# Technical Review of Savannah River Site Saltstone Disposal Unit 6 Documents SRMC-CWDA-2024-00045 and SRMC-CWDA-2024-00052 (draft C)

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## REVIEWER CREDENTIALS

*Ronald W. Falta* is a Professor of Environmental Engineering and Earth Sciences in the School of Civil and Environmental Engineering and Earth Sciences at Clemson University. He received his B.S. and M.S. degrees in Civil Engineering from Auburn University in 1982 and 1984, respectively. He received his Ph.D. degree in 1990 from the University of California, Berkeley in Mineral Engineering. His PhD dissertation developed a multiphase flow three-dimensional numerical model for simulating nonaqueous phase liquid (NAPL) transport and remediation by thermal methods. Following his Ph.D., he worked as a Post-Doctoral Researcher at the Lawrence Berkeley National Laboratory, where he continued research on multiphase flow and remediation modeling.

He was hired as an Assistant Professor of Geology and Environmental Engineering at Clemson University in 1992, where he helped found the graduate program in Hydrogeology. he was promoted to Associate Professor (with tenure) in 1995 and to Full Professor in 1999. Dr. Falta has performed scientific research in hydrogeology, contaminant transport, and subsurface remediation since 1982. He has published more than 100 journal papers, book chapters, and reports in this field.

Dr. Falta's publications have been cited more than 4,800 times in the literature, including 850 citations since 2020. He co-edited a 1540-page book on vadose zone hydrogeology for the Department of Energy, and he has developed several computer software packages for hydrogeology and contaminant transport. These include the U.S. Department of Energy code T2VOC that is used to model 3-dimensional LNAPL and DNAPL transport and remediation, the U.S. Environmental Protection Agency codes REMChlor and REMFuel that are used to evaluate groundwater remediation options at hazardous waste sites, and the Department of Defense ESTCP REMChlor-MD code that simulates matrix diffusion in fractured porous media.

Dr. Falta has served as Principal Investigator on 30 research projects related to contaminant remediation, subsurface flow and transport, and hydrogeology, with funding totaling $10.6M. These projects have included subsurface contamination remediation field tests, mathematical modeling of subsurface chemical transport and remediation, and laboratory tests of contaminant remediation. In 2020, he received the John Hem Award for Excellence in Science & Engineering from the National Groundwater Association. That same year, he also received the Honor Award for University Research from the American Academy of Environmental Engineers & Scientists. Both awards were related to his research in groundwater contaminant transport and remediation.

At Clemson University, Dr. Falta has taught a graduate level groundwater modeling course 25 times since 1993, and he has taught a graduate level course on multiphase flow chemical transport and remediation 28 times since 1992. He has taught short courses on contaminant transport and remediation in the US, Germany, Finland, Taiwan, and the Netherlands. He has given invited talks on these subjects to Federal and State government agencies, companies, universities, and consulting firms. He has also given more than 60 scientific presentations on these topics at national and international meetings.

Dr. Falta has worked on multiple consulting projects that involved contaminant transport, groundwater remediation and hydrogeology. This has included work at government nuclear production facilities, chemical, industrial and manufacturing sites, gasoline service stations, refineries, rock quarries, and electrical power plants.

*Lawrence C. Murdoch* is a Professor of Environmental Engineering and Earth Sciences in the School of Civil and Environmental Engineering and Earth Sciences at Clemson University. He received his B.S. degree in Geology from the Pennsylvania State University and he was awarded two M.S. degrees and a Ph.D. from the University of Cincinnati. One of his M.S. degrees is in Environmental Science and the other M.S. degree and his Ph.D. degree are in Geology. His Ph.D. dissertation described the mechanics of hydraulic fracturing of soil. He joined the Center Hill Research Lab at the University of Cincinnati while a graduate student where he proposed to use hydraulic fracturing to help remediate contaminated sites. That proposal led to a series of grants from 1987 to 1997 developing environmental hydraulic fracturing. Today, environmental hydraulic fracturing is widely used to clean up some of the most challenging contaminated sites using techniques that were developed by Dr. Murdoch.

Dr. Murdoch was promoted to Director of Research of the Center for GeoEnvironmental Science and Technology at the University of Cincinnati in 1990 and he held a research faculty appointment from 1991 to 1996. He started a company called FRx Inc. in 1994 to provide environmental hydraulic fracturing services to the remediation industry. FRx has helped clean up more than 400 contaminated sites in the past 30 years and today they are widely recognized as industry leaders in environmental hydraulic fracturing. Dr. Murdoch's research is the basis for another company called Tensora, which was recently started by two members of Dr. Murdoch's research group to provide strain tensor monitoring services to the energy and geologic resources industries.

In 1997, Dr. Murdoch moved to Clemson University where he was an Assistant Professor in the Geology Department with Ron Falta. He was promoted to Associate Professor with tenure in 2002 and to Full Professor in 2008. His research areas include transient well testing, geomechanics, environmental remediation, carbon and energy storage and he typically integrates field methods, instrument development and simulations. He has published more than 75 journal papers, four book chapters, seven patents and more than 130 technical reports, abstracts and presentations.

Dr. Murdoch has been the Principal Investigator on 26 projects totaling $10.5M since 1987. These projects investigated methods for environmental remediation, aquifer or reservoir characterization and related topics. A new $8.5M DOE project that uses environmental hydraulic fracturing for carbon removal is currently under budget negotiation. One of Dr. Murdoch's grants was a prestigious Career Award from the National Science Foundation to continue his work on environmental hydraulic fracturing. Dr, Murdoch has also been co-PI on more than $10M in projects in similar fields.

At Clemson University, Dr. Murdoch has taught a variety of courses in field and theoretical methods in hydrogeology. He has taught a course in applied hydrogeology approximately 25 times, and a graduate-level course in aquifer systems approximately 10 times. His course on applied multiphysics modeling has been offered seven times. Dr. Murdoch has led a team that teaches the Clemson Hydrogeology Field Camp since 1999. That course has been offered more than 20 times since 1999.

## INTRODUCTION

The production of nuclear materials at the Savannah River Site (SRS) during the Cold War resulted in the generation of radioactive liquid wastes. These liquid wastes were stored in 51 underground storage tanks. The waste in these tanks is now being removed and separated into a high-radioactivity waste with a low volume, and a lower radioactivity waste that has a high volume. The lower radioactivity waste form is an aqueous liquid with high pH and a high dissolved concentration of salts, primarily sodium nitrate. The mass concentration of salts in this solution is about 400 g/L, with an ionic strength of about 5.1 mol/L (SRMC, 2024b).

This lower radioactivity salt solution is combined with cementitious materials in the Saltstone Production Facility (SPF), and the resulting slurry is pumped into Saltstone Disposal Units (SDUs) where it solidifies into a form of cement called saltstone. This saltstone has been studied extensively at the SRS, and laboratory tests show that it has a very low saturated hydraulic conductivity, on the order of $5\text{x}10^{-10}$ cm/s, equivalent to an intrinsic permeability of about $5\text{x}10^{-19}$ $m^2$. This saltstone permeability is comparable to very low permeability rocks such as unfractured shales, and unfractured crystalline rocks. The intact saltstone measured in the laboratory has a high porosity of about 0.66, and an extremely high capillary pressure, with an air entry head of more than 400m. The saltstone is liquid saturated, and the high ionic strength pore fluid is held in place by the high capillary air entry pressure, and by the low permeability.

Several SDUs have already been constructed at the SRS. Core testing from one of the existing SDUs, SDU 2A indicated a low saltstone hydraulic conductivity of $1\text{x}10^{-9}$ cm/s (SRMC, 2024a). SDU 6 is the first of a larger generation of SDUs being constructed at the SRS. SDU 6 has a diameter of 375 ft, and a height of 43 ft, with a volume of about 4.75 million cubic feet (134,000 $m^3$). The saltstone slurry is pumped into SDU 6 as relatively thin layers of about an inch during an 8–12-hour shift. The saltstone emplacement in the SDU generates liquid, partly from the saltstone itself, and partly from fresh process water that is used to flush the processing equipment and lines. This water is periodically drained from SDU 6 using 8 drainwells installed in the SDU. These drainwells are 30-inch diameter fully screened wells that extend from the SDU floor to the SDU roof. Four of the drainwells (D1, D2, D8, and D5) are located adjacent to the outside wall of the SDU. The other four SDU 6 drainwells (D3, D4, D6, and D7) are located on the interior, in a square pattern, at 71 ft from the center of the SDU (SRMC, 2024a).

It was expected that these drainwells would operate independently, to remove water that accumulated at the top of the saltstone, but in practice, operators are able to remove drainwater from SDU 6 by only pumping drainwell 1. The water level in drainwell 1 recovers from pumping in a few hours, even when the water level is below the top of the saltstone. Furthermore, all the drainwells show an equilibration to the same water elevation within a couple of days. These observations show that the drainwells are all hydraulically connected by a high permeability pathway. An order of magnitude analysis in SRMC (2024b) shows that the drainwells respond hydraulically as though the saltstone between the wells has a bulk hydraulic conductivity of $3\text{x}10^{-3}$ cm/s. This value of hydraulic conductivity is seven orders of magnitude larger than the laboratory measured values and it is a level expected from a permeable sand or a fractured rock.

## GENERAL FINDINGS

SRMC (2024a) describes three possible ways that the drainwells could be hydraulically connected to each other, and SRMC (2024b) evaluates these potential pathways through numerical modeling. The three potential hydraulic connections between the drainwells are:

*1) The presence of a higher permeability layer near the SDU floor*. SRMC (2024a) postulates that this might have developed during emplacement of the initial saltstone layers, when the relative humidity was sometimes less than 100%. During this initial period, the grout layers were thin (averaging 0.5 inch), and the average time between lifts was 9 days. Cement made with pure water can develop extremely high capillary pressure when exposed to a relative humidity of less than 100% (see, for example Poyet, 2013). This occurs due to water vapor pressure lowering at air-water interfaces having a very low radius of curvature. The capillary pressure in equilibrium with air with a certain relative humidity is:

$$P_c = \frac{-\rho_w RT}{M_{wt}} \ln(RH) \qquad (1)$$

where $P_c$ is the capillary pressure, $\rho_w$ is the density of water, $R$ is the universal gas constant, $T$ is the absolute temperature, $M_{wt}$ is the water molecular weight, and $RH$ is the relative humidity.

Assuming a pore fluid that is pure water, at a relative humidity of 97%, the capillary pressure would be 41 bar. Using the measured capillary properties of the saltstone, again assuming a pore fluid of pure water, the equilibrium water saturation would be 77% at this capillary pressure (SRMC, 2024b). If this type of drying occurred, there could be shrinkage and cracking of the thin saltstone layers. This possibility is countered by the fact that the saltstone pore water has a salt concentration of more than 400 g/L. This high salt concentration gives rise to a large osmotic suction, as described in SRMC (2024b). The water vapor pressure in equilibrium with a salt solution is significantly lower than the vapor pressure of pure water, to the point where it can counteract the effects of high capillary pressure generated by the vapor pressure lowering mechanism. For example, a saturated sodium nitrate saltwater solution has an equilibrium vapor pressure that corresponds to a relative humidity of only 77% (Adams and Merz, 1929). An air relative humidity higher that the salt solution relative humidity would result in condensing conditions with respect to the saltstone pore fluid. SRMC (2024b) uses this osmotic pressure effect to discount the possibility of saltstone drying due to exposure to air with relative humidity less than 100%.

We agree with SRMC (2024b) that drying of the saltstone due to exposure to relative humidities less than 100% is unlikely, except that there are times where fresh water was introduced to the system. It seems possible that there could have been periods where some of the grout had a lower salt concentration, which could have led to drying and possible cracking. Simulation cases G, H, and I in SRMC (2024b) include a 0.7 m thick layer of saltstone at the bottom of the SDU with a somewhat higher hydraulic conductivity ($5.0 \times 10^{-7}$ cm/s) than the bulk saltstone.

*2) The presence of a gap between the saltstone and the bromobutyl rubber liner at the SDU floor*. There is a potentially weak bond between the rubber liner on the SDU floor and the initially emplaced saltstone. It is significant that this liner extends across the entire SDU, so that a gap between the liner and the saltstone, if present, could hydraulically connect the 8 drainwells.

It is postulated that shrinkage of the initial saltstone pours could have caused delamination at the saltstone-rubber liner interface (SRMC, 2024a). There is also a significant difference in the coefficient of thermal expansion between the bromobutyl rubber (120-300x$10^{-6}$ $^{o}C^{-1}$) and the saltstone (6-12x$10^{-6}$ $^{o}C^{-1}$). Temperatures in SDU 6 measured 0.5 ft. above the floor dropped by more than 15 °C during the initial months following the start of saltstone emplacement. SRMC (2024a) proposes that temperature fluctuations could have led to contraction of the rubber liner over the width of the SDU of a foot or more, compared to an inch or less contraction of the saltstone. It is possible that a differential change may have resulted in the delamination of the rubber liner from the bottom of the saltstone. We note that this mechanism of delamination would only occur if the shear strength between the saltstone and the rubber was overcome by layer parallel stresses. Prior to slip along the saltstone-rubber interface, stresses would build up during expansion or contraction. These stresses would be proportional to the elastic modulus, which is likely small in the softer rubber.

The thickness or aperture of a gap between the rubber floor liner and the bottom of the saltstone that would lead to a bulk hydraulic conductivity of 3x$10^{-3}$ cm/s can be estimated. Using the properties of pure water, a hydraulic conductivity of 3x$10^{-3}$ cm/s corresponds to an intrinsic permeability 3.1x$10^{-12}$ $m^2$. The effective horizontal bulk permeability of a saltstone volume containing a horizontal fracture can be calculated by computing the permeability of the fracture, and then using a volume weighted average of the fracture permeability and the unfractured saltstone permeability. Assuming that the fracture permeability is much larger than the saltstone permeability, and using the cubic law to estimate the fracture permeability,

$$k_{eff} = \frac{k_f b}{B} = \frac{\left(\frac{b^2}{12}\right) b}{B} \tag{2}$$

where $k_{eff}$ is the effective bulk permeability, $k_f$ is the fracture permeability, $b$ is the fracture aperture, and $B$ is the total thickness of the saltstone. Rearranging (2), the required fracture aperture to achieve a bulk permeability of 3.1x$10^{-12}$ $m^2$ is:

$$b = \left(12 k_{eff} B\right)^{1/3} \tag{3}$$

Using the saltstone thickness at the time of the drainwell observations of 4m, a floor gap aperture of 0.53 mm or 530 μm would lead to the observed bulk hydraulic conductivity. SRMC (2024b) uses a similar calculation to assign a high hydraulic conductivity to the bottom 0.1 m of the PFLOTRAN model cases C, D, E, F, G, H, and I.

We believe that the presence of a small gap between the bottom of the saltstone and the rubber floor liner is the most likely explanation for the hydraulic connectivity between the drainwells.

*3) The presence of permeable cold joints*. The saltstone is emplaced during 8–12-hour single shift operations, with an average pour thickness of about 1 inch. This operational process results in many cold joints in the saltstone, where the fresh saltstone slurry spreads over cured or partially cured saltstone.

Testing of saltstone samples prepared in the laboratory showed that the presence of cold joints could increase the horizontal hydraulic conductivity by as much as three orders of magnitude, with an upper bound of about $1\text{x}10^{-7}$ cm/s. This increase would not explain the observed apparent hydraulic conductivity of $3\text{x}10^{-3}$ cm/s, which is 6-7 orders of magnitude larger than the expected saltstone hydraulic conductivity of $5\text{x}10^{-10}$ cm/s.

The laboratory testing of the cold joint samples did not exactly replicate conditions that occur in the SDU (SRMC 2024a). Some differences between the laboratory conditions and the actual conditions during saltstone emplacement in the SDU include: the presence of standing water on the previously poured saltstone during emplacement of the saltstone slurry (mainly near the outer drainwells); differences in the relative humidity between the laboratory tests and the SDU operation; and the time interval between saltstone lifts in the laboratory (~3 days) and the SDU (several days to several weeks)

It is conceivable that some of the cold joints could behave like open fractures, with a more significant permeability than was measured in the laboratory testing. If this was the case, the fully screened vertical drainwells could connect otherwise isolated permeable joints to create a hydraulically connected system.

The bulk effective permeability of an impermeable rock containing parallel fractures can be estimated by multiplying the right-hand side of equation (2) by the number of fractures (*n*). Solving for the required fracture aperture to get a given value of $k_{\text{eff}}$ gives:

$$b = \left(12k_{eff}\frac{B}{n}\right)^{1/3} \tag{4}$$

where *B/n* is the fracture spacing. Using a $k_{\text{eff}}$ value of $3.1\text{x}10^{-12}$ m$^2$, Table 1 shows the required fracture aperture as a function of fracture spacing.

**Table 1. Fracture apertures corresponding to a bulk hydraulic conductivity of $3\text{x}10^{-3}$ cm/s.**

| Number of fractures | Fracture spacing | Fracture aperture, m | Fracture aperture, µm |
|---|---|---|---|
| 1 | 4 m | 0.000530 | 530 |
| 4 | 1 m | 0.000210 | 210 |
| 10 | 0.4 m (16 inches) | 0.000155 | 155 |
| 40 | 0.1 m (4 inches) | 0.000098 | 98 |
| 160 | 0.025 m (1 inch) | 0.000061 | 61 |

SRMC (2024b) considers simulation cases (Cases A and B) with a bulk hydraulic conductivity of $3\text{x}10^{-3}$ cm/s, and these cases are capable of reproducing observed drainwell behavior. That report notes that a fractured material could have a bulk hydraulic conductivity this high. SRMC (2024b) rejects this conceptual model because visual surveillance of SDU 6 does not indicate significant cracks in the saltstone.

We believe that the possibility of significant permeable cracks along the cold joints is less likely than other explanations for the high bulk permeability, but do not think it can be completely ruled out based on the evidence presented to us. The fracture apertures for the more closely spaced fractures in Table 1 (0.1m and 0.025m) are less than 100 µm, which is approximately the thickness of a sheet of paper. The case with a fracture spacing of 1m corresponds to a fracture aperture of about 200 µm, which would be the thickness of 2 or 3 sheets of paper. Given that these joints are horizontal, it could be difficult to verify that open cold joints were not present by visual inspection from above.

## RESPONSES TO CRITICAL LINES OF INQUIRY

*Do the subject documents overlook or misinterpret any phenomena that might alter understanding of facility behavior?*

**General** The documents identify and provide reasonable interpretations of data that characterize major phenomena that affect the bulk permeability and compressibility of saltstone within the SDU.

**Improving confidence in conclusions** Confidence in the interpretation could be improved by identifying a most likely conceptual model using field data alone. The current approach requires eliminating four conceptual models because the parameters required for those models to fit the data are outside the values measured in the laboratory. This tacitly assumes that the processes used in the field are incapable of generating material with the properties predicted by the models. It is our understanding that there is currently no evidence that field-scale processes in the SDU would differ significantly from those in the laboratory. Nevertheless, that does not rule out the possibility that this could occur.

**Importance of leaks** The documents recognize the existence of a leak in the SDU. This phenomenon is related to the properties of the structure containing the saltstone and it receives less attention than the properties of the saltstone itself. This weighting gives the impression that leakage is less of a priority than the properties of the saltstone.

**Effects of drainwells** The drainwells may be contributing to the problem of hydraulic connection more than is apparent in the subject documents. For example, placement of the saltstone may have created permeable layers of limited lateral extent that are enveloped in low permeability material. The relatively small volumes of saltstone placed early in the history of the SDU probably covered only a fraction of the area of SDU6. Some of these saltstone pours may have become permeable, perhaps because they were exposed to low humidity air for an extended period, whereas the saltstone from other pours may have retained a low permeability. Alternatively, volume changes during curing may have created subhorizontal cracks of limited lateral extent between saltstone pours.

The effective permeability of saltstone with internal permeable zones that are embedded in a matrix of low permeability saltstone would be dominated by the low permeability matrix. The bulk effective permeability in this scenario would be much lower than what is observed at the SDU. However, this situation would be significantly different if the drainwells are included. In this case, isolated zones of high permeability would be connected through the drainwells and this could significantly increase the overall effective permeability of the SDU. For example, a horizontal permeable zone near the bottom of saltstone could be connected to one higher up through a drainwell, thereby creating a through-going flow path.

The significance of this scenario is that it introduces the concept that the effective permeability of the saltstone could be low, but that the effective bulk permeability of SDU is increased by the drainwells.

This scenario also introduces the potential negative effects of the current drainwell design. The effects of the location of the drainwells on SDU performance could be re-evaluated. For example, drainwells around the periphery may be sufficient to remove water while avoiding interconnections created by internal drainwells.

The use of drainwells for monitoring pore pressure could also be re-evaluated. Future applications may benefit from measuring pore pressure as a function of depth. This is not possible with the current drainwells. Some sensor technologies are available and others are emerging for measuring pressure along the length of a sealed structure, like a tube. Using sensors like this instead of drainwells would allow pressure to be measured within the saltstone while avoiding the potential hydraulic connections introduced by using a fully screened drainwells.

*Is the conceptual model testing sufficiently robust to support the conclusions of SRMC-CWDA-2024-00052 (draft C)?*

The report proposes and evaluates conceptual models that could explain water level observations. The report includes a particularly detailed review of concepts and processes central to flow and pressure changes in porous media, and this provides clarity and credibility to the analyses that follow.

The report proposes nine conceptual models and evaluates them by comparing results of simulations to water levels observed during dewatering events conducted on nine different days over approximately two weeks in December 2022. Water was pumped out of drainwell #1 and then allowed to refill and pumped again two to three times during each day. The water level dropped by several meters in the pumped drainwell, and it dropped by several cm in the other drainwells.

The conceptual models assume there are up to three permeable units within the SDU. An upper and lower unit are recognized in the saltstone, and the other unit is a layer at the base of the saltstone along the floor of the SDU. Each unit is assumed to be a horizontal, continuous layer with a specific permeability, compressibility and water retention curve. Two of the conceptual models (A and B) assume the properties of the two saltstone layers are identical and the base layer is impermeable. The bottom of the saltstone consists of 23 grout layers with average thicknesses of 0.1 to 0.96 inches (0.52 inch average) and an average of 9 days between the emplacement of each layer. The concern is that a thin layer of grout would be vulnerable to cracking, mixing with standing water, disturbance by falling water drops or other processes while it was exposed before the next layer was emplaced. Those processes could have increased the permeability and compressibility compared to saltstone samples prepared under more controlled conditions and tested in the laboratory.

The volume of each layer was increased and the duration between emplacement was shortened during the latter stages of filling the SDU and this could have caused the properties of the upper saltstone to differ from those of the lower saltstone.

The saltstone is underlain by layers of cement, geomembrane and clay designed to be a barrier to flow, and to drain water to a sump. Significant leaks through the floor of the SDU were observed when the SDU was initially filled with water. The floor was covered with a layer of rubber to remedy the leaks and this allowed the SDU to pass additional leak tests. Nevertheless, it was recognized that the floor structure may be permeable enough to transmit water, so some of the conceptual models considered a permeable unit along the floor of the SDU.

The development of the nine conceptual models appears to adequately reflect important aspects of the SDU construction that could affect the water level response.

Our understanding is that a preliminary calibration of each conceptual model involved adjusting the permeability and compressibility, so the volume of water produced by the model matched the volume produced in the field. This is not explicitly stated, but this appears to be the procedure. The predicted water levels were then compared to the observed data at a few representative times and monitoring well locations. In some cases, additional simulations were conducted by modifying parameter values using engineering judgement in an effort to reduce the residual between predicted and observed drawdown and water production.

The conceptual models were evaluated by (1) comparing the parameters determined during the calibration process to values measured in the laboratory (Cases A-D), and (2) comparing the observed water level data to observed data (Cases E – I). Evaluation of the Cases is summarized in Table 6-3.

Evaluation of the conceptual models using the approach outlined above appears to be robust within the context of the available data.

One shortcoming is that it is challenging to discriminate between many of the conceptual models based on the field data alone. Most of the models can predict the observed data fairly well. A few of the models give results with relatively high residuals, but the report suggests that the residuals could potentially be reduced and the fit improved with additional adjustments in the parameter values. Computational methods are available for searching a parameter space more thoroughly than can be accomplished manually, but those methods are not currently available for PFLOTRAN and this may have limited the use of inverse methods. The evaluation could be made more robust by more thoroughly searching the parameter space, and more thoroughly describing the procedures that were used.

Even the simplest conceptual models predicted the field data fairly well and this requires that additional constraints based on laboratory methods be used to eliminate those models. This approach appears to be justified under the circumstances, but studies have shown that properties like hydraulic conductivity can increase with scale. One explanation for this is that large scale tests, like well tests, are affected by large heterogeneities that are generally avoided in small scale tests, like tests using core samples. Indeed, the ultimate conclusion of the study is that a permeable zone at the floor of the SDU is most likely responsible for the observed response. This large-scale heterogeneity is included explicitly in cases C through I.

Figures 6-7 through 6-13 and Figure 6-15 could be improved by clarifying what is the measured data and what is simulated. In the upper graphs for each figure, it appears that the thin colored lines are data and the thicker black line, labeled Case A-I, is simulated. However, the location of the simulated result is not given. In lower graphs, the plots appear to be only simulation results, and it is unclear how data during the pumping events compares to the simulations. An important consequence of Figures 6-7 through 6-13 and 6-15, is that it is somewhat unclear how the simulations were evaluated.

*Is a conceptual model other than "H" more likely?*

The reasoning presented in the report is justified and H appears to be the most likely conceptual model within the uncertainty created by the available data, and the other considerations, caveats and assumptions outlined in the report. This conclusion could be strengthened by describing the details of the models more completely. It would be significantly strengthened if the conclusions could be based on field evidence alone.

*What additional analysis of existing data and/or field work could be pursued to reduce uncertainty?*

**1. Well testing analysis** Several of the conceptual models, including Case H, include two permeable zones, one with a relatively high transmissivity and low storage characteristics, and an adjacent layer with higher storage characteristics. This type of conceptual model is recognized in the well testing field and it has a type curve with a sigmoidal shape on semi-log axes, which differs from the semi-log linear shape of types curves from uniform aquifer. This type of conceptual model was called a leaky confining layer by Hantush, 1960 and Moench, 1985, who describe analytical models that can be used to interpret drawdowns in monitoring wells during well tests. Numerical models can solve variations where analytical models are not available.

A conceptual model assuming a fractured porous media could be tested using either a numerical dual porosity model, or a discrete fracture-matrix model

*Response in monitoring wells.* Water level response in monitoring wells (Figure 6-1 and 6-2) appear to respond to pumping. Water levels in monitoring wells predicted by the simulations also appear to be affected by pumping (e.g. Figure 6-7 bottom), but the extent to which these transients were used to evaluate the conceptual models is unclear. The scales and configuration of the plots make it infeasible to evaluate the drawdown data for characteristics of leaky aquifers—for example, it is impossible to identify the sigmoidal shape that is expected from a leaky aquifer.

The shapes of the simulated drawdown plots in response to each pumping event could be compared to the shapes in the data to provide additional constraints on the conceptual model. This would involve removing background trends and then evaluating each pumping event as a well test. The pumping events on 12/15/2022 and 12/21/2022 would be particularly well suited to further evaluation because they should be less affected by interference than the seven pumping events on consecutive days in early December.

*Alternative forward models.* PFLOTRAN was an excellent choice for an initial evaluation of the pumping data, but other models could be considered. It appears that the saltstone remained saturated during the test, so groundwater flow codes that only consider saturated conditions could be used instead of PFLOTRAN. Using a saturated flow model such as MODFLOW would reduce the time for each simulation, which would allow a broader range of conceptual models to be evaluated.

It could be valuable to perform simulations that use the actual geometry of the SDU and attempt to match the individual drainwell water levels during the drainwell 1 pumping events. Unstructured grid versions of MODFLOW such as MODFLOW-USG and MODFLOW 6 could simplify the grid generation process for the cylindrical SDU with local grid refinement around the drainwells.

*Use inversion methods.* Numerical inversion methods should be considered to more thoroughly evaluate parameter space. This would provide a stronger basis for evaluating conceptual models based on goodness of fit. Data from the individual pumping events, and individual drainwells should be considered in the inversion, if feasible. Inversion methods also estimate parameter uncertainty. Parameter uncertainty would provide a more quantitative basis for evaluating conceptual models.

*Data trends and the leak.* The hydraulic heads decrease throughout the time period used for the analysis as a result of a leak. How the leak is included in the model, and how this affects the evaluation of the data are unclear. There are two options for making this more transparent. The easiest option would be to address the leak more completely in the report. If the leak does not affect the selection of the conceptual model, then another option is to remove the data trend caused by the leak and then analyze the transient data from pumping using a model that does not include a leak. Hydraulic heads commonly either decrease or increase due to factors unrelated to well tests and it is common practice to remove this type of trend when analyzing the data from the well test.

**2. Well testing field implementation** The drawdown and rate data used in the analysis could be improved by conducting additional tests designed to evaluate the saltstone—the current data were obtained as a by-product of dewatering efforts. Pumping could be done at a slower rate to increase the duration of the pumping time, and to eliminate cycling of the pump. This could be done using a different pump, or by controlling the existing pump with a variable frequency drive. This could result in drawdown responses that are typical of a leaky aquifer, or dual domain system, such as Case H. This would help discriminate between conceptual models. Some of the pressure measurements in the existing data appear to be coarse either in time or pressure (angular shapes on the pressure time series), so either better transducers or faster sampling should be considered to improve data quality.

Conducting a more refined set of well tests would generate datasets that should improve the discrimination of conceptual models. For example, Case H is probably characterized by a drawdown curve with a sigmoidal shape, so data with this shape would help confirm that conceptual model. Other options to help identify conceptual models are outlined below.

**3. Perform interwell tracer tests**. Injecting a tracer solution into drainwells and producing fluid from other drainwells would provide a different way to evaluate the saltstone-drainwell connectivity. This type of testing could be initiated by setting up a steady-state flow with extraction from one or more drainwells, and injection into other drainwells, possibly with recirculation. After the flow system stabilized, tracers could be added to the injection drainwell(s). The nature of the tracer breakthrough curve at the extraction drainwell(s) will be strongly affected by the characteristics of the permeable pathway between the two wells. If the wells are connected by a single gap or fracture, the tracer would be expected to breakthrough in the extraction well rapidly due to the small mobile pore volume and high pore velocity. On the other hand, if the saltstone between the drainwells is uniformly permeable, or highly fractured, the mobile pore volume would be larger, leading to a slower pore velocity, and a delayed tracer breakthrough at the extraction drainwell.

Tracers that preferentially sorb to rubber could be used to test conceptual models that consider a permeable pathway along the bromobutyl rubber liner.

The tracer test would be analyzed by using a flow model coupled with a chemical transport model (for example, MODFLOW and MT3DMS). For a given saltstone conceptual model, a flow model would first be calibrated to match the flow characteristics of the pumping test (item 2 above), and then it would be further calibrated to match the flow behavior of the tracer test. Then the transport model would be run to see if the saltstone conceptual model can match the observed tracer behavior. This numerical model could represent the fracture or fractures directly, by discretizing them, or they could be represented as the permeable fraction of a dual porosity model.

**4. Drilling to obtain samples of the saltstone and create monitoring borings**. The analyses of the conceptual models requires assumptions about the properties of the saltstone, and Case H assumes the properties of the lower saltstone differ from the upper saltstone. These differences should be detectable by direct measurement of samples. Moreover, it should be feasible to analyze samples of the saltstone to better understand what caused the properties in the SDU to differ from properties measured in the lab. Coring of the saltstone could be used to assess the permeability of the numerous cold joints in the saltstone.

Obtaining core samples will require boring holes in the saltstone. This process could be combined with additional transient well testing to maximize cost effectiveness. For example, the coring process could be paused after the corehole extended part way into the saltstone and then that hole could be used to monitor the pressure during a transient well test. Ideally, this process would be repeated with the corehole at several depths. This would help characterize the permeability as a function of depth, which would help discriminate between conceptual models.

**5. Use freezing to temporarily isolate zones** It could be feasible to test the hypothesis that the permeability of saltstone varies with depth by selectively sealing portions of the drainwells and repeating the pumping tests. The bottom portion of a drainwell and the enveloping permeable filter could be sealed temporarily by freezing, and then either hydraulic or tracer tests repeated. Sealing could be done using a coiled tube heat exchanger with height sufficient to seal the lower zone in the bottom of the drainwell. Circulating a cold liquid through the coil will freeze the water next to the heat exchanger, forming a temporary seal.

This general approach is widely used to create barriers in permeable sediments to limit groundwater flow (https://apps.dtic.mil/sti/tr/pdf/ADA571582.pdf). It is also a technique used in the oil industry to temporarily seal zones (https://www.wildwell.com/unconventional-intervention/freeze-services), much the same application that is suggested here.

We have used this technique to create a cryogenic packer that sealed an interval in a boring in a lacustrine clay. The formation was too soft to use a conventional packer. We sealed the boring by circulating liquid nitrogen through a coil with a central pass through. This system successfully sealed the well and allowed fluid to be injected beneath it.

Freezing could be used to seal the bottom of the drainwell used for pumping, thereby isolating access to a potential floor gap. Drawdown should increase significantly when the bottom of the well is sealed if the floor gap is permeable. Alternatively, the bottom of a monitoring well could be sealed temporarily. The drawdown should be reduced if the floor gap is permeable.

It should be feasible to temporarily isolate the entire lower unit of the saltstone in either the pumping or the monitoring well, to further evaluate the conceptual models.

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