Report on Leaching Simulation and Required Number of Caverns

Larne CAES Project

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1 Introduction

Ulster University is investigating the development of a compressed air energy storage (CAES) plant at Larne, Northern Ireland. The proposed project is a bulk renewable energy infrastructure project consisting of a generation/compression station and one or more underground salt storage caverns. A number of caverns will be created, to deliver compressed air to the above ground gas turbine plant.

KBB UT (Hannover, Germany) was requested to prepare a leaching simulation to establish a reference scenario for a cavern leaching concept. The geological model is based on findings from exploration drilling performed in 2013 at the Carnduff #1 well in Larne and especially on leaching tests performed with cores from that well (see "Report on Leaching Tests and Insolubles Profile of Exploration Well Carnduff #1").

For this report it is assumed that the conditions at the cavern site will be the same as those encountered in Carnduff #1.

This report provides information about the feasibility of solution mining the proposed caverns. Other investigations were carried out to characterise the rock's technical suitability for the construction and operation of the cavern, considering the load bearing system.

This report presents leaching simulation results based on representative data to assess the feasibility of creating caverns of a size that is economically reasonable for the intended project. This is done by combining conservative estimates with a relatively large number of workovers (as well as modification of blanket depth and leaching string perforations). In later design steps this leaching concept may be further optimised in terms of cavern volume, leaching duration or costs.

2 Cavern Leaching Simulations

The aim of the simulation is to develop a leaching concept to create caverns with a maximum volume, despite the unfavourable geology that provides large contents of insolubles.

The starting point of the simulation was the rock mechanical model introduced in the "Pre-Feasibility Study Project-CAES Larne" dated April 5th 2012 (PFS), which was altered to match the conditions encountered at the Carnduff #1 well, see below.

2.1 Leaching Model and Input Data

The simulations were performed using the solution mining modelling software **UbroAsym for Windows**. In many years of experience with this planning tool, the simulation results produced by this software have consistently proven to be very reliable when compared to the actual leaching process.

Table 1 lists the parameters applied for the leaching simulation. Some of the parameters (especially the bulking factor) are described in sub-sections below.

Model dimensions and rock mechanical envelope (RME)	
Last cemented casing shoe (LCCS) depth	**740m**
Cavern roof	**760m**
Cavern bottom	**880m**
Average cavern height	**120m**
Allowable cavern diameter	**90m**
Salt rock properties	
Measured bulking factor in specified section	**2.6**
Interpreted bulking factor in specified section	**2.31**
Mean insolubles content in cavern section	**25%**
Assumed leaching limitations	
Leaching factor	**60%**
Effectively reachable cavern diameter	**70m**

Table 1 Parameters for leaching simulation

2.1.1 Insolubles Content, Profile and Leaching Velocity

The vertical distribution of the insolubles is a result of a number of logs run at Carnduff #1 well (Gamma, Caliper and Density logs) and the insolubles content measured fromleaching tests, see Enclosure 1.

A table of the insolubles content that is averaged for 5 m steps is listed in Enclosure 2.

The horizontal and vertical leaching velocities were derived from the same leaching tests (see Enclosure 1) and were averaged for the entire model height.

2.1.2 Bulking Factor

A large spread of bulking factors was determined from lab tests. Especially cores with little insolubles content showed very high bulking factors of up to 3.5, while the mean bulking factors in the intended cavern section is determined as 2.6.

The leaching tests cannot represent the bulking in the cavern directly, especially when very high contents of insolubles occur. Therefore several aspects may be discussed to interpret the test results:

- During reviewing the leaching tests it showed that the cores were coated with drilling mud, whereas the standard core handling at the drill site requires washing such fluids from the cores immediately. This coating could have led to an increase of the bulking factor, because common drilling fluids are designed to establish increased viscosity and decrease settling of the particles.
- Extended observation of the probes showed a settling process that is ongoing even after several days. Bulking at some probes decreased by about 0.5 after some days of settling.
- Especially when very high contents of insolubles occur, as is the case for Carnduff #1 a high thickness of the mudstone sump in the cavern will lead to further compaction of the insolubles and reduction of the re-filled sump volume.

All of the above discussed effects lead to an overestimate of the bulking factor. Therefore, the measured bulking factor of 2.6 was reduced to the more realistic **bulking factor of 2.3** for the simulation of the entire cavern.

2. Further reduction of the bulking factor seems feasible, if additional long term settling tests or tests with an increased height of the modeled sump are performed.

2.1.3 Leaching Factor and Cavern Diameter

The rock mechanical envelope (RME) introduced in the PFS represents the maximum diameter allowed. From experience, it is known that only a certain portion of the diameter is reachable for cavern construction. This is due to natural inhomogeneities within the rock (e.g. dipping, faulting, distribution of insolubles/salt, etc.), which prevent the leaching process to form an ideal circular cavern without any lateral restriction. The diameter of the RME was set to 90 m, but the reachable volume was estimated to be less because of the previously mentioned factors. This volume limitation was defined by the leaching factor which was assumed to be 60% of the RME. The resulting realistic cavern diameter is 70 m.

The maximum reachable diameter of the envelope serves as a limiting condition in the simulation process (slight exceeding are tolerated in some steps). If this limit is reached, an appropriate subsequent leaching step is introduced to mine levels with remaining salt resources. The simulation is completed when the RME is sufficiently exploited and a domal cavern roof is developed at the intended roof depth.

2.2 Leaching Simulation

After the model was established, the leaching scenario was adapted in an iterative process. Together with the initial depth of the nitrogen blanket and the leaching mode, the feasible leaching rate was defined. Considering these boundary conditions, solution mining was simulated by generating a sequence of leaching steps that ultimately created a completed cavern. A number of modifiable operational parameters were available for the controlling of the leaching simulation:

- fresh water injection rate
- blanket level

- depths of inner and outer leaching strings
- leaching mode (direct or reverse fresh water injection)
- duration allotted to each leaching step

3 Results of leaching simulation

The goal of the simulation is to develop a leaching concept that gives a conservative estimate of the feasible cavern volume, as basis for further optimisation regarding to cavern volume, duration, costs, etc. The simulated cavern is depicted in Enclosure 3. The different colours represent changed leaching settings made during a workover, while changes made without a workover rig (e.g. perforations, altered blanket level) are enlisted only in Enclosure 4. Also the operational parameters of each leaching step are represented in Enclosure 4. Key results of the leaching simulation are listed in table 2.

Leaching concept	
Number of leaching steps TBC	**TBC**
Number of workovers TBC	**TBC**
Number of cuttings / perforations TBC	**TBC**
Maximum injection rate per cavern	**150 m^3/h**
Cavern volumes	
Rock mechanical gross volume	**500,000 m^3**
Solution mining gross volume	**300,000 m^3**
Net cavern volume = usable volume	**150,000 m^3**
Further results	
Total solution mining duration	**TBC**

Table 2 Results of leaching simulation

During the first leaching steps the inner and outer leaching strings as well as the blanket level are positioned at a very short distance from each other and only slow leaching rates are run to create as much diameter as possible from the beginning. Because of the high content of insolubles these steps can only be held for short durations, until the subsequent leaching step requires altered setting depths of the leaching strings and the blanket. Longer intervals can be maintained during the later leaching steps. The rock mechanical gross volume is derived from the rock mechanical envelope, set by the rock mechanical expert, based on geology and rock mechanical limitations. A volume of about 500,000 m³ is enclosed by the RME.

The solution mining gross volume considers leaching irregularities due to interbeds and is influenced by the number of workovers, leaching rate and other factors. These effects are considered altogether by the assumed leaching factor. A volume of about 300,000 m³ will be "opened" during leaching. However, a large portion of it will be filled with bulked insolubles. The net cavern volume is the volume that can later be filled with compressed air and represents the usable cavern volume. A cavern volume of 150,000 m³ is shown to be feasible by the leaching simulation.

As mentioned above, this report is based solely on the information available about the exploration well Carnduff #1. Thus geological modelling would be required to identify a forecast of the geology at the later cavern site. The bulking factor can be seen as conservative, as latest observations of the settling behavior show a potential for on-going settling and compaction of the mudstone particles and thus a decrease of the bulking factor. It is proposed to perform additional measurements to identify this potential.

This report shows the feasibility to solution mine caverns of a reasonable volume, despite the concentration of mud stone insolubles encountered. However, the rock mechanical assessment, which will be in parallel to this report, is required to identify the potential to construct and operate the intended caverns. The results of the rock mechanical assessment may affect the feasible cavern volume, if the rock mechanical envelope needs to be altered.

4. Required number of caverns and brine rate

4.1 Assumptions

The results of the leaching simulation are used to calculate the feasible cavern volume. With this volume, the required number of caverns is calculated below to produce the required compressed air mass flow for the CAES plant.

The following is assumed for the calculation:

- Cavern net volume: 150,000 m^3
- Required mass flow: 181.5 kg/s 1
- Required duration of production: 6 h
- Production string ID 500 mm (24 ½” LCC)
- Maximum flow velocity 15 m/s
- Initial pressure at LCCS 90 bar2

The thermodynamic simulation is checked in terms of maximum flow velocity of 15 m/s, as this value also represents a reasonable dynamic pressure loss in the production string.
In the PFS a **maximum pressure rate** of 20 bar/day is used as the limit. Results of the exploration drilling indicate that a reduced pressure rate may need to be applied. However, since no updated pressure rate is yet available, 20 bar/day is still applied as a threshold in the following.

4.2 Simulation results and required cavern number

The simulation results show that 3 caverns are sufficient to deliver a mass flow of 181.5 kg/s for a duration of 6 h.

After the production phase of 6 h the pressure at the casing shoe of the LCS has decreased from 90 bar to 72.6 bar. Thus the pressure reduction is within the 20 bar/d limitation.

The key results are listed below:

- Compressed air rate per cavern = 61 kg/s
- Minimum pressure at LCCS after production = 72,6 bar
- Maximum pressure reduction rate = 2 bar/h
- Maximum flow velocity in production string = 3.8 m/s
- Maximum pressure loss in production string < 1 bar

In the case of **two sets of 134 MW turbines,** 5 caverns would be sufficient to deliver a mass flow of 363 kg/s for a duration of 6 h.

During the 6 h production phase the casing shoe pressure would only slightly exceed the limitation. However, this could probably be managed with slight modifications of the system.

The results of the simulation for 2 sets of turbines and 5 caverns are:

- Compressed air rate per cavern = 73 kg/s
- Minimum pressure at LCCS after production = 69.8 bar
- Maximum pressure reduction rate = 2.4 bar/h
- Maximum flow velocity in production string = 4.7 m/s
- Maximum pressure loss in production string < 1 bar

4.3 Brine rate to solution mine 3 caverns in parallel

As shown by the solution mining simulation, a brine and freshwater maximum rate of 150m³/h is sufficient for solution mining of 3 caverns in parallel. Especially in the first phase, leaching rates of 50 m³/h or even lower are applied to develop a large cavern diameter. Additional optimization of the leaching simulation in terms of leaching time may require higher rates. Therefore a capacity for the brine pipeline of 700 m³/h is recommended.

In the case of 5 caverns to be solution mined in parallel (2 x 134 MW), a brine rate of 1000 m³/h can be considered as the maximum requirement. In both cases the total brine rate and thus the required pipeline diameter can be decreased if leaching of some of the caverns is shifted by about one year, as the first leaching steps will require only low fresh water pumping rates.

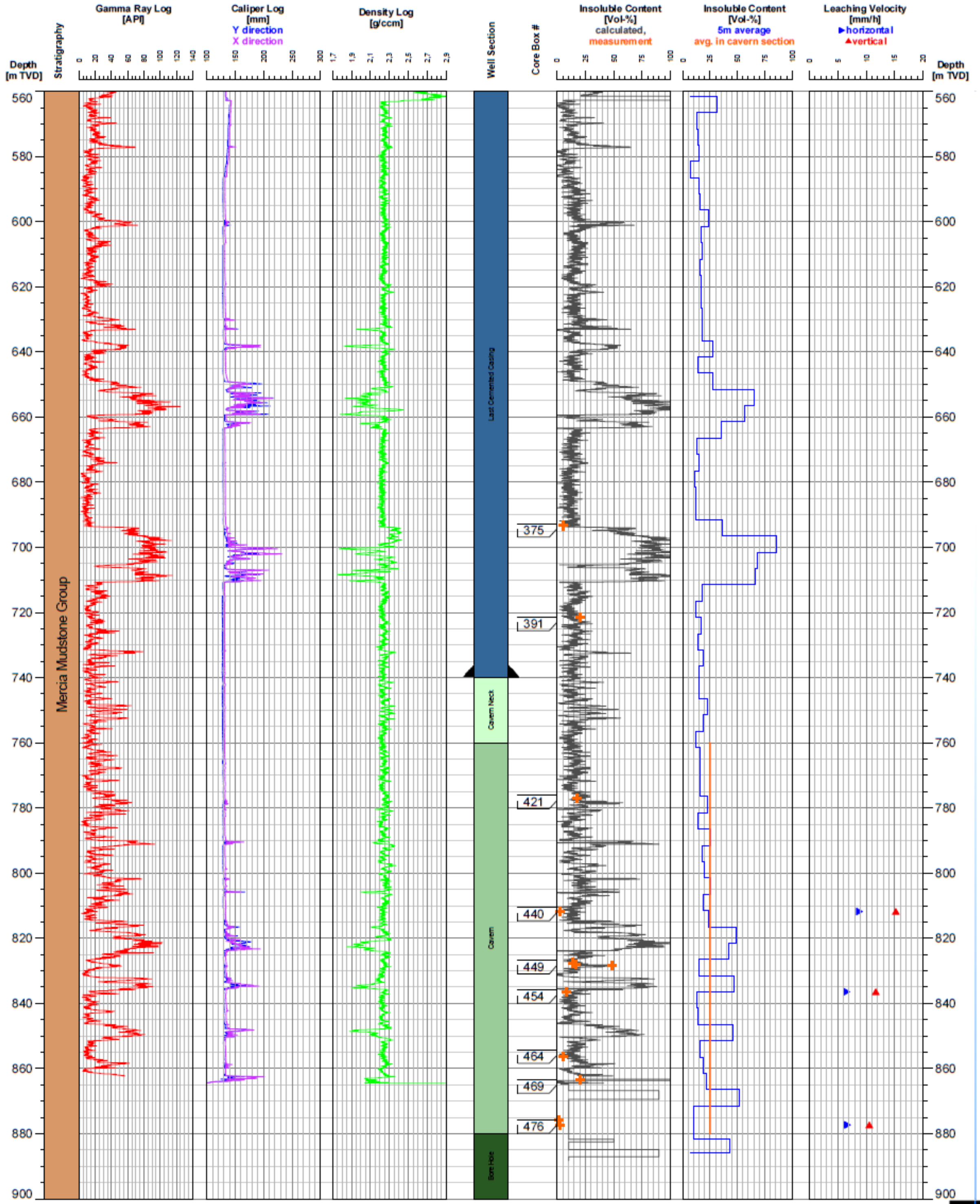
Enclosures

Enclosure 1: Insoluble Profile with Leaching Test Results and Log Data

Enclosure 2: Table of in Insolubles Profile Carnduff #1

Enclosure 3: Simulated cavern shape Larne

Enclosure 1: Insoluble Profile with Leaching Test Results and Log Data



Enclosure 1: Insoluble profile with leaching test results and log data
140303_GES_Carnduff01_InsolublesProfile_rev00.sdg/LD

Enclosure 2: Table of in Insolubles Profile Carnduff #1

Enclosure 2: Insolubles Profile Carnduff #1

Depth range [m] (MD = TVD)		Insolubles [%]
596.5	601.5	24
601.5	606.5	17
606.5	611.5	18
611.5	616.5	16
616.5	621.5	17
621.5	626.5	17
626.5	631.5	18
631.5	636.5	18
636.5	641.5	28
641.5	646.5	14
646.5	651.5	28
651.5	656.5	65
656.5	661.5	57
661.5	666.5	35
666.5	671.5	13
671.5	676.5	15
676.5	681.5	11
681.5	686.5	12
686.5	691.5	12
691.5	696.5	36
696.5	701.5	86
701.5	706.5	68
706.5	711.5	66
711.5	716.5	18
716.5	721.5	12
721.5	726.5	17
726.5	731.5	14
731.5	736.5	19
736.5	741.5	15
741.5	746.5	15
746.5	751.5	23
751.5	756.5	19
756.5	761.5	12
761.5	766.5	16
766.5	771.5	16
771.5	776.5	16
776.5	781.5	23
781.5	786.5	14
786.5	791.5	26
791.5	796.5	18
796.5	801.5	20
801.5	806.5	26
806.5	811.5	19
811.5	816.5	24
816.5	821.5	49
821.5	826.5	42
826.5	831.5	15
831.5	836.5	47
836.5	841.5	13
841.5	846.5	14
846.5	851.5	46
851.5	856.5	16
856.5	861.5	19
861.5	866.5	22
866.5	871.5	52
871.5	876.5	10
876.5	881.5	10
881.5	886.5	43

Enclosure 3: Simulated cavern shape Larne