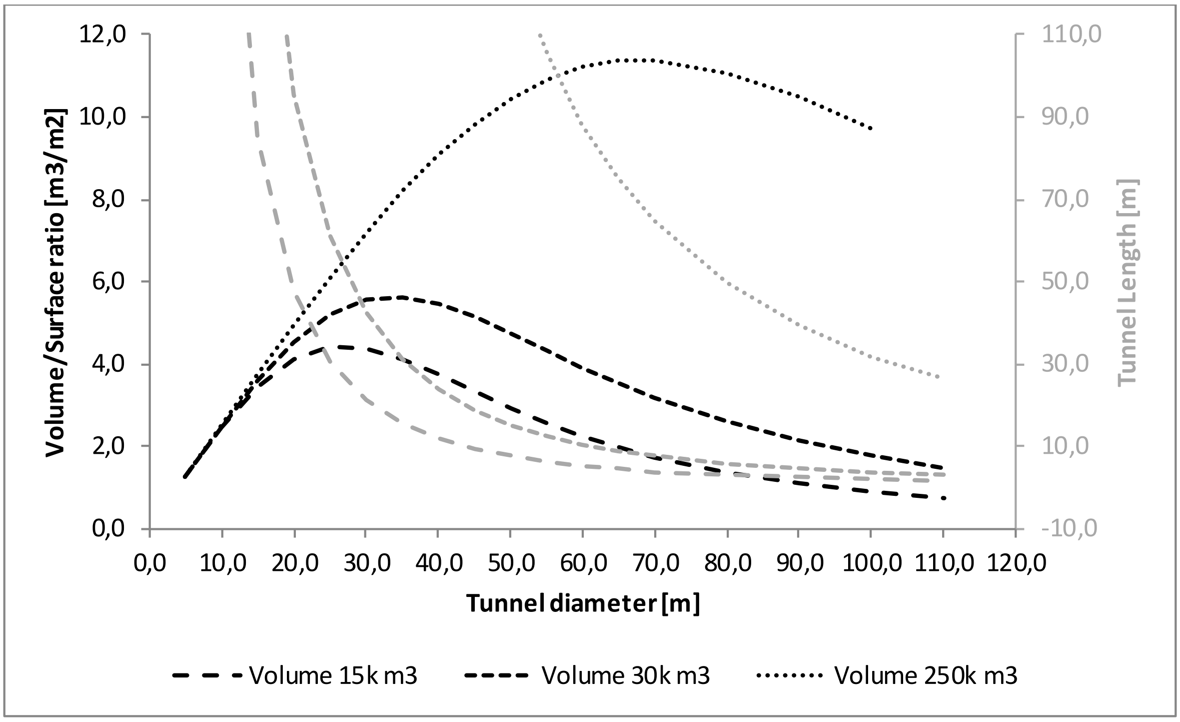


Figure 16: Volume to surface ratio as function of the tunnel diameter for different total storage volumes

According to the plot reported in Figure 16, the optimal tunnel diameter for the RICAS pilot plat (required storage volume 15k m^3) is approximately D=25m letting to a total tunnel length of 30m (assuming a circular shape). However, this tunnel diameter is difficult to construct.

7.4 Uplift requirements

One of the main safety requirements of a CAES storage system is related to the overburn requirement to prevent the roof cavern uplift. This parameter, provide the minimum depth at which a CAES storage can be located as function of the maximum internal pressure.

The most simple approach to evaluate the needed depth is to consider the weight of the rock above the cavern in a cone with an angle of 30-45 degree (see Figure 17). This needs to be equal or higher than the load generated on the cavern roof by the internal pressure (in addition to the required safety factor). Using the schematic reported in Figure 17:

$$W = Sf \times P$$

where W is the rock weight, P is the storage pressure and Sf is the required safety factor.

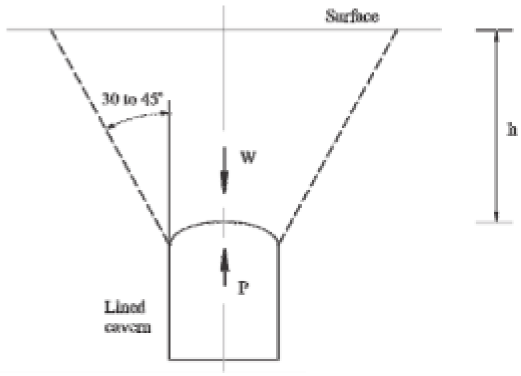


Figure 17: Uplift schematic representation

It is important to note that this parameter is crucial if no special measures are taken to sustain the internal storage pressure and all the load transfer to the surrounding rock. In case of structural reinforcement in the tunnel, a different evaluation of the minimum required safety depth can be calculated with more advance numerical models.

7.5 RICAS requirements for small-scale CAES facility

Containment method: due to the necessity of using shallow depth (or even installation in mountains) and the technical impossibility to use hydrodynamic high-pressure containment, the only feasible solution in RICAS is to use a lined cavern. This allows also an even more location independent approach that can be then generalized to any other location.

Between the different lining solutions, the use of segmented lining solution can represent the optimal design approach to overcome the structural challenges related to both the high internal pressure and the poor rock quality. More details about the specific lining solution in the following section.

Chamber or shaft: chamber seems to be the most suitable solution for RICAS due to the possibility of locating the cavern in an area with limited rock discontinuities. In addition, if it is planned to use abandon installations, chamber are more widely available than shaft. Chamber/tunnel will be considered for the RICAS2020 application.

Shape of the cavity: The use of segmented liner solution for the sealing of the cavern, will require the use of a circular shape for the tunnel.

Volume to surface ratio: According to the graph reported in Figure 16, for a small-scale CAES with a required total volume of approximately 15k m^3, the optimal aspect ratio would require a tunnel diameter of 25m (see Figure 18 and Table 3). This would require a total tunnel length of $L \approx 30m$. However, the construction of 25m diameter tunnel in low quality rock (as the one defined here) would be challenging. For this reason a more reasonable 10m diameter need to be chosen. In this case the total required tunnel length will be $L \approx 190m$

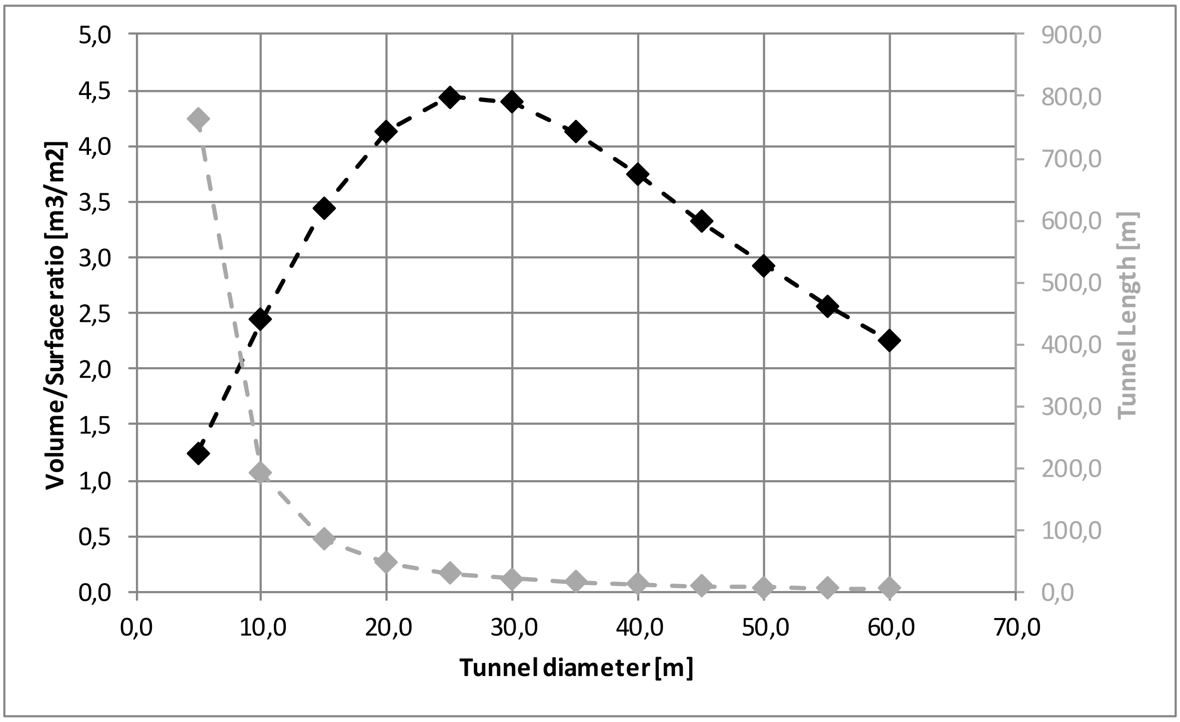


Figure 18: Volume/surface ratio and tunnel length as function of the tunnel diameter for the small-scale CAES facility for a total storage volume of 15k m^3

Table 3: Volume/surface ratio and tunnel length as function of the tunnel diameter for the small-scale CAES facility for a total storage volume of 15k m^3

Tunnel diameter [m]	Tunnel Length [m]	Volume/surface ratio [m^3/m^2]
5.0	763.9	1.2
10.0	191.0	2.4
15.0	84.9	3.4
20.0	47.7	4.1
25.0	30.6	4.4
30.0	21.2	4.4
35.0	15.6	4.1
40.0	11.9	3.7
45.0	9.4	3.3
50.0	7.6	2.9
55.0	6.3	2.6
60.0	5.3	2.3

Uplift requirements - Overburned or rock cover: The uplift requirement can be a challenge for the defined location of the small-scale CAES facility. The storage will be located in a mountain with no possibility to reach the required overburned for the max internal pressure of 36Bar. Under this condition according to the provided formulation, the required overburn can be calculated as:

Assuming a rock density of: $\rho = 2.5 \times 10^3 kg/m^3$

Tunnel diameter: $D = 10m$

Internal pressure: $P_{Max} = 36Bar = 3.6MPa = 3.6 \times 10^6 N/m^2$

Assuming a safety factor: $S_f = 1.5$

Min overburned: $Overburn = 1.5 \times 144m = 216m$

The minimum required overburn assuming a safety factor or 1.5, is 216m. However, this value can be overcome if other measures are used to strength the tunnel providing additional resistance to the internal pressure. The use of segmented liner solution with precast concrete segments can highly increase the structural safety of the installation overcoming the uplift requirements.

8 Possible material selection for liner solutions

The selection of the proper material for the specific function is of a crucial importance for the success of a large CAES facility in rock formation.

For the RICAS2020 project, the most promising design for the storage is represented by a segmented liner (more details in the previous chapter). The possible candidate materials for each part of the structure components (see Figure 19) are here reported and analysed.

Even if, the main air sealing method is provided by the internal membrane, the complete system should be design to minimize the air leakage. Each of the designed components should considered as an additional air barrier.

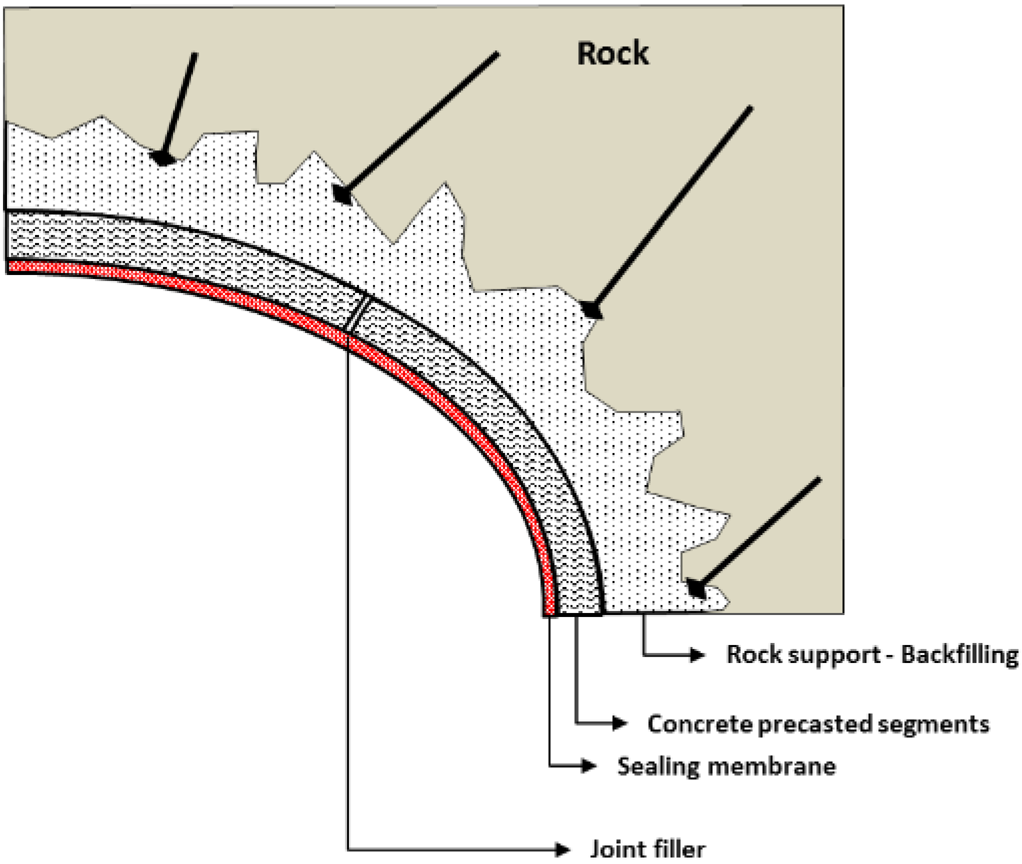


Figure 19: Schematic representation of the different component of the presented segmented liner design for the CAES facility

8.1 Rock Support stabilization of the cavern

Rock support and cavern stabilization need to be carried out according to the common tunnelling methodologies. However, in order to decrease the permeability of the surrounding rock, pre grouting can be a valid solution. This should be applied for the whole excavation length. In addition, pre grouting will also beneficially effect the water ingress together with the tunnel stability. This can crucial for CAES installation in soft rocks.

8.2 Backfilling

The precast concrete segments will require a smoot homogenous surface to be located on. This can be provided by using a thick layer of shotcrete. This can be either reinforced or not by using steel mesh of short steel fibre. The use of polymer-modified shotcrete could represent the optimal choice of shotcrete [47]. The enchanted mechanical properties achieved by the addition of polymer in the shotcrete composition, can be highly beneficial due to the increased structural properties and decreasing the air permeability.

Drainage system for channelling the ground water should be also included in the backfilling. For this purpose geotextile fabric layer can be used.

In addition, the backfilling should be also including a sliding layer in between the liner segment and the shotcrete in order to allow the segment movement under the internal pressure.

8.3 Concrete precast segments

Concrete precast segment are commonly available for the tunnelling industry. These are generally design to sustain external load induced by the surrounding rock. For the use in CAES storage system, the precast segments require a specific design of the internal reinforcement to sustain the mechanical load generated by the internal pressure.

In addition, it is crucial a proper design of the connection system between the different segments. In common tunnel applications, the connection are used only for the block installation and are not required to sustain any direct load. In the CAES system instead, a segmented liner concept will require a particular attention to design a proper connection methodology that can sustain the hoop stress acting on them during the tunnel pressurization.

Figure 20: Examples of precast segments for tunnelling applications

8.4 Sealing membrane

One of the main components for a segmented liner system is represented by the internal sealing membrane. This represents the main air-sealing barrier of the system and special attention needs to be allocated for the definition of the correct material.

In the previous CAES pilot plan in Japan, 3mm polymeric layers were used as internal air sealing membrane. From the available data, this solution showed promising results, however the installation and maintaining cost could be high.

A more economical solution can be represented by sprayable membrane commonly used for tunnel waterproofing application. These are commonly available and several producers around the world have been developing proprietary products (e.g. BASF and Normet). These are generally based on Ethylene vinyl acetate (EVA) polymers.

The application of this layer is quite simple and very cost efficient with very limited labour cost involved. Common tunnelling equipment for shotcrete can be used making this application method quite easy. According to the provided data by the available material producer, as a minimum one or preferably two layers of the membrane should be applied. According to the recommendation, each layer should have a minimum thickness of 3mm.

Due to the main use of this membrane for waterproofing applications, no properties are available in relation to air permeability. However, from initial evaluation, this material solution should provide the required air tightness requirements for CAES storage.

Figure 21: Example of application of sealing membrane in tunnels

8.5 Joint filler

The main challenge of a segmented lining solution is represented by the design of the joining filling solution. Under the internal pressure (Figure 22), due to the hoop stress acting, the segments open in the connection area generating an unsupported area for the membrane. These need to be covered and filled in order to provide the required support to the internal membrane and avoid any damage (see Figure 22).

Due to the large involved deformation in the area, a rubber material seems to be the optimal candidate for providing large deformation under the elastic condition.

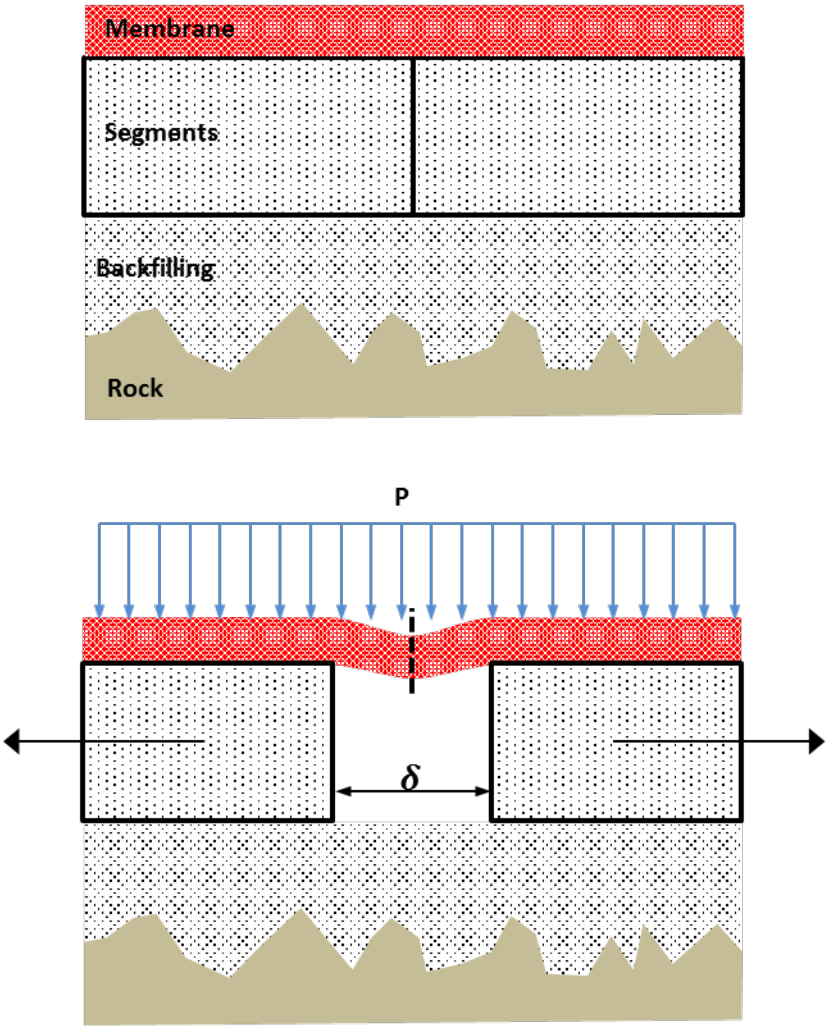


Figure 22: Segment deformation under internal pressure and possible failure of the internal membrane

9 Segmented Liner simulation for Small-Scale CAES of RICAS2020

9.1 Introduction

Numerical simulations were carried out using the finite element method (FEM). This is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It subdivides a large problem into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variation methods from the calculus of variations to approximate a solution by minimizing an associated error function.

The code Phase2 was selected for the numerical simulations. Phase2 is a 2-dimensional elasto-plastic finite element program for calculating stresses and displacements around underground openings, and can be used to solve a wide range of mining, geotechnical and civil engineering problems.

9.2 Model description

A composite liner has been used to simulate the rock support (shotcrete) and grout.

The composite consists of the shotcrete layer (30 cm) and the gout layer (15 cm). A joint is placed between the rock and the shotcrete. It has not been considered any joint on the contact between shotcrete-grout and between grout-concrete lining. The details of the selected liner are reported in Figure 23 and Figure 24.

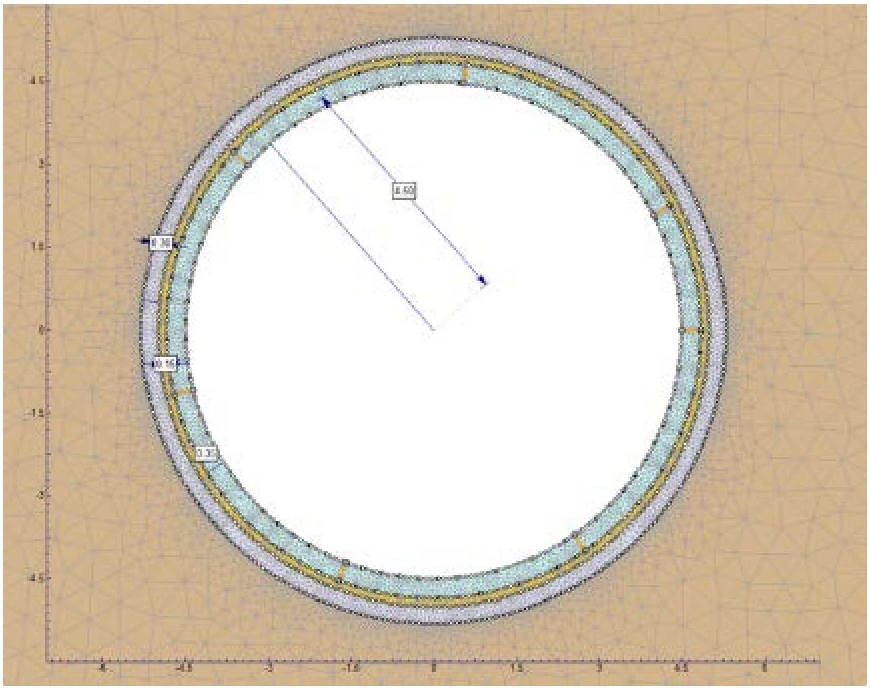


Figure 23: Segmental lining layout

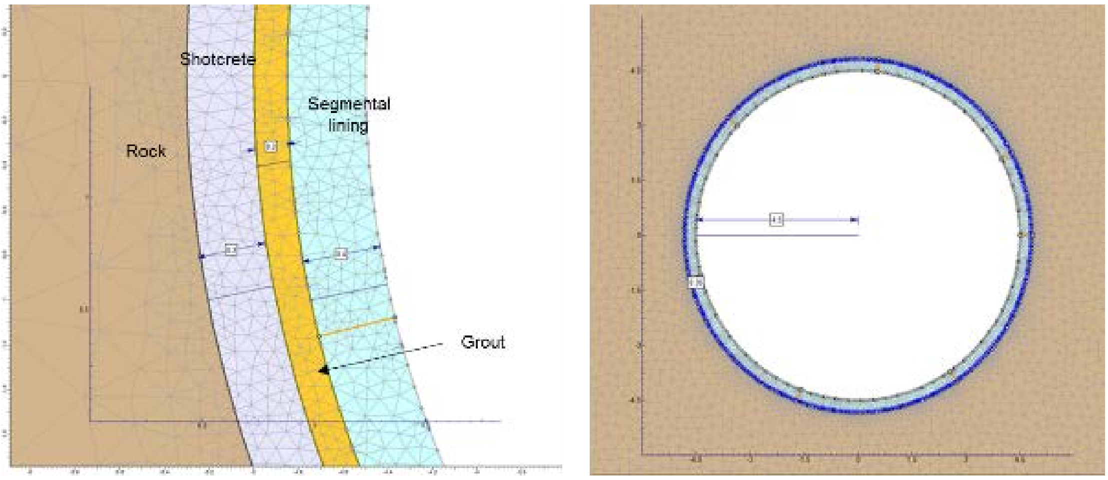


Figure 24: Detailed view of the selected lining

9.2.1 Material properties of different layers

Following the material properties for each of the different used materials:

Table 4: Shotcrete properties

Property	Value
Compressive strength (MPa)	30
Young's modulus (MPa)	$30 \cdot 10^3$
Poisson's ratio	0.2
Specific weight (N/m^3)	27 000
Thickness (m)	0.3

Table 5: Grout properties

Property	Value
Compressive strength (MPa)	20
Young's modulus	$15 \cdot 10^3$
Poisson's ratio	0.2
Specific weight (N/m^3)	27 000
Thickness (m)	0.15

9.3 Simulation stages and related results

The simulation of the tunnel preparation has been divided in five sub sequential stages:

- **Stage 1**: Complete rock mass - No excavation
- **Stage 2**: Excavation
- **Stage 3**: Rock support (joint with elastic springs between rock and shotcrete)
- **Stage 4**: Segmental concrete lining (Layer of grout 15 cm between segmental lining and shotcrete)
- **Stage 5**: Pressure (38 bar = 3.8 MN/m^2)

Stage 2: Excavation

The ground characteristic curve or convergence confinement graph plots displacement versus ground pressure. To create the graph, internal pressure is applied to the tunnel excavation. Several stages were defined starting with the pressure which would produce no deformation and decaying to the maximum displacement (zero internal pressure).

For the model, 50% of the maximum internal pressure factor was used, resulting in a displacement around the excavation of around 4 mm.

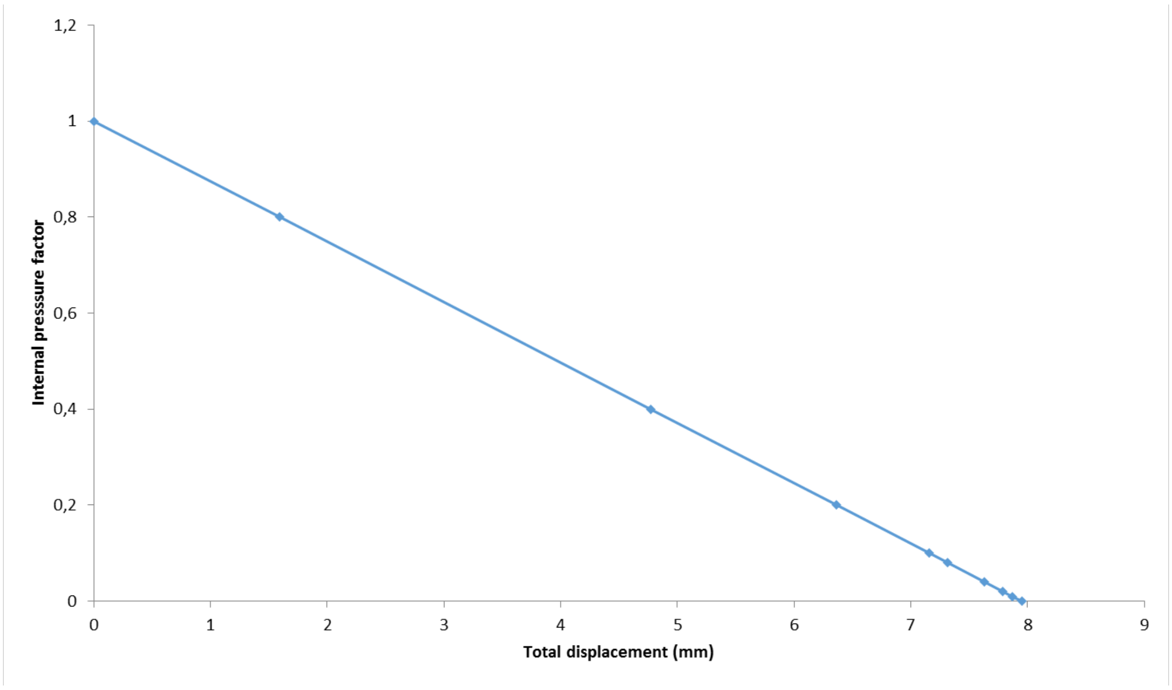


Figure 25: Convergence confinement graph

The use of liners in Phase 2 facilitates the stability analysis of rock support (shotcrete 30 cm) installed after excavation (Stage 3). The maximum total displacement around the excavation will be 4 mm.

Stage 3: Rock support (joint with elastic springs between rock and shotcrete)

As previously stablished, a composite liner has been used to simulate the rock support (shotcrete) and grout. The composite consists of the shotcrete layer (30 cm) and the grout layer (15 cm). A joint is placed between the rock and the shotcrete. It has not been considered any joint on the contact between shotcrete-grout and between grout-concrete lining.

Following the moments and axial force along the rock support. The maximum axial force is 4.38 MN and the maximum moment 10 kNm positive and negative.

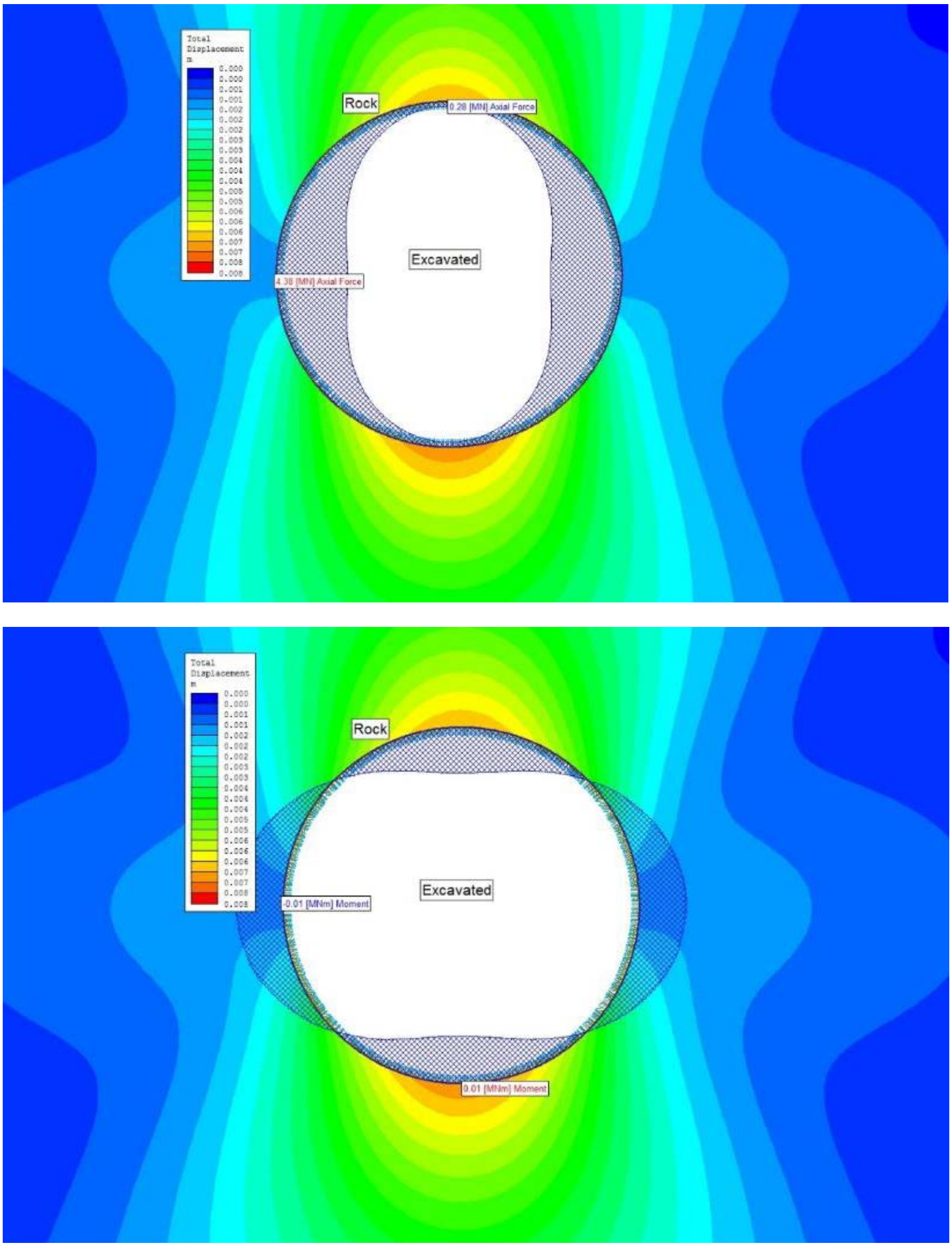


Figure 26: Axial forces and bending moments along the liner on stage 3

Figure 27 shows the graph stability plots of the shotcrete (moment and shear) with factor of safety 1.0, 1.2 and 1.4.

The analysis results for each liner beam element are displayed as individual data points on each plot. This allows visualizing the stresses in the liner with respect to the strength envelopes.

The results indicate that the excavation will be stable with the defined rock support (shotcrete, 30 cm) considering the delay and therefore the initial ground displacement.

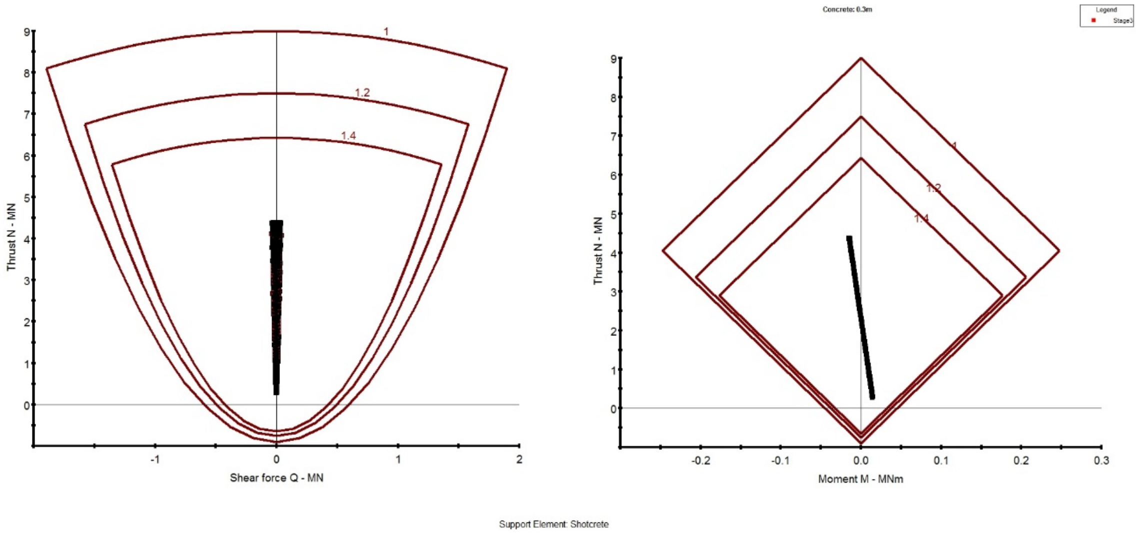


Figure 27: Support capacity diagrams of the rock support (shotcrete) on stage 3

The support capacity diagram is a method to determine the factor of safety of concrete liner. For a given factor of safety, capacity envelopes are plotted in axial force versus moment space and axial force versus shear force space. Values of axial force, moment and shear force for the liner are then compared to the capacity envelopes. If the computed liner values fall inside an envelope, they have a factor of safety greater than the envelope value. So if all the computed liner values fall inside the design factor of safety capacity envelope, the factor of safety of the liner exceeds the design factor of safety.

The dark red lines represent the capacity envelopes for the 3 factors of safety (1, 1.2, 1.4). Notice that no data points that fall outside the 1.4 design factor of safety envelope, meaning they have a factor of safety above 1.4.

Stage 4: Segmental concrete lining (Layer of grout 15 cm between segmental lining and shotcrete)

A total of 7 segments (including a key segment with reduced size) compose every ring of the segmental lining according to the selected design. This will result in seven longitudinal joints (see Figure 28).

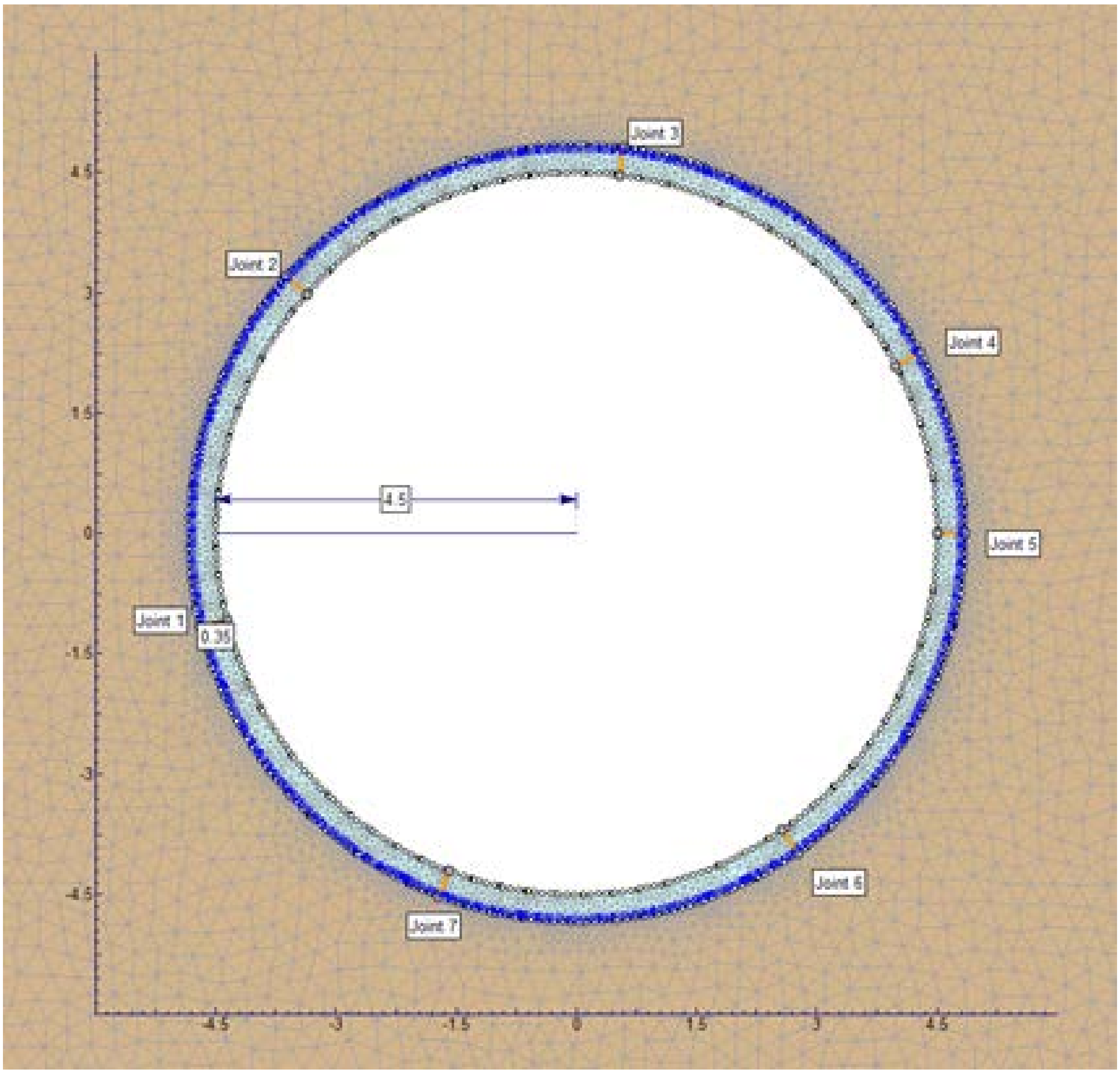


Figure 28: Lining solution with precast segments

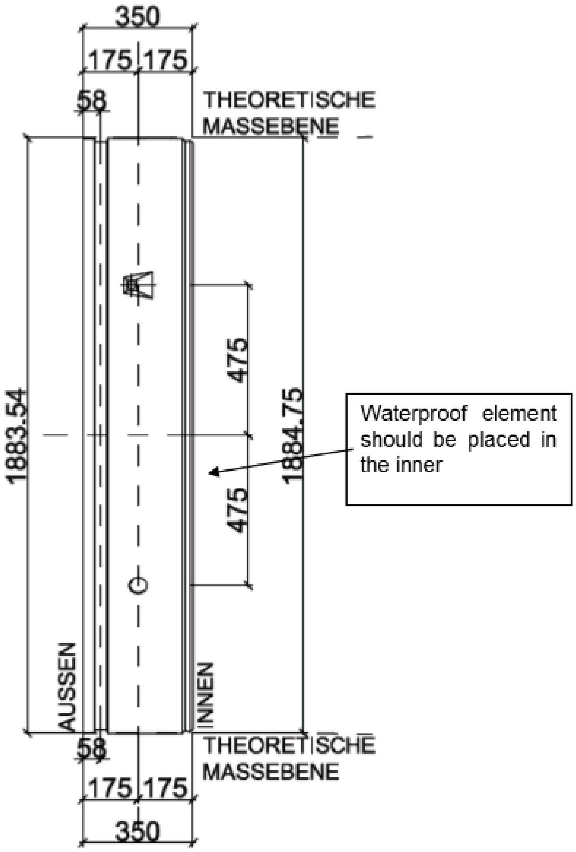


Figure 29: Example of concrete segment cross section

The longitudinal joints were preliminary defined as 210 mm length (following picture). The grout will fill the gaps.

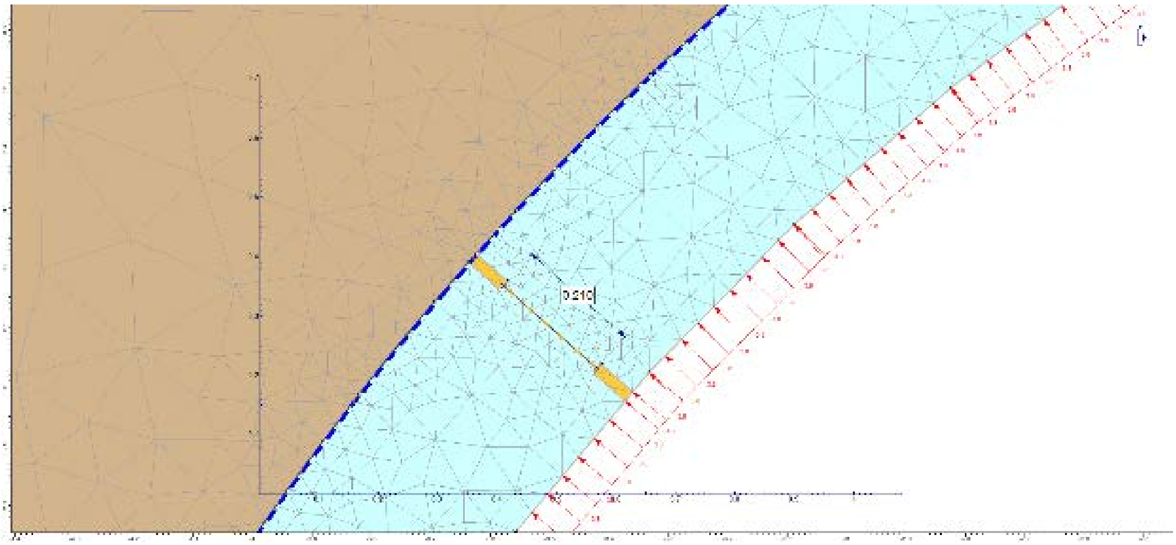


Figure 30: Detail of the longitudinal joints

The commercial code used for 2D modelling (Phase2D 8.0-Rocscience) is widely applied in the underground industry. It has been considered for a preliminary analysis of the excavation, rock support and segmental lining

The longitudinal joints between the segments were simulated by the use of the property "Joint". A joint in Phase "D is composed of two faces that are attached to each other by normal and shear springs at the nodes (Rocscience). Shear and Normal displacement at the node is composed of both elastic (spring) and plastic (slip) components. Only elastic mode was applied.

Stage 5: Pressure (38 bar = 3.8 MN/m2)

The pressure is applied in the inner of the segmental lining.

The next figures show the moments and axial force along the rock support. The maximum axial force is 2.75 MN positive and 1.26 MN negative and the maximum moment 20 kNm positive and negative.

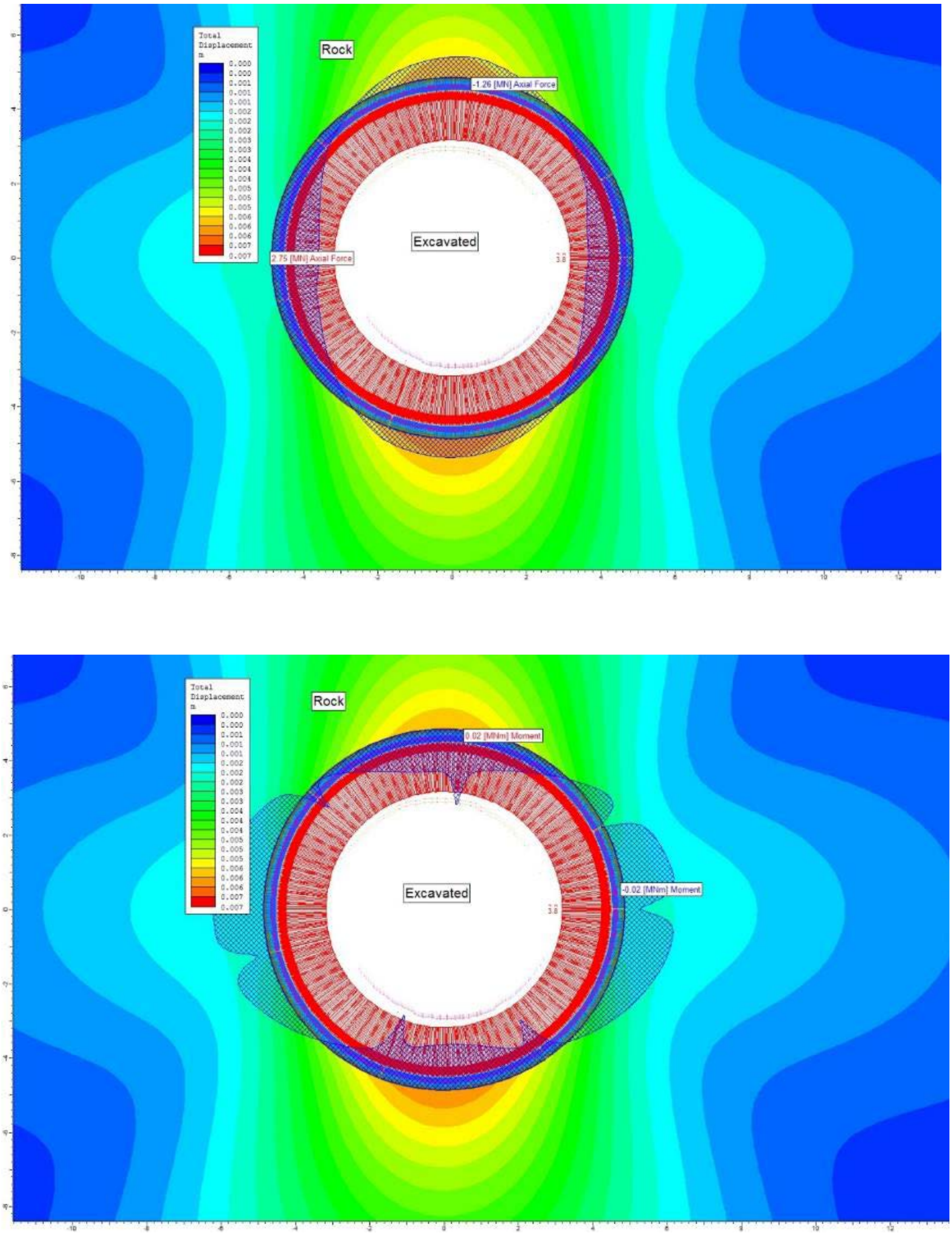


Figure 31: Axial forces and bending moments along the liner on stage 5

When the pressure is applied over the segmental lining, a failure due to traction is shown in the shotcrete and grout.

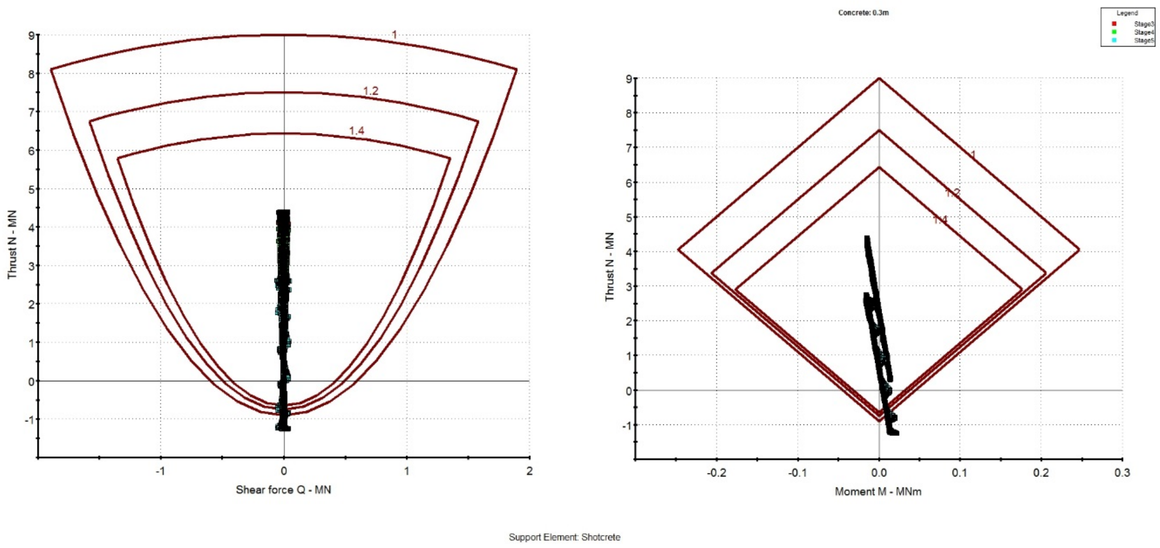


Figure 32: Support capacity diagrams of the rock support (shotcrete) on stage 3 and 5

The behaviour in the longitudinal joints in the stage 5 is shown in the next figures (normal stress and shear stress):

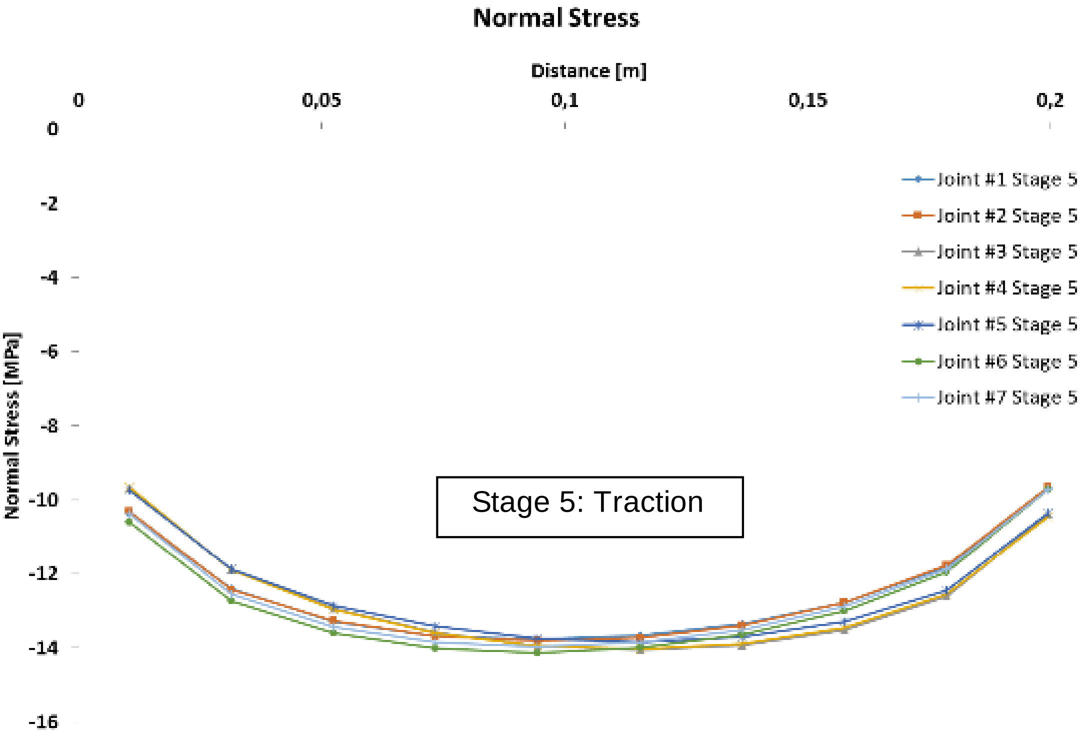


Figure 33: Normal stress distribution along the longitudinal joints between segments

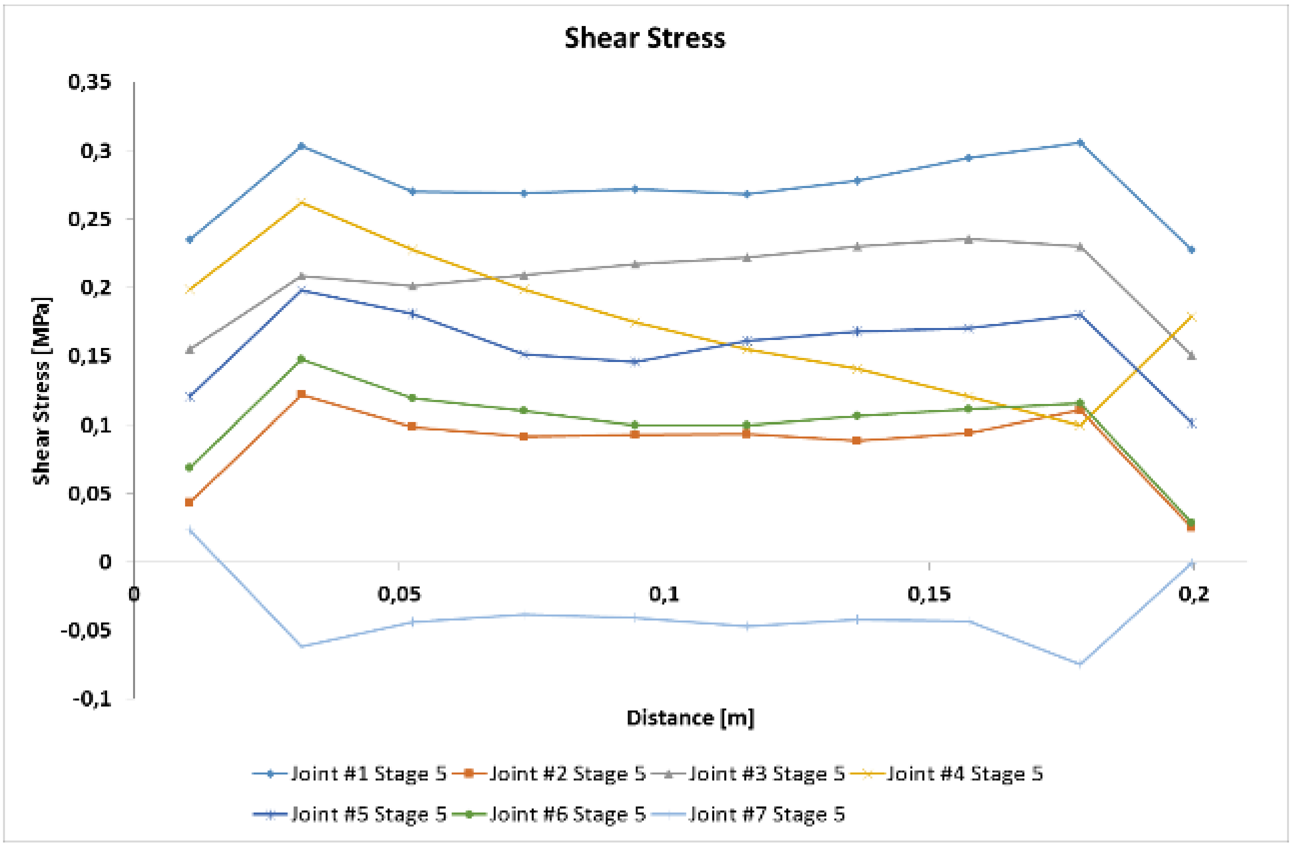
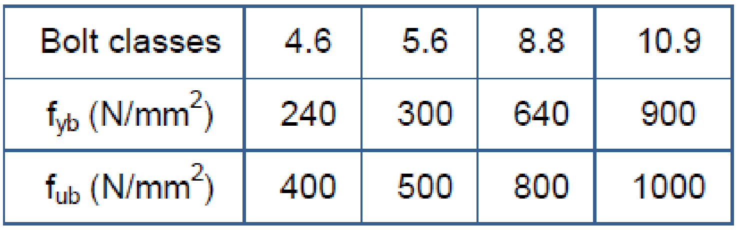


Figure 34: Shear stress distribution along the longitudinal joints between segments

Considering the maximum normal stress in the joints (-14 MPa) results in 2 940 kN/m and considering the maximum shear stress (-0.3 MPa) results in 63 kN/m.

This force needs to be supported by bolts. According to the Eurocode 3 Part: 1-8, a calculation for a standard bolt is carried out. Only tension and shear calculations are included.

Selecting a bolt class 8.8 according to the next table and 24 mm diameter.



Bolt classes	4.6	5.6	8.8	10.9
f_{yb} (N/mm^2)	240	300	640	900
f_{ub} (N/mm^2)	400	500	800	1000

EN 1993-1-8 Table 3.1 - Nominal values of f_{yb} and f_{ub} for bolts

Table 6: Bolt properties and calculations

Property	Value
fub (MPa)	800
Bolt cross section (mm^2)	452
Factor of safety	1.25
Tensile strength (kN)	260.6
Shear strength (kN)	173.7

The tensile strength will be more critical and 12 bolts per metre will be necessary.

9.4 Simulation results

A simulation using a 2-dimensional elasto-plastic finite element program was performed. The stability of the ground support and later segmental lining behaviour was analysed. The rock support based on shotcrete (30 cm) was stable.

The results show that applying the internal pressure, the support behind the segmental lining may collapse.

Regarding to the longitudinal joints, considering the preliminary parameter and the maximum normal stress in the joints (-14 MPa) results in 2 940 kN/m and considering the maximum shear stress (-0.3 MPa) results in 63 kN/m. This amount of force is feasible for bolts.

These results should be taken as preliminary and limited due to the code limitations. A more advanced simulation, considering 3D, of the segmental lining including longitudinal joints and bolts should be carried out.

The use of prestressed and precast concrete segmental lining should be studied and analysed. According to Nishikawa (2003), it can have advantages for tunnels with medium to large span and exposed to internal pressure.

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