KEM Research Question (max. 4 pages + annex)			
TITLE	**How does controlled brine bleed-off (CBBO) influence cavern and cavern cluster stability?**		
Title acronym	**CBBO**		
Initiator	*SodM*		
Project owner	*Barend van Engelenburg*		
Contact person	*Heijn van Gent*	**Max. duration**	*1,5-2 years*
KEM subtheme	*Salt Caverns*	**Est. Budget**	*euros*
KEM project code	*KEM-45*	**Contractors**	
Research category	*LT*	**Contractors**	
Risk instr. Innovation	*no*	**Contractors**	

Objective

This research (this research question) focuses on the behavior of salt caverns after closure or abandonment. In abandoned salt caverns the internal pressure can be increased by salt creep and by expansion of brine caused by a rise in temperature. The internal pressure can be reduced by controlled or uncontrolled release of brine from the cavern. The currently identified mechanisms for brine release are:

i) Controlled pressure reduction during brine bleed-off (according to an intended and prescribed procedure).
ii) Uncontrolled pressure reduction by permeation.
iii) Uncontrolled pressure reduction due to the formation of hydraulic fractures.
iv) Uncontrolled pressure reduction through a preferential leak-path.

These mechanisms can occur simultaneously, sequentially, or not at all, depending on the complex interactions among the cavern properties, salt properties and other external controls. Leakage mechanisms (ii), (iii) and (iv) were studied in KEM-17[1]. The study proposed here will focus on mechanism (i), to which we refer in this document as “controlled brine bleed-off” (CBBO).

CBBO will result in a decrease of cavern pressure. This will subsequently affect the state of stress around the cavern to some degree, and at different rates. Basic research questions for CBBO are: how will the stress state change around the cavern or between multiple caverns and what is the potential effect of a changing stress state on cavern integrity (tightness) and stability? A special case is where the abandonment of caverns will be combined with the simultaneous creation or operation of new (storage) caverns in the same salt dome.

SodM would like to understand the effects of CBBO: on subsidence, on stability and on integrity of the cavern. SodM would also like to learn more about what best practices might be: which is better for stability "fast and a lot" or “slow and few" releases? The study will be one of the building blocks that helps SodM to assess the risks of various cavern abandonment scenarios: like hard shut-in, CBBO, controlled high pressure or cavern filling.

[1] See list of references at the end of this document.

State of the art, background

The current understanding of cavern abandonment is largely based on the hard shut-in scenarios, where caverns are filled with brine and closed off. This has long been assumed to be a safe method. Recent experiences in the Netherlands (fracture formation and leakage in the cavern cluster of Nedmag[2], and a hydraulic connection between an abandoned and an active cavern in the Frisia concession[3]) have led to doubts about the safety of this method of abandonment. An alternative method could be CBBO[4].

CBBO has been identified by Ratigan[5] and the KEM-17 report (2020) as an alternative for hard shut-in. While applying the mechanism of CBBO, a cavern is allowed to passively close by creep, with one or more wells either being constantly or intermittently opened up to let brine flow out. The brine production is being driven by the combined effects of brine heating and expansion, and the closure of the cavern due to creeping salt. This research has the aim to determine the impacts and effects of CBBO and, especially, what is known about the safety of this method of closure?

According to the current literature, permeation of brine into the salt wall might (depending on the pressures in the cavern) still play a role in the case of CBBO, even though these caverns are generally expected to be under the equilibrium pressure (see KEM-17, 2020). It is expected that CBBO has to last for multiple years to multiple decades, depending on the cavern characteristics. This expectation would mean a significant extension of the operational commitment of an operator. Currently the Nedmag cavern system is being bled-off in a controlled manner. Fokker (2018) describes this bleed-off and it is one of the few studies currently available that looks at pre-abandonment bleed-off. These caverns are unique for salt mining in the Netherlands, as they are clusters of caverns, designed to mine magnesium salts (bischofite, carnallite), interlayered with halite. Fokker (2018) has used FEM modelling to study the effects of the bleed-off on the stress state of caverns and subsidence in the Nedmag cavern cluster. Fokker (2018) shows that the cavern situation is apparently stable, but with significantly increased subsidence.

Nobian is currently (2023) undertaking a number of ”controlled outflow tests”[6], in line with recommendations in the KEM-17[1] report. Results of these tests might also be incorporated in the proposed study.

Other examples of bleed-offs in the literature appear to be more related to uncontrolled or accidental bleed-off (see for example Bérest and Brouard, 2003). As these are unexpected effects, both the dominant mechanisms and the parameters of the bleed-off (rate leakage or frequency of pulses) are therefore difficult to determine. Also, the build-up to the event and the early effects may be difficult to detect and monitor, especially in an abandoned cavern. Nevertheless, these cases might offer insights in the processes and effects of CBBO.

In a general sense, the modelling of in-situ stress states is a relatively mature field, but improvements are still necessary in order to obtain the insights needed for supervision and safety assessments. The KEM-17 (2020) project has shown that the application of salt creep laws, in practical situations like a real cavern, is not balanced. Generally, emphasis is put on the “non-linear creep” behavior caused by dislocation creep, which is dominant in laboratory settings. There is, however, increasing evidence that the linear behavior of pressure solution is dominant at cavern scales, but that the upper and lower ends of this domain are not well defined yet (see for example section 2.1 of Rowan et al., 2019, for a concise review). Recent scientific research is starting to define these boundaries, and are also starting to define laws for other, non-halite evaporites (see for example, de Bresser *et al.*, 2022 and Oosterhout *et al.*, 2022). Inclusion of linear creep (pressure solution creep) under low differential stresses can have a profound effect on both the subsidence and the state of stress next to, and, in between caverns (Baumann *et al.*, 2022).

Our provisional conclusion is that the effects of CBBO are not well known yet and further research is needed. Given the limited number of real existing cases, some analogous activities might bring valuable insights into understanding of CBBO.

A possible analogue to CBBO might be the pressure cycles that are required to keep the pressure stable in the long-term crude storage caverns of the US strategic crude reserves (see for example: Chekai, 2021). Here, salt creep requires regular bleed-off of brine, very much like CBBO, but within a storage cavern in this case. There is a significant and growing body of research focused at understanding the effect of cyclic pressure variations on the integrity of storage caverns in salt (see for example: Liu and Xiao, 2014; Liu, et al., 2014; van der Valk, et al., 2020). However, these cycles are on a much shorter time span and deal with different fluids and gases (under higher pressures) than in the CBBO case. So, the applicability of this research to CBBO is not evident. The applicability of this analogue needs to be further investigated to see if lessons learned from these cases might be relevant for CBBO.

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[2] Oordeel SodM over overkoepelend rapport lekkage Nedmag april 2018 | Nieuwsbericht | Staatstoezicht op de Mijnen
[3] Reactie SodM op afsluiten Frisia’s zoutcaverne Oosterbierum | Brief | Staatstoezicht op de Mijnen
[4] It should be noted that according to the Dutch Mining law CBBO does not qualify as a formal abandonment, as the well is still in place and being used. CBBO should therefore be seen as a temporary measure, but the legal implications of this are beyond the scope of this work.
[5] Ratigan was program manager of the SMRI sealed and abandoned caverns (CS&A) long-term research program, initiated 1996.
[6] https://www.nobian.com/nl/zoutwinning/groningen/werkzaamheden/uitstroomtesten-bij-boring-hl-a-voor-fundamenteel-onderzoek

Another source of useful information might be the monitoring of cavern behavior. One tool to monitor cavern stability is monitoring micro-seismicity (see for example: Mercerat et al., 2010; Ford and Dredger, 2020). At the Cerville-Buissoncourt site in France, the deliberate progressive collapse of a cavern by solution mining was monitored using several tools, including micro-seismicity (Daupley et al., 2010). The data collected from micro-seismicity records, especially in cases where cavern pressures are known, can serve as input for the real-world testing of models generated in this study. Another tool is sonar measurements to monitor cavern shape. It is possible that these studies contain useful information with respect to the creep behavior and thus the processes of CBBO.

With this study, we aim to complement the KEM-17 project, by looking at CBBO. SodM wishes to understand the effects of CBBO on the local stress field, and changes therein, and, ultimately on the stability of the cavern/cavern field, and potential interaction with surrounding underground activities, in other caverns in the same field.

Keywords: bleed-off leakage, numerical modelling, stress state, cavern, cavern stability, abandonment.

Research Question

Maximum 400 characters (what to be addressed and what not AND Link to KEM Research Agenda)

Main question: What happens to the cavern stability and its integrity in the case of CBBO?

Sub-questions:

1) How does the stress state around a cavern change during bleed-off? How is this dependent on the bleed-off rate or the convergence rate?
2) How is the cavern stability influenced by these stress changes? Is it dependent on depth or temperature?
3) What are the uncertainties/sensitivities/interactions among various parameters and how can uncertainties be quantified or reduced?
4) Is there a safe/unsafe speed of bleed-off? What are advantages/disadvantages of certain bleed-off cycles?
5) What are additional risks when leakage occurs uncontrolled?

Deliverables expected

a) Report of the **Kick-off meeting**
b) Report of the literature study and critical review of modelling approaches and field cases.
c) Report on the model:
    a. A detailed description of assumptions, parameters/parameter space, sensitivities, uncertainties and model limitations.
    b. A detailed model description (detailed enough so others could reproduce it)
d) Progress report #1
e) Report of the **progress meeting (includes GO/NO GO decision for the project)**
f) Report on the analysis:
    a. A suite of modeled scenarios that accurately capture the uncertainties and all realistic scenario's.
    b. Results that are compared with benchmark data (micro-seismic data, subsidence curves, etc.).
g) Progress report #2
h) Report on the **meeting to review intermediate results**
i) Optional: Report on the fine tuning of modelling
j) Draft final report:
    a. Answering the research questions.
    b. Recommendations.
k) Report of the **final meeting**
l) Final report

Timeline

About two (1,5-2) years.
Detailed project plan to be proposed by candidates based on above deliverables.

Expected use

This additional knowledge will help SodM (and hopefully also others) to improve the assessment of studies from operators. This knowledge will also help SodM to give advice to the ministry on operational plans for salt solution mining and gas storage caverns (production plan and storage plan). Understanding of this process will be essential in order to determine whether caverns can be abandoned safely before they are created. Also, it will help assessing the safest method for abandoning existing caverns.

Expertise and tools preferred for the team

The project team needs to have a detailed grasp of both numerical modelling and salt creep. Here, it must be noted that we expect relatively large displacements and strains in these models, for which numerical models generally are not well suited. So, methods that are able to deal with these displacements, and also fulfil the creep laws would be needed. We are also looking to model the overburden not as fully elastic (as is current practices) but as a fully plasto-elastic medium. Novel approaches would be preferred. Models to be run preferably on non-proprietary/reproducible platforms, with the full salt creep laws included.

All relevant groups of researchers have, or have had, in one way or another a connection to the Dutch salt mining industry. The independence and objectivity of the research is achieved as well as possible through the supervision of the KEM panel and SodM experts.

Quality assurance, Organisational and communication requirements

Regular contact with the party doing the modelling is required, to ensure all parties have clear understandings of what they can expect and where the final results are going, and to identify problems, or gaps in understanding early.

Remarks and Suggestions

This project could benefit significantly from novel, and out of the box ideas. This will avoid unwanted anchoring and confirmation bias. This project could also be used to identify partners outside the usual pool of consultants and institutes who do this type of work.

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Selection, ranking criteria (for KEM expert panel only). *Scale: 1(no) - 5(yes) and short comment*

	Considerations	**PE 1**	**PE 2**	**PE3**	**PE4**	**PE5**
Scientific	State of the art OK?					
	Valid I/R question?					
	Realistic expectation?					
	Categorisation OK?					
	Scientific publishable?					
	RA Tool improvement?					
	….					
Feasibility	Deliverables?					
	Deadlines?					
	Budget allocated?					
	Openness?					
	…					
	….					
Building trust	Concerns addressed?					
	Risk reduction focus?					
	Quality assured?					
	Communication OK?					
	Reputation team OK?					
	Open products?					
	….					
Total (weighted) score						

Suggestions of experts and/or research entities (for KEM expert panel only)

PE	**Organisation name**	**Names of experts** **Arguments**
PE 1	Soil Mechanics Laboratory, EPFL, Switzerland	Prof. Lyesse Laloui; Vast experience in geomechanics of underground structures
PE 2		
PE 3		