EXTERNAL MEMORANDUM

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Subject: Geomechanical Evaluation of Westlake Caverns PPG 6 and PPG 7 at the Sulphur Mines Salt Dome, Calcasieu Parish, Louisiana: Phase 3 Results

INTRODUCTION

This memorandum provides RESPEC Company, LLC's (RESPEC's) summary discussion of the Phase 3 geomechanical modeling focused on the Westlake caverns PPG 6, Louisiana Serial Number (S.N.) 57788, and PPG 7, S.N. 67270, in the Sulphur Mines salt dome. RESPEC is conducting a multiphase geomechanical study of the Westlake caverns, which began with a baseline geomechanical assessment of the caverns using typical modeling assumptions and methods [Nieland, 2023]. RESPEC completed Phase 2 of the study to estimate the in situ salt dilation strength in the salt web between PPG 7 and the dome flank based on the historical sonar surveys conducted in PPG 7 [Heiberger and Nieland, 2024]. The in situ salt dilation strength in the web between PPG 7 and the dome flank was estimated to be approximately 63 percent less than the strength based on RESPEC's testing of salt core recovered from Well PPG 22 [Arnold, 2015].

The estimated in situ salt strength for the salt web between PPG 7 and the dome flank is considered conservative because of limited data available to calibrate the model to match the rock falls indicated by historical sonar surveys taken in PPG 7. The entire salt web between PPG 7 and the dome flank was conservatively assumed to have a lower strength for modeling purposes in Phase 3, as illustrated in Figure 1. This assumption may not be representative of the actual web, which may exhibit variations in strength and deformation characteristics. The in situ salt dilation strength estimated in Phase 2 for the web between PPG 7 and the dome flank was used in Phase 3 of this study to evaluate a hypothetical low-pressure scenario for caverns PPG 6 and PPG 7. The rest of the salt stock in the dome was assumed to have a dilation strength based on the laboratory testing of the salt core recovered from Well PPG 22.

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Phase 3 primarily focused on evaluating hypothetical low-pressure conditions in PPG 6 and PPG 7 as well as the near-term potential effects on the caverns' and surrounding salt webs' stability. The 3D geomechanical model was used to simulate a hypothetical, controlled depressurization scenario for caverns PPG 6 and PPG 7. The model-predicted stress states in the salt surrounding the caverns were post-analyzed to assess the potential for salt dilation assuming the different dilation strengths for the salt webs.

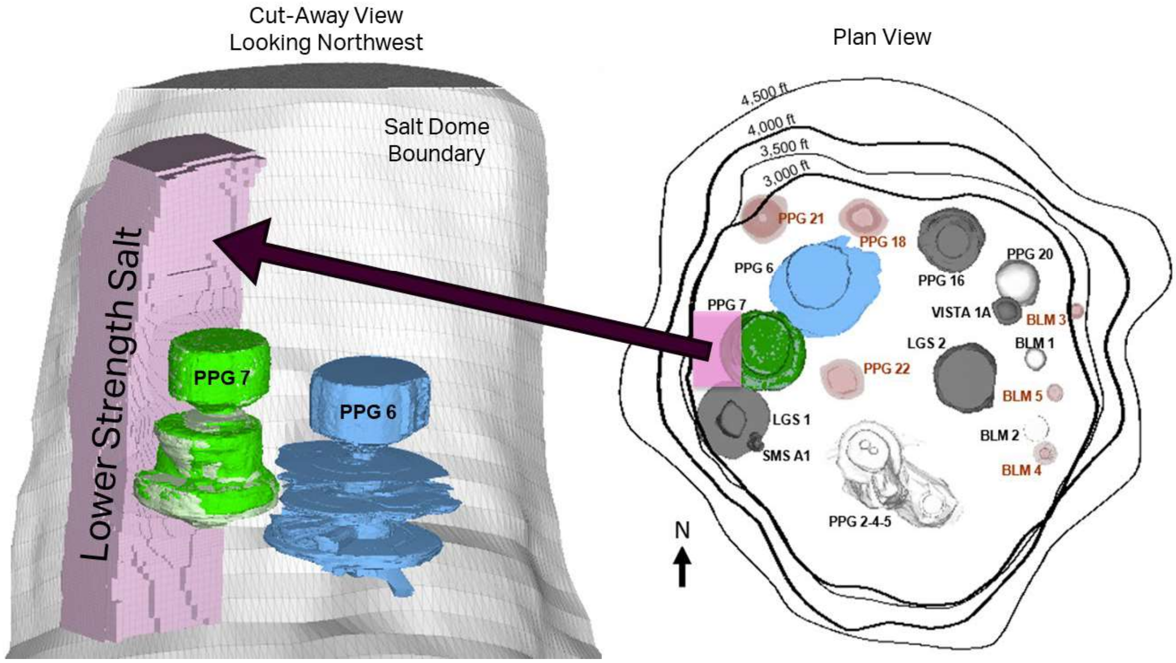

Figure 1. Illustration of Salt Web Between PPG 7 and the Dome Flank Assumed to Have Lower Strength.

BACKGROUND

The fluid pressure in a solution-mined cavern helps support the geologic loads that act on the rock surrounding and overlying the cavern. As the cavern pressure decreases, the loads that must be supported by the surrounding rock increase. If the loads exceed the rock strength, the rock will fail and lose strength. Unlike brittle rock types that fail suddenly, rock salt around a solution-mined cavern will typically begin to fail through microfracturing along the grain boundaries, a process referred to as dilation (or damage). If dilatant states of stress are maintained, the microfractures will increase and coalesce, which, in turn, reduces the strength of the salt, as illustrated in Figure 2. Salt damage is a progressive process that can lead to salt spalling from the roof and walls of the cavern and may lead to salt web failure or roof collapse.

The cavern and salt web stability between adjacent caverns and between the caverns and the edge of salt (i.e., dome flank) is a function of web thickness, web height, and cavern fluid pressures. If the web thickness is small and the cavern pressure is too low, the shear stresses in the salt surrounding the caverns can exceed the strength of the salt. Shear stresses are always present in the salt surrounding solution-mined caverns that are not plugged or shut-in because the internal fluid pressure is always less than the in situ stress in the surrounding salt stock. Designing and operating salt caverns in a manner that precludes the onset of salt dilation is desirable to maintain cavern stability.

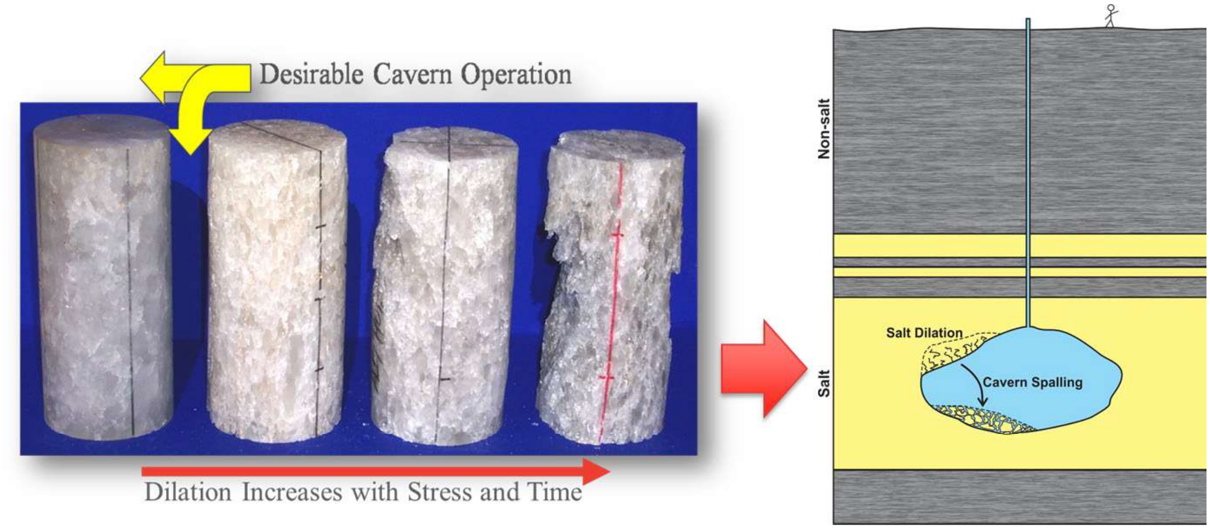

Figure 2. Example of Salt Dilation Illustrating How Dilation Will Increase With Stress and Time (Progression From Left to Right in the Left Image).

SIMULATED CAVERN PRESSURES

The caverns' historical development was approximated by sequentially excavating the caverns based on the well spud dates. The caverns' historical operating conditions were approximated in the model by conservatively representing all caverns as being brine-filled with minimal wellhead pressure. The modeled historical cavern pressures in PPG 6 and PPG 7 were adjusted beginning in January 2021 to approximate the recent cavern pressure histories up to the present day more closely. Several caverns in the salt dome have already been plugged and abandoned, and these caverns were represented in the 3D model as plugged caverns after their approximate plugged and abandoned dates (i.e., the cavern pressures were gradually increased based on the model-predicted creep closure of the caverns).

Recent historical operating pressures indicate that the pressure in PPG 6 has typically been approximately 90 to 100 pounds per square inch (psi) higher than the pressure in PPG 7. In Phase 3 of the study, the wellhead pressure of PPG 6 was gradually reduced to equal the wellhead pressure of PPG 7 before simulating the hypothetical, controlled depressurization scenario for both caverns. The pressure in the caverns was then reduced simultaneously at a rate of 25 pounds per square inch per day (psi/day) until reaching a pressure gradient of approximately 0.424 pound per square inch per foot (psi/ft) at a depth of 3,118 feet (ft), or approximately 1,323 psi. The low-pressure evaluated in Phase 3 was selected based on the assumption that the cavern fluid pressure will equilibrate with the pressure within a reservoir next to the salt dome in which brine is assumed to be flowing into from the PPG 7 cavern. A recent pressure log taken in an off-dome well, located near the salt dome flank next to PPG 7, was analyzed to estimate the reservoir pressure at the depth of the minimum web thickness between PPG 7 and the dome flank (i.e., a pressure of approximately 1,323 psi at a depth of 3,118 ft). The simulated cavern pressure profiles for the hypothetical, controlled depressurization scenario are illustrated in Figure 3.

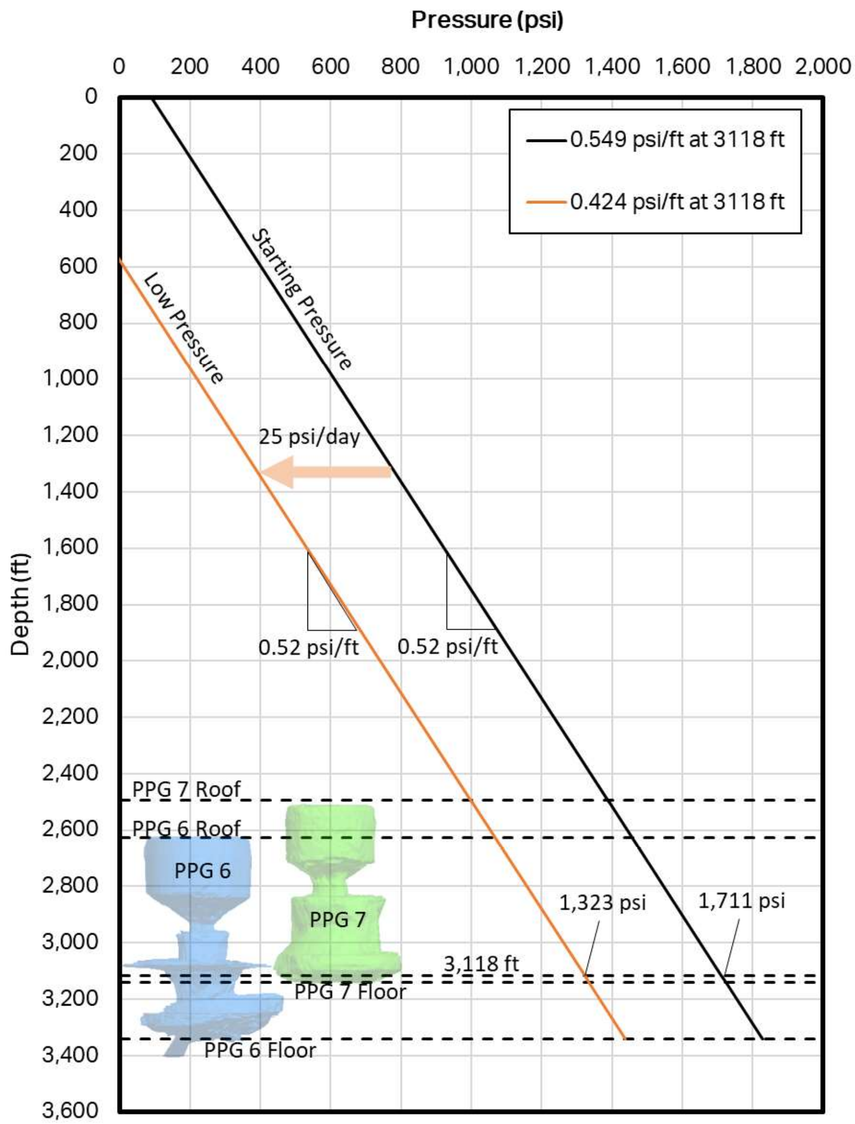

Figure 3. Schematic Illustration of the Cavern Pressure Profiles at the Beginning and End of the Hypothetical Depressurization Scenario Simulated for PPG 6 and PPG 7.

MODELING RESULTS

The salt dilation factor-of-safety (FS) values in the salt webs surrounding the Westlake caverns before simulating the hypothetical depressurization scenario are illustrated in Figure 4, with the caverns modeled as being filled with saturated brine and having a wellhead pressure of approximately 90 psi. The cavern pressures are approximately equal to 1,711 psi or 0.549 psi/ft at a depth of 3,118 ft before the simulated depressurization scenario. The salt dilation FS values are generally greater than approximately 3.0 within the salt surrounding the caverns except for the salt web between PPG 7 and the dome flank, which was assumed to have the dilation strength estimated in Phase 2. In the web between PPG 7 and the dome flank, the dilation FS values range from approximately 1.0 at the cavern surface to approximately 2.5 at the dome flank. Large regions of FS values between 1.0 and 1.5 along the west side of PPG 7 indicate that the stress state in the salt web between PPG 7 and the dome flank is near the estimated in situ dilation strength for that web.

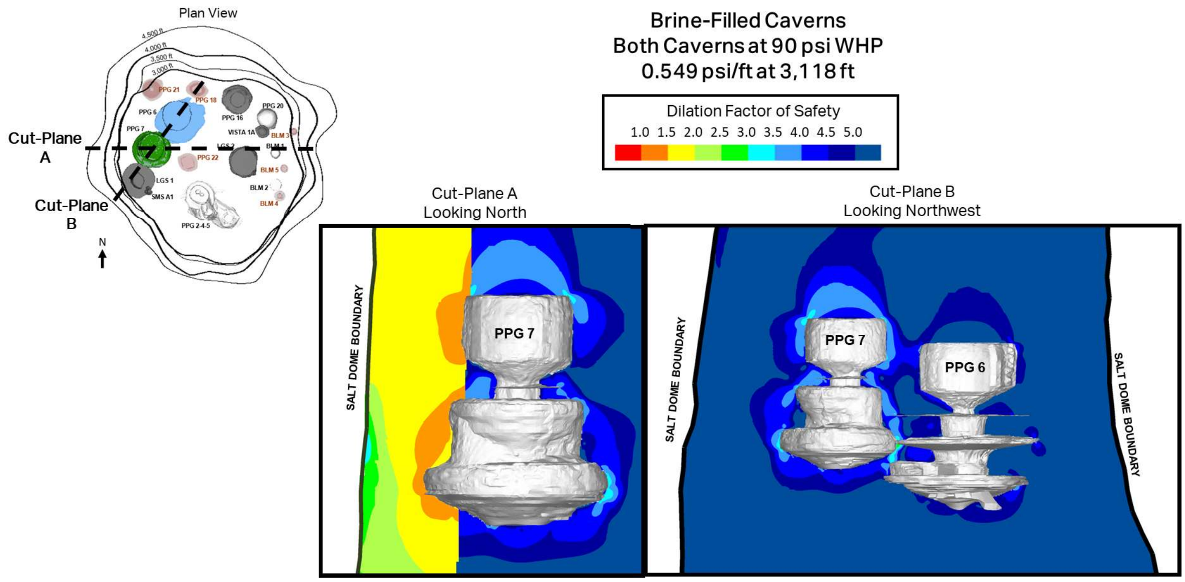

Figure 4. Salt Dilation Factor-of-Safety Values for the Salt Surrounding PPG 6 and PPG 7 Before Depressurization With the Caverns Modeled as Brine-Filled With a Wellhead Pressure of Approximately 90 psi.

The pressure in both caverns was then simultaneously decreased at a rate of 25 psi/day until reaching a pressure approximately equal to 1,323 psi or 0.424 psi/ft at a depth of 3,118 ft. The salt dilation FS values at this low-pressure condition are illustrated in Figures 5 and 6, which decrease significantly after the cavern pressure is reduced to the hypothetical low-pressure condition. Large regions of salt are predicted to be in a dilatant stress state within the web between PPG 7 and the dome flank, as shown in Figure 5. The dilation FS values elsewhere generally decrease to approximately 1.5 to 2.0 near the caverns' surfaces, and the minimum FS values in the web between PPG 6 and PPG 7 are reduced to approximately 2.5 to 3.0 in the middle of the upper web. Figure 6 indicates that the dilation FS values in the salt web between PPG 7 and the coalesced gallery of PPG 2, PPG 4, and PPG 5 are reduced to approximately 4.0 to 4.5 in the middle of the web. A comparison of the predicted FS values assuming the original dilation strength and the estimated reduced dilation strength in the web between PPG 7 and the dome flank is provided in Figures 7 and 8.

After simulating the hypothetical, controlled depressurization of PPG 6 and PPG 7, the cavern pressures were held constant at approximately 1,323 psi or 0.424 psi/ft at a depth of 3,118 ft, and 6 months of future salt creep was simulated to assess the near-term effects of the low-pressure conditions. Figures 9 and 10 illustrate the salt dilation FS values through the salt webs surrounding PPG 6 and PPG 7 after 6 months of future salt creep. *These results assume that the predicted dilatant salt in the web between PPG 7 and the dome flank does not lose strength or fail (i.e., the salt does not spall from the cavern wall, and the web does not catastrophically fail within 6 months).* The FS values are predicted to significantly decrease throughout the salt surrounding PPG 6 and PPG 7 within less than 6 months of the caverns being held at the low-pressure conditions. Large regions of dilating salt are predicted in the web between PPG 7 and the dome flank, with low FS values (i.e., FS < 1.5) through the web thickness. *These results suggest that the salt web will become unstable and likely progressively fail through the edge of the dome, assuming the reduced salt strength is accurate for this web.*

The dilation FS values in the other salt webs surrounding PPG 6 and PPG 7 are predicted to generally reduce significantly within less than six months with the caverns held at the low-pressure conditions. Several of the salt webs are predicted to have dilation FS values reduced to approximately 2.5 to 3.5

in the middle of the webs less than six months after the depressurization of PPG 6 and PPG 7. These results suggest that the low-pressure conditions in PPG 6 and PPG 7 will continue to have deleterious effects on the surrounding salt webs in the future; however, the webs are predicted to remain stable for the first six months. *These results also assume that the predicted dilatant salt in the web between PPG 7 and the dome flank does not lose strength or fail (i.e., the salt does not spall from the cavern wall and the web does not catastrophically fail within 6 months).*

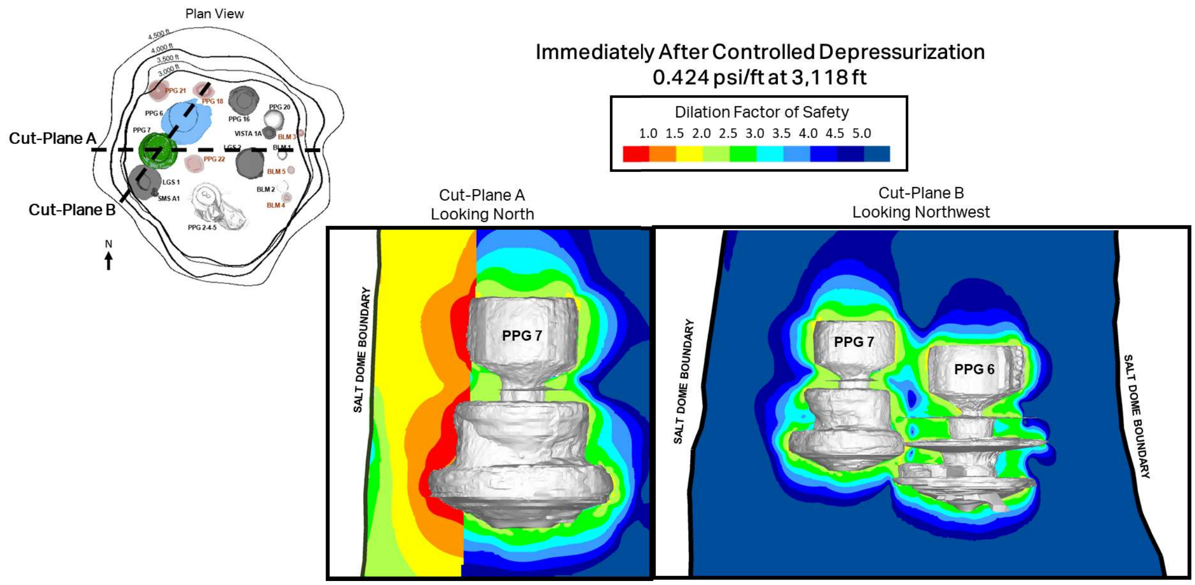

Figure 5. Salt Dilation Factor-of-Safety Values on Imaginary Vertical Cut-Planes Through PPG 6 and PPG 7 Immediately After Simulating a Hypothetical Controlled Depressurization Scenario With the Caverns at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

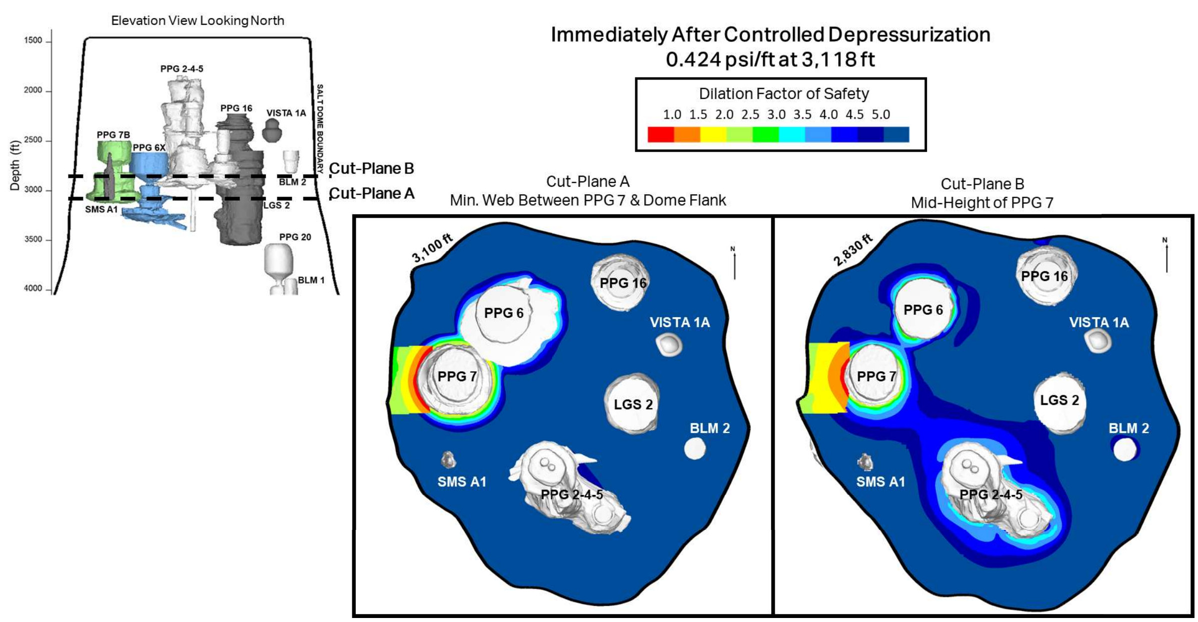

Figure 6. Salt Dilation Factor-of-Safety Values on Imaginary Horizontal Cut-Planes Through the Salt Dome Immediately After Simulating a Hypothetical Controlled Depressurization Scenario With Caverns PPG 6 and PPG 7 at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

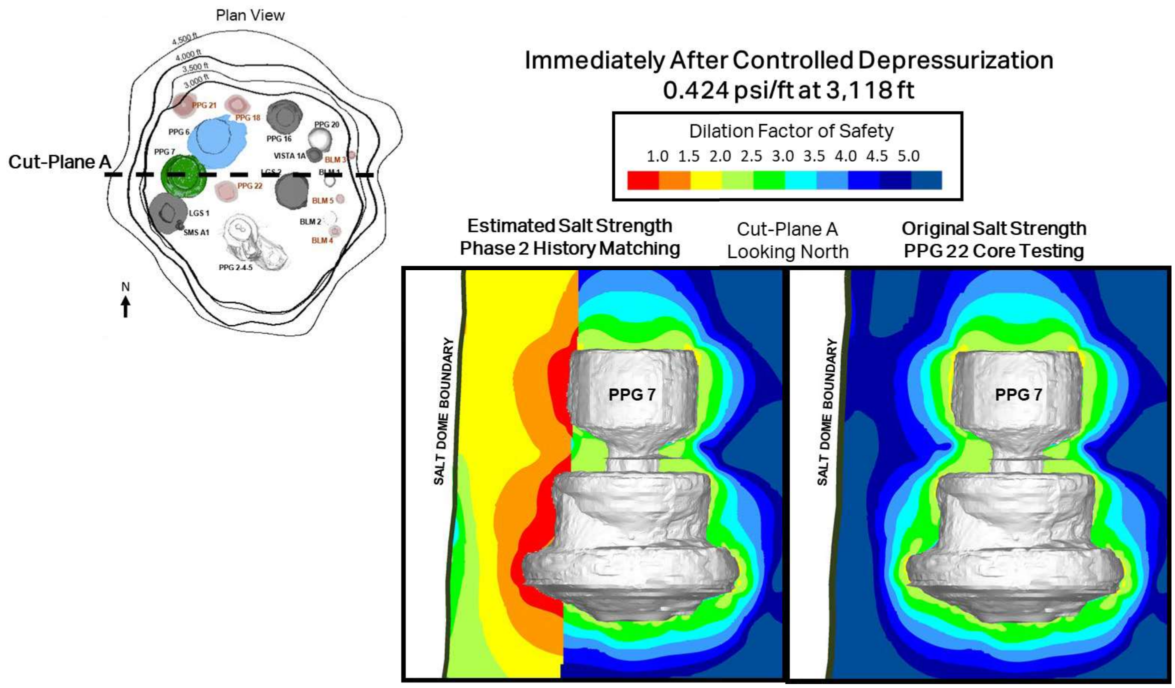

Figure 7. Comparison of Predicted Dilation FS Values in the Web Between PPG 7 and the Dome Flank Assuming the Original Salt Strength (Right) and the Estimated Reduced Salt Dilation Strength (Left) Immediately After Simulating a Hypothetical Controlled Depressurization Scenario With Caverns PPG 6 and PPG 7 at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

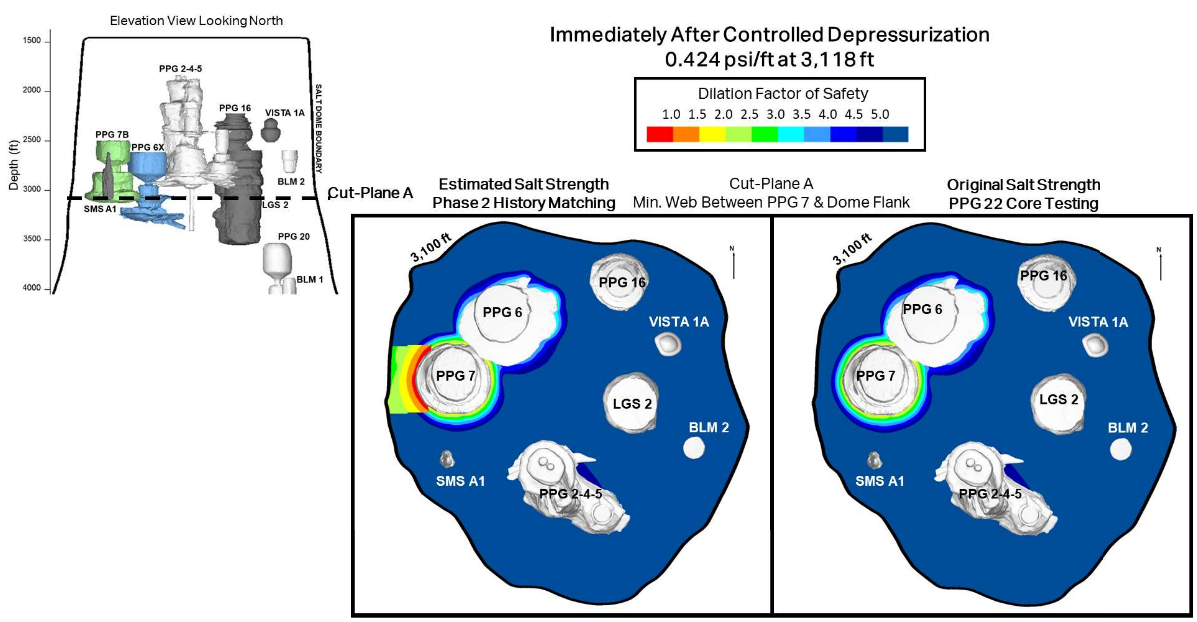

Figure 8. Comparison of Predicted Dilation FS Values in the Web Between PPG 7 and the Dome Flank Assuming the Original Salt Strength (Right) and the Estimated Reduced Salt Dilation Strength (Left) Immediately After Simulating a Hypothetical Controlled Depressurization Scenario With Caverns PPG 6 and PPG 7 at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

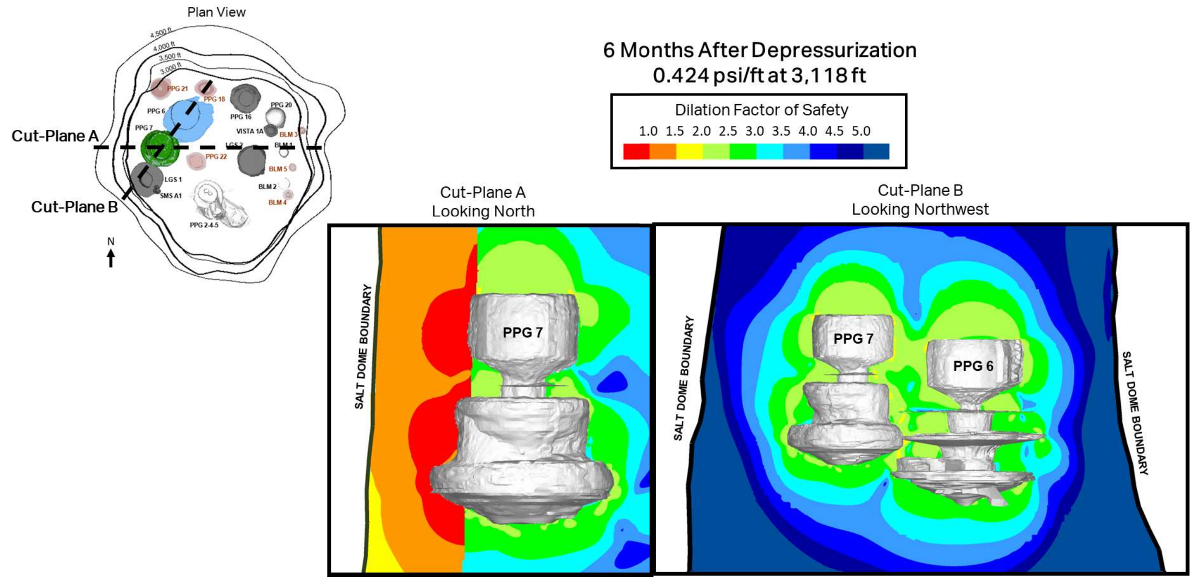

Figure 9. Salt Dilation Factor-of-Safety Values on Imaginary Vertical Cut-Planes Through PPG 6 and PPG 7 Six Months After Simulating a Hypothetical Controlled Depressurization Scenario With the Caverns at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

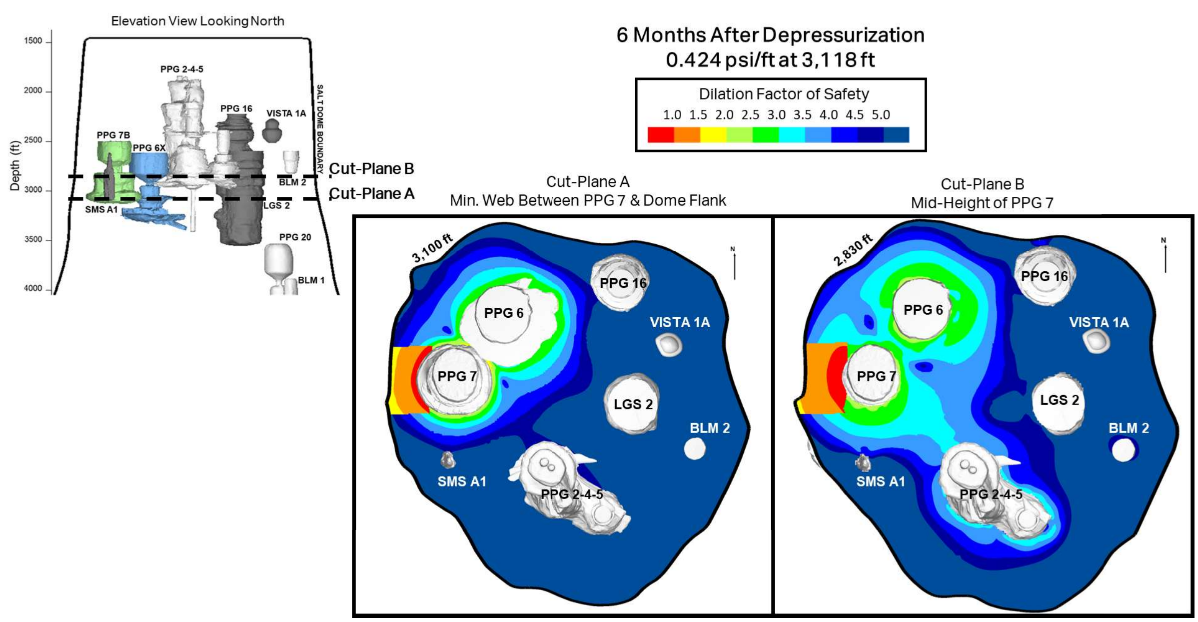

Figure 10. Salt Dilation Factor-of-Safety Values on Imaginary Horizontal Cut-Planes Through the Salt Dome at Six Months After Simulating a Hypothetical Controlled Depressurization Scenario With Caverns PPG 6 and PPG 7 at a Pressure Equal to Approximately 0.424 psi/ft at a Depth of 3,118 ft.

RESPEC

SUMMARY AND CONCLUSIONS

The 3D geomechanical model of the Sulphur Mines salt dome was used to assess a hypothetical controlled depressurization scenario for PPG 6 and PPG 7 and the near-term (i.e., within six months) effects of low-pressure conditions on the surrounding salt webs. The in situ salt dilation strength estimated for the salt web between PPG 7 and the dome flank in Phase 2 was assumed in this assessment, and the salt dilation strength derived from laboratory testing of core recovered from Well PPG 22 was assumed for the rest of the salt within the dome. Caverns PPG 6 and PPG 7 were modeled at a hypothetical low-pressure condition equal to approximately 1,323 psi or 0.424 psi/ft at a depth of 3,118 ft.

The modeling results indicate that the hypothetical low-pressure conditions reduce the salt dilation FS values surrounding the caverns. Significant regions of the salt web between PPG 7 and the dome flank are predicted to be in a dilatant stress state at low-pressure conditions, assuming the estimated in situ dilation strength accurately represents the strength of the salt web. The dilation FS values elsewhere in the salt stock surrounding PPG 6 and PPG 7 are predicted to remain greater than approximately 1.5 to 2.0, with the caverns at the hypothetical low-pressure conditions. After six months of future salt creep with the caverns held at constant low pressures, the dilation FS values generally decrease further into the salt webs surrounding the caverns. The salt webs between PPG 6 and PPG 7 and the surrounding caverns are predicted to remain stable within six months after reaching the low-pressure conditions, with dilation FS values generally greater than approximately 2.0 through the surrounding salt webs. *These results assume that the predicted dilating salt in the web between PPG 7 and the dome flank does not spall, and the web does not catastrophically fail within six months.*

The salt web between PPG 7 and the dome flank is predicted to have FS values less than 1.5 through the web thickness within less than six months after reaching the low-pressure condition. *These results suggest that the salt web will likely become unstable and fail through the edge of the dome, assuming the reduced salt strength is accurate for this web.*

Based on the Phase 3 modeling and analysis results, RESPEC recommends reviewing the results of the geomechanical study to date with the Louisiana Department of Natural Resources and discussing options for a path forward.

REFERENCES

Arnold, R. D., 2015. *Mechanical Properties Testing of Core From Axiall PPG Brine 22 Sulphur Mines Salt Dome, Calcasieu Parish, Louisiana,* RSI-2533, prepared by RESPEC, Rapid City, SD, for Lonquist & Co., LLC, Austin, TX.

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Nieland, J. D., 2023. *Baseline Geomechanical Evaluation of Hypothetical Low-Pressure Conditions in Westlake Cavern 7B at the Sulphur Mines Salt Dome, Calcasieu Parish, Louisiana (RSI/P-8041) (Revision 2)*, RSI(RAP)-996/3-23/12, prepared by RESPEC, Rapid City, SD, for C. Hale, Lonquist & Co., LLC, Houston, TX, March 10.