**A Brief Review**

of the report on

**“Abandonment of solution mining cavern field Zuidwending, The Netherlands”**

by the

**Cavern Closure Consortium (CCC)**

(Version dated 08 April 2024)

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**Aims**

This document consists of a brief review of the above study, focusing in particular on the main body of work presented in Chapters 3, 4 and 5. The review is conducted from the perspective of the author’s expertise in the mechanical and transport properties of rocksalt.

**Overall assessment of the work**

The Zuidwending cavern abandonment study, by the Cavern Closure Consortium, represents the most comprehensive and physically realistic investigation of cavern behaviour, on operational and abandonment time scales, that this reviewer has encountered. It forms a ground-breaking step, in that it integrates laboratory work on salt microstructure, creep mechanisms and permeation behaviour, with numerical modelling and analysis of field data at the cavern and dome scales, to assess real cavern and cavern-field evolution. Aspects of evolution addressed range from the initial dome-scale stress distribution, to the progress of cavern convergence, brine pressurization/permeation and subsidence, over periods extending up to some 200 years beyond operation and abandonment. The study adopts a unique multi-scale, multi-process modelling approach which, unlike previous work, considers all of the physical processes that are currently known to influence the coupled thermo-hydro-mechanical (THM) behaviour of salt - as far as these can presently be quantified or practically implemented in current numerical codes (specifically Brouard’s LOCAS code at the cavern scale, and the LaMEM code used by SmartTectonics at the dome scale). Many of the shortcomings of previous cavern modelling work for the abandonment phase, identified in the 2019 KEM-17 study, are thus addressed in the present CCC study, demonstrating a major advance in modelling capability for underpinning cavern risk mitigation.

One of the key strengths of the CCC work lies in the way that the steady state creep behaviour of the Zuidwending salt is quantified. In contrast to most engineering studies, steady state creep is quantified in terms of deformation mechanisms known from materials science research on salt, namely as the sum of 1) a power law dislocation creep component and 2) a grain-size-dependent, linear-viscous pressure solution term. The latter, which is often neglected, is precisely the term that dominates long term, low stress creep following cavern abandonment. Creep laws for the two mechanisms are calibrated by the CCC team not only by fitting to creep test and microstructural (grain size distribution) data, but using cavern and borehole convergence/pressurization data, plus constraints from modelling dome-scale deformation over geological time. The creep laws obtained, and the statistical analysis employed to quantify uncertainties, offer a well-constrained range of salt creep models at cavern and field scale, which fit well with theoretical expectations in the key, low stress (pressure solution) regime. The CCC team also allows for other microstructural effects that are generally ignored, namely grain size reduction by dynamic recrystallization and the theoretical possibility that grain boundary healing prevents pressure solution creep below a low threshold stress. The influence of recrystallization seen in the CCC creep tests, and of anhydrite impurities, are in effect incorporated in the uncertainty ranges of the final creep laws, while the influence of a threshold stress for pressure solution on cavern modelling is probed via limited sensitivity tests (dome-scale).

A further strength of the CCC study is the cavern-scale modelling work, conducted for real Zuidwending cavern and cavern-cluster geometries, in 2- and 3-D, using the LOCAS code. This is one of the very few cavern codes allowing full coupling of the thermodynamic (P-T) evolution of the cavern fluid with the thermo-mechanical evolution of the surrounding salt, from mining through to operation and abandonment. It is these features that allow the abovementioned creep laws for Zuidwending salt to be calibrated accurately at field scale, using cavern and borehole tests. In addition to steady state creep, the code incorporates transient creep, standard tensile failure, a (conservative) dilatancy criterion, and a fluid permeation (~zero effective tensile stress) criterion, the last with CCC experimental/microstructural support. Fluid migration into the salt is modelled assuming a virgin permeability of $10^{-21}$ m$^2$, increasing rapidly to $10^{-16}$ m$^2$ around the permeation criterion. Dilatancy, a key integrity indicator, appears to be mapped via post-processing, allowing for changes in effective stress by permeating fluid, though this requires further exploration in future, as do possible poro-elastic effects.

An additional, unique aspect of the CCC work, is the modelling of dome-scale response to cavern (field) abandonment, using the LaMEM code. With the focus on long term convergence-driven deformation, permeation, subsidence and the potential for induced seismicity, the salt and surrounding rock are treated as visco-elastic-brittle materials, with the salt undergoing steady state flow by combined dislocation and pressure solution creep, described by the creep laws already discussed. Cavern-fluid permeation into the salt is modelled in a manner similar to that at cavern-scale. Short term cavern operational stages are handled in a simplified way approximating cavern-scale results. Reference simulations without caverns allow discrimination of induced effects. Results predict the 3-D evolution of stress and deformation within and around the Zuidwending dome, as well as surface subsidence/uplift patterns over periods >200 years. Locations of high deviatoric stress and brittle failure are also predicted and match strikingly well with microseismic events detected to date.

**Conclusions and recommendations for follow-up work**

On the basis of the above, it is evident that the CCC study represents a major step forward in cavern modelling into the abandonment phase, providing a significantly improved basis for effect studies, risk assessment and mitigation. The results and conclusions have an essentially sound basis. At the same time, uncertainties inevitably remain. Data uncertainties are mostly minor or incorporated in the statistical treatment of creep parameters, for example. Uncertainties that remain lie mainly in model assumptions and/or formulations.

To address these, the following follow-up work is recommended as abandonment strategies are developed:

1) The extent of dilatancy, fluid penetration and the role of poro-elasticity in cavern walls should be explored further at cavern scale, mapping the effective mean stress distribution and testing post-processing results v. dynamic calculations.

2) Noting the fine grained matrix observed in much of the Zuidwending salt by CCC (MaP), the sensitivity of model results to possible acceleration of pressure solution creep by brine penetration into cavern walls via permeation or dilatancy, and the possibility of localized shear/permeation zones developing as instabilities, should also be explored (see Niemeijer et al. 2022, SaltMech X) – as should possible sensitivity to compositional layering and salt anisotropy. Experimental and microstructural research may also be needed to clarify the competing effects of dilatancy and permeation vs. crack healing, and to constrain any threshold stress for pressure solution.

3) Since dynamic recrystallization, grain size reduction and associated acceleration of pressure solution creep in deforming salt occurs only after a threshold strain in experiments, it would be useful to map cavern-wall strain distribution in future cavern-scale modelling, to assess the volume and location of salt affected.

4) Future simulations at cavern scale would benefit from mapping the evolution of surface subsidence profiles with time, to make the distribution of both subsidence and uplift components visible, besides vertical displacement computed directly above the cavern (present report). This would aid comparison with model predictions by others.

5) Ongoing monitoring of cavern and borehole behaviour in the Zuidwending field is crucial for continuous model testing and improvement of the parameter values, parameter distributions and assumptions incorporated in the CCC codes. Surface displacement and microseismic monitoring offer useful additional constraints.

6) To further constrain the role of pressure solution creep, automated microstructural and grain size analysis of large core sections from the Zuidwending field could also prove useful, if the necessary methods can be developed.

7) Last but not least, while the LOCAS and LaMEM code suites have been widely validated against closed form solutions, other numerical simulations and field observations, cross-validation against the predictions of codes with similar capability that emerge in future would be desirable. Few, if any, are available now, though it would be useful to make a state-of-the-art inventory and to consider interim comparison with codes that capture key features.