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SUBJECT: TECHNICAL REVIEW: SALTSTONE WASTE FORM HYDRAULIC PERFORMANCE, DOCKET NO. PROJ0734

The U.S. Nuclear Regulatory Commission (NRC) staff has performed a technical review of saltstone waste form hydraulic performance as part of NRC monitoring of U.S. Department of Energy (DOE) disposal actions at the Savannah River Site (SRS) Saltstone Disposal Facility (SDF). The NRC review was performed in accordance with monitoring activities described in the *U.S. Nuclear Regulatory Commission Plan for Monitoring Disposal Actions Taken by the U.S. Department of Energy at the Savannah River Site Saltstone Disposal Facility in Accordance with the National Defense Authorization Act for Fiscal Year 2005, Revision 1* (ML13100A076). This technical review report relates to Monitoring Area 3 “Waste Form Hydraulic Performance” and Monitoring Area 10 “Performance Assessment Model Revisions” from that monitoring plan.

Enclosure:
Technical Review of the Saltstone Waste Form Hydraulic Properties

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Within those two monitoring areas, this technical review report addresses Monitoring Factor (MF) 3.01 “Hydraulic Conductivity of Field-Emplaced Saltstone”, MF 3.02 “Variability of Field-Emplaced Saltstone”, MF 3.03 “Applicability of Laboratory Data to Field-Emplaced Saltstone”, MF 3.04 “Effect of Curing Temperature on Saltstone Hydraulic Properties”, and MF 10.05 “Moisture Characteristic Curves”.

In the Evaluation Cases in both the DOE SDF Fiscal Year (FY) 2013 and FY 2014 Special Analysis documents (SRR-CWDA-2013-00062 Rev.2, SRR-CWDA-2014-00006, Rev.2), the DOE revised several key assumed hydraulic properties of saltstone based on recent research conducted since the issuance of the DOE 2009 SDF Performance Assessment (PA). The initial saturated hydraulic conductivity used in the model was increased from the 2009 PA value of 2.0×10^{-9} centimeters per second (cm/s) to 6.4×10^{-9} cm/s. The modeled effective diffusion coefficient for intact saltstone was decreased from 1×10^{-7} cm^2/s to 1×10^{-8} cm^2/s. In addition to the revised saturated hydraulic conductivity and effective diffusivity, the DOE revised the assumed moisture characteristic curve for saltstone.

The revised effective diffusion coefficient of 1×10^{-8} cm^2/s in both the FY 2013 and FY 2014 Special Analysis documents was based on laboratory measurements for a simulated non-radioactive saltstone simulant. The DOE also conducted diffusivity tests on additional simulated saltstone samples and actual saltstone core samples collected from SDS 2A. For the simulant samples, the effective diffusivity for nitrate averaged 1.6×10^{-8} cm^2/s. For the saltstone core samples, the effective diffusivity averaged 7.6×10^{-9} cm^2/s. Based on those tests of controlled simulated samples and actual saltstone core samples, the NRC determined that the assumed effective diffusion coefficient in both the FY 2013 and FY 2014 Special Analysis documents was well supported.

In the Evaluation Cases for both the FY 2013 and FY 2014 Special Analysis documents, the DOE revised the initial saturated hydraulic conductivity of saltstone upwards from the 2009 PA value of 2.0×10^{-9} cm/s to 6.4×10^{-9} cm/s. To support the assumed initial hydraulic conductivity of saltstone, the DOE conducted additional laboratory studies and testing on actual saltstone core samples since the 2009 PA. The measurements of the saltstone core samples provided the most compelling support for the initial saturated hydraulic conductivity of field-emplaced saltstone. That included six core samples tested at the Savannah River National Laboratory (SRNL) and two core samples tested at the Savannah River Ecology Laboratory (SREL). The hydraulic conductivity measurements from the core samples were all less than the assumed value of 6.4×10^{-9} cm/s in the FY 2013 and FY 2014 Special Analysis documents. In addition to the direct evidence of the hydraulic conductivity of saltstone from the core sample study, the DOE conducted additional studies and analyses to support the assumed hydraulic conductivity value. Research results from the Vitreous State Laboratory at The Catholic University of America for the simulated saltstone samples prepared under realistic curing conditions yielded hydraulic conductivity values that were consistent with the assumed values in the FY 2013 and FY 2014 Special Analysis documents. Thus, the Performance Assessment Branch (PAB) staff recommends closing MF 3.01 (Hydraulic Conductivity of Field-Emplaced Saltstone) under both 10 CFR Part 61 Performance Objective (PO) §61.41 (Protection of the General Population from Releases of Radiation) and PO §61.42 (Protection of Individuals from Inadvertent Intrusion), because the NRC determined that research results provided by the DOE is adequate to support the assumed initial saturated hydraulic conductivity of field-emplaced saltstone in both the FY 2013 and FY 2014 Special Analysis documents.

In the NRC 2013 SDF Monitoring Plan, the NRC described concerns related to the variability in the hydraulic properties of saltstone (i.e., MF 3.02 – *Variability of Field-Emplaced Saltstone*). That variability can result from changes in process feeds (e.g., dry feed component percentages, dry feed sources and storage conditions, salt waste composition, liquid-to-premix ratio) or saltstone production, emplacement, and curing processes (e.g., method of mixing, method of emplacement, flush water volume used, curing conditions). The recent DOE research results, in particular the measured properties of saltstone core samples, provided significant insight into variability in field-emplaced saltstone. As described in this Technical Review Report (TRR), the NRC determined that the production, placement, and curing conditions that could cause significant variability in saltstone performance were well-controlled and were not expected to result in significant variability. In addition, the NRC determined that the DOE process to evaluate variability due to potential future changes was an adequate basis for the DOE to use to assess and control saltstone variability. For the reasons above, the PAB staff recommends closing MF 3.02 (Variability of Field-Emplaced Saltstone) under both PO §61.41 and PO §61.42. The NRC will monitor the effects of any future DOE process changes as part of the NRC monitoring role at the SDF.

In the 2009 PA, the DOE relied on laboratory data to support assumptions related to the hydraulic performance of saltstone. In the 2013 SDF Monitoring Plan, the NRC described concerns about relying solely on laboratory data without sufficient evidence that the laboratory data reflects the properties of field-emplaced saltstone (i.e., MF 3.03 – *Applicability of Laboratory Data to Field-Emplaced Saltstone*). Recent DOE research results on the physical and hydraulic properties of saltstone core samples provided support for use of laboratory data in representing field-emplaced saltstone, as long as key field conditions (e.g., temperature, humidity, liquid-to-premix ratio) were replicated. However, differences in recently observed leaching behavior between laboratory-prepared and field-emplaced samples may be due to differences in hydraulic properties. For the reasons above, the PAB staff recommends narrowing the scope of MF 3.03 (Applicability of Laboratory Data to Field-Emplaced Saltstone) under both PO §61.41 and PO §61.42 to understanding of the short-term (i.e., within the first several pore volumes) changes in the hydraulic conductivity between laboratory-prepared and field-emplaced saltstone samples.

In the 2012 SDF Technical Evaluation Report (TER), the NRC described that, based on then available DOE research results, the curing conditions (i.e., temperature and humidity) appeared to have a significant effect on the hydraulic properties of saltstone. In the 2013 SDF Monitoring Plan, the NRC developed a MF to describe that concern (i.e., MF 3.04 – *Effect of Curing Temperature on Saltstone Hydraulic Properties*). Since the 2009 PA, the DOE developed several new lines of evidence, including: (1) research results that indicated that unrealistic curing conditions were responsible for anomalously high hydraulic properties in previous studies, (2) laboratory studies of simulated saltstone produced under realistic conditions, and (3) research results from actual saltstone core samples. The NRC determined that the DOE research results demonstrated that the effects of curing conditions were adequately accounted for in the assumed initial hydraulic conductivity and effective diffusivity values in both the FY 2013 and FY 2014 Special Analyses documents. For the above reasons, the PAB staff recommends closing MF 3.04 (Effect of Curing Temperature on Saltstone Hydraulic Properties) under both PO §61.41 and PO §61.42.

In the 2012 SDF TER, the NRC described concerns related to the DOE assumed moisture characteristic curves (MCCs) in the 2009 PA Base Case. In the 2013 SDF Monitoring Plan, the

NRC developed a MF to describe that concern (i.e., MF 10.05 – *Moisture Characteristic Curves*). However, in a sensitivity case (Case K), the DOE revised the approach to unsaturated flow through saltstone and assumed that the relative permeability was 1.0 – independent of saltstone saturation (i.e., the DOE assumed a MCC that did not diminish the hydraulic conductivity from the saturated hydraulic conductivity). In both the FY 2013 and FY 2014 Special Analysis documents, the DOE again included a MCC for saltstone that was not equal to 1.0, but it was revised from the curve in the 2009 PA. Because of the assumed saturation of saltstone in the hydrologic model supporting the FY 2014 Special Analysis document, the MCC does not reduce the hydraulic conductivity significantly compared to the saturated hydraulic conductivity. Therefore, based on its limited risk significance because of the assumed high initial saltstone saturation, the NRC determined that the DOE support for the initial MCC (i.e., prior to saltstone degradation) in the FY 2014 Special Analysis document was adequate. However, future changes to modeling assumptions and parameterization may result in this MCC becoming more risk significant and additional support may be needed for future analyses. For the above reasons, the PAB staff recommends keeping MF 10.05 open under both PO §61.41 and PO §61.42.

SUBJECT: TECHNICAL REVIEW: SALTSTONE WASTE FORM HYDRAULIC PERFORMANCE, DOCKET NO. PROJ0734

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Technical Review of Saltstone Waste Form Hydraulic Performance

Date March, 2017

Reviewers

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Background

The hydraulic properties of saltstone are important to Saltstone Disposal Facility (SDF) performance because of their effects on the rate of radionuclide release into the groundwater. This Technical Review Report (TRR) addresses saturated hydraulic conductivity, moisture characteristic curves (MCC), and diffusivity. Hydraulic conductivity is important because water flow through saltstone is limited in part by saltstone hydraulic conductivity. Flow can be further limited under unsaturated conditions by the assumed MCC. Water flow through saltstone directly affects radionuclide release into groundwater. Diffusivity is important for two reasons: (1) depending on the nature of long-term saltstone degradation, radionuclide release may be limited by diffusion of radionuclides from the saltstone matrix; and (2) diffusivity affects the rate of saltstone oxidation, which directly affects the rate of technetium (Tc) release.

As discussed in the NRC 2013 SDF Monitoring Plan (ML13100A076), the hydraulic performance of saltstone is a key barrier to radionuclide release from the SDF. Monitoring Area (MA) 3 in the SDF Monitoring Plan is Waste Form Hydraulic Performance and the four Monitoring Factors (MFs) in MA 3 are designated as "high priority" MFs. MA 10 in the SDF Monitoring Plan is Performance Assessment Model Revisions, which includes MF 10.05 (Moisture Characteristic Curves) and MCCs are also relevant to waste form hydraulic performance. Recently, the DOE has obtained new research data to support the hydraulic properties assumed for the saltstone waste form in the Department of Energy (DOE) SDF Fiscal Year (FY) 2014 Special Analysis document. Based on the recent DOE research results, this TRR evaluates the available data for the initial saturated hydraulic conductivity, effective diffusivity, and MCCs for the saltstone waste form. This TRR also addresses the DOE support for the variability of field-emplaced saltstone and the use of laboratory-formed samples to represent field-emplaced saltstone.

In the DOE 2009 SDF Performance Assessment (PA), the DOE assumed a saturated hydraulic conductivity value of 2.0×10^{-9} centimeters per second (cm/s) and an effective diffusion coefficient of 1.0×10^{-7} cm^2/s for the saltstone grout waste form in the Base Case[1], which the

[1] In the DOE 2009 PA, the DOE referred to Case A as the Base Case, which was described as the scenario that the DOE most expected for the duration of the performance period. In the DOE SDF FY 2013 and FY 2014 Special Analysis documents, the DOE did not use the term "Base Case", but instead developed an "Evaluation Case" by selecting parameter values that the DOE considered to be most probable and defensible. The DOE also ran a variety of sensitivity analysis cases with "Best Estimate" values. Although there were slight differences in how the DOE described the Base Case and Evaluation Case, the DOE used the Base Case and Evaluation Case results for comparison to the 10 CFR Part 61

DOE called Case A. The DOE used deterministic sensitivity analyses to evaluate the effects of different assumptions about saltstone hydraulic performance. In an alternate case, Case K, the initial saturated hydraulic conductivity was assumed to be $1.0x10^{-8}$ cm/s, the initial effective diffusion coefficient was assumed to be $1.0x10^{-7}$ cm^2/s, and the relative permeability was assumed to be 1.0 – independent of saltstone saturation (i.e., the DOE assumed a MCC that did not diminish the hydraulic conductivity from the saturated hydraulic conductivity). Also, in Case K, the DOE assumed that the saltstone degrades with time with the hydraulic conductivity increasing log-linearly from a value of $1.0x10^{-8}$ cm/s to $1.0x10^{-6}$ cm/s at 10,000 years. That was described in the DOE response to NRC Request for Additional Information Question (RAI) Performance Assessment-8 (PA-8) (SRR-CWDA-2011-00044, Rev. 1). Similarly, the effective diffusion coefficient was assumed to increase log-linearly from an initial value of $1.0x10^{-7}$ cm^2/s to $5.0x10^{-6}$ cm^2/s at 10,000 years.

In Section 2.6.4.2 of the NRC 2012 SDF Technical Evaluation Report (TER) (ML121020140), the NRC described that the saturated hydraulic conductivity that was assumed for saltstone in the DOE Base Case in the 2009 PA (i.e., $2.0x10^{-9}$ cm/s) was in the range of measured hydraulic conductivity values for laboratory-prepared samples cured at low temperatures. However, multiple laboratory studies measured saltstone hydraulic conductivity values that exceeded that value by three orders of magnitude. The DOE hypothesized that experimental artifacts, such as low-humidity curing environments, could explain the disparities in several of those studies. Since 2007, the NRC had a concern that variations between the preparations of laboratory- versus field-emplaced saltstone may be responsible for the differences in observed saturated hydraulic conductivity values. Details about the two Open Issues identified by the NRC about that concern during an SDF Onsite Observation Visit (OOV) in 2007 are in the OOV Report (ML073461038) and are summarized below.

In 2007, the NRC identified Open Issue 2007-1 to address the potential differences between the properties of laboratory-prepared and field-emplaced saltstone. Those differences could result from differences in mixing, curing temperature, curing humidity, air entrainment, liquid-to-cementitious materials ratio, differences in the treatment of dry ingredients for field- and laboratory-prepared saltstone (e.g., differences in storage), or other differences between lab production and production of saltstone grout at the Saltstone Production Facility (SPF). In 2008, the DOE collected nine core samples from Saltstone Disposal Structure (SDS) 4, Cell E, to begin to understand these potential differences (SRNL-STI-2009-00804, ML121020140). Permeability testing of five of the samples showed a mean saturated hydraulic conductivity of $4.0x10^{-7} \pm 1.9x10^{-7}$ cm/s. As described in the 2013 SDF Monitoring Plan, the DOE hypothesized that the relatively high saturated hydraulic conductivity values of the core samples were artifacts of the sample collection method (e.g., artificially high hydraulic conductivity due to damage caused by field coring of samples). To reduce the potential for experimental artifacts, the DOE began to develop a formed-core sampling technique.

In 2007, the NRC identified Open Issue 2007-2 to verify that intra-batch variability, flush-water additions, and the use of additives do not adversely affect the properties of the as-emplaced saltstone grout. In addition, Open Issue 2007-2 indicated that the DOE should show that the hydraulic and chemical properties of saltstone are consistent with the assumptions in the waste determination or show that any deviations are not significant with respect to demonstrating compliance with the performance objectives. As discussed in Section 2.6 of the 2012 NRC SDF TER, the DOE conducted studies to assess saltstone grout variables, including: intra-batch

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performance objectives. Therefore, the NRC regards the DOE Base Case and the DOE Evaluation Case as serving the same purpose.

variability, salt-waste composition, effects of admixtures, organic content, liquid-to-premix[2] ratio, aluminate concentration, curing temperature, and the amount of fly ash. As discussed in more detail below, the results from several studies indicated that both the liquid-to-premix ratio and curing temperature could have a significant effect on the hydraulic conductivity of the saltstone grout.

In Sections 2.1.3 and 2.7.4.4 of the 2012 NRC SDF TER, the NRC described that the MCCs implemented in the DOE Base Case for intact and fractured cementitious materials significantly reduced modeled flow, were substantially different from literature values, and lacked adequate support based on their risk significance. Accordingly, the NRC was concerned that the dose could have been underestimated due to the reduction in modeled flow from the assumed MCCs. In Case K, the DOE assumed that the relative permeability of saltstone was 1.0 – independent of saltstone saturation (i.e., the DOE assumed a MCC that did not diminish the hydraulic conductivity from the saturated hydraulic conductivity). The NRC found that approach to be reasonable based on: (i) uncertainty in unsaturated flow through cementitious materials over long periods of time; and (ii) limited amount of reduction in flow that would be expected for cementitious materials that are predicted by the DOE to be near saturation.

With respect to diffusivity, the NRC found that the assumed initial effective diffusion coefficient[3] in the 2009 PA of $1x10^{-7}$ cm^2/s for DOE Cases A and E appeared to be reasonable, based on the information in SRNL-STI-2010-00515 (ML121020140). However, the NRC indicated in the 2012 SDF TER that the effective diffusivity of field-emplaced saltstone could differ from the laboratory-prepared simulated saltstone used in that DOE study. For Case K in the 2009 PA, the DOE assumed the initial effective diffusion coefficient of $1x10^{-7}$ cm^2/s increased log-linearly to $5x10^{-6}$ cm^2/s at 10,000 years. The value of $5x10^{-6}$ cm^2/s was justified by DOE as matching the effective diffusivity of the surrounding soil.

To address the NRC concerns related to the hydraulic performance of saltstone, the NRC identified four MFs in the 2013 SDF Monitoring Plan under Monitoring Area 3 (Waste Form Hydraulic Performance):

- MF 3.01 – “Hydraulic Conductivity of Field-Emplaced Saltstone”
- MF 3.02 – “Variability of Field-Emplaced Saltstone”
- MF 3.03 – “Applicability of Laboratory Data to Field-Emplaced Saltstone”
- MF 3.04 – “Effect of Curing Temperature on Saltstone Hydraulic Properties”

The NRC also identified one MF in MA 10 (Performance Assessment Model Revisions) related to support for MCCs that may be used in future PAs and special analyses:

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[2] The water-to-cement ratio is a parameter important to ordinary cementitious materials. Because the liquid used to form saltstone is decontaminated salt waste, and because saltstone grout contains a significant fraction of slag, the analogous quantity for saltstone is referred to as the “liquid-to-premix” ratio.

[3] Documents differ in the terminology used to describe diffusion. Section 3.3 of SRNL-STI-2010-00515 describes that SRNL refers to the effective diffusion coefficient as the free/molecular ion diffusion coefficient multiplied by the tortuosity, while SIMCO Technologies, Inc. (SIMCO) refers to that as an intrinsic diffusion coefficient. Thus, the SRNL effective diffusion coefficient is equivalent to the SIMCO intrinsic diffusion coefficient, which is only a function of the material microstructure and the properties of the dissolved radionuclides in water (e.g., ionic radius), but is not influenced by chemical reactions (e.g., sorption) between the radionuclides and the porous solid. The DOE uses the term apparent diffusion coefficient, to include the effects of tortuosity, porosity, and sorption (WSRC-STI-2006-00198). The DOE uses the SRNL terminology in the PA and both the FY 2013 and FY 2014 Special Analysis documents, which the NRC will continue to follow for consistency.

- MF 10.05 – "Moisture Characteristic Curves"

As described in the 2013 SDF Monitoring Plan, the NRC closed the Open Issues, including closing both Open Issue 2007-1 and 2007-2, because all the Open Issues were folded into the new MFs.

DOE SDF FY 2013 and FY 2014 Special Analysis Documents and Recent DOE Research

Based on recent research conducted in 2012 (SRNL-STI-2012-00558), in the Evaluation Cases for the FY 2013 and FY 2014 Special Analysis documents, the DOE revised the initial saturated hydraulic conductivity of saltstone upwards from the 2009 PA value of $2.0x10^{-9}$ cm/s to the value of $6.4x10^{-9}$ cm/s. Based on results reported in SRNL-STI-2010-00515, the DOE revised the value of the effective diffusion coefficient for intact saltstone (i.e., the initial value) from the value of $1x10^{-7}$ cm^2/s in the 2009 PA to the value of $1x10^{-8}$ cm^2/s. In the study reported in SRNL-STI-2010-00515, a value of $7.5x10^{-9}$ cm^2/s was measured for the hydroxide ion (OH^-) in a simulated non-radioactive Saltstone sample that was cured for 28 days. In the FY 2013 and FY 2014 Special Analysis documents, both the hydraulic conductivity and effective diffusion coefficient were assumed to increase linearly over time to the values of the surrounding soils (i.e., $4.1x10^{-5}$ cm/s and $5.3x10^{-6}$ cm^2/s, respectively) due to degradation. In the PORFLOW model supporting the FY 2014 Special Analysis document, the effective diffusion coefficient for saltstone reached the value of $1x10^{-7}$ cm^2/s (i.e., the value assumed in the 2009 PA) at 8,800 years after site closure.

In addition to revising the saturated hydraulic conductivity and effective diffusivity in the FY 2013 and FY 2014 Special Analysis documents, the DOE revised the MCCs for saltstone based on SRNL-STI-2011-00661. The curves varied in time to simulate degradation (SRR-CWDA-2014-00006), which will be addressed in a future NRC technical review report related to degradation of SDS cementitious materials and saltstone. This TRR only addresses the initial MCC used in the PORFLOW simulation (i.e., prior to degradation).

In the 2012 SDF TER, the NRC described a concern about saturated hydraulic conductivity measurements (SRNL-STI-2009-00184; SRNL-STI-2009-00810; SRNL-STI-2011-00665) that were higher than the values assumed in the 2009 PA. Each of those reports included hydraulic conductivity measurements significantly greater than the value assumed in the 2009 PA (i.e., 2.0×10^{-9} cm/s). Based on these results, it was not clear to the NRC that the initial saturated hydraulic conductivity value selected was justified. Similarly, as the NRC described in the report for the December 2012 OOV (ML13010A499), it was not clear why the DOE did not consider those measurements from SRNL-STI-2010-00745 to be applicable, because the samples were cured at temperatures consistent with field curing temperatures (i.e., not ambient temperature) and the samples were sealed to minimize water loss. The measurements from that study, as reported in SRNL-STI-2010-00745, were two to three orders of magnitude greater than the assumed Base Case value from the 2009 PA.

In 2015, there was a review of a series of reports related to the hydraulic conductivity of saltstone under various curing conditions (e.g., temperature, humidity, curing duration) relevant to field conditions (SRR-CWDA-2014-00118). That review concluded that a combination of rapid thermal ramping and short cure duration (i.e., 21 days) could have been responsible for the elevated hydraulic conductivities that were observed in SRNL-STI-2010-00745. The authors hypothesized that additional curing time would have resulted in additional cementitious product formation, thereby compensating for the enhanced reaction kinetics and connected pore networks associated with rapid thermal ramping. That hypothesis was supported by later research reports (VSL-13R3010-1, VSL-14R3210-1), which demonstrated lower hydraulic conductivities for samples cured for 90 days versus identically-prepared samples cured for 28 days. Two of the reports that NRC cited in the 2012 SDF TER (SRNL-STI-2009-00184; SRNL-STI-2009-00810) were based on measurements made after 28-day cure times, and therefore may not be representative of field-emplaced saltstone. The report (SRNL-STI-2011-00665) showed an increasing trend of hydraulic conductivity with cure temperature among samples cured for 90 days. However, relative humidity during curing was not controlled for those samples, which was expected to adversely affect the hydraulic conductivity and is not representative of the curing conditions for field-emplaced saltstone.

In addition, the DOE cited updated research in SRR-CWDA-2014-00118 from SREL and the Vitreous State Laboratory (VSL) at The Catholic University of America, which used realistic curing conditions (SREL Doc. R-14-0006, VSL-14R3210-1). The DOE discussed that the hydraulic conductivity values from those studies were on the order of 10^{-9} cm/s and were consistent with the assumed value of $6.4x10^{-9}$ cm/s in the Evaluation Cases for the FY 2013 and FY 2014 Special Analysis documents.

In addition to the review of laboratory research regarding saltstone hydraulic conductivity, the DOE has continued to develop technology for the collection of field-emplaced saltstone samples. As previously described, the initial DOE attempts to extract cores of emplaced saltstone yielded results that DOE indicated were unreliable because of damage done to the cores during drilling. Although the NRC previously indicated that samples taken from laboratory-prepared saltstone with the same coring method had saturated hydraulic conductivity values similar to measured values from laboratory samples prepared in molds (ML121020140), the DOE suggested that coring in the field was more damaging to the samples than coring under controlled laboratory conditions. In response to the difficulties of obtaining representative cores, the DOE developed and later attempted to use the formed coring technique.

The formed-core sampling technique was not successful because the DOE encountered difficulty in removing the formed-core device from the monolith (SRNL-STI-2012-00551). The DOE then decided to pursue a revised core-drilling approach to take samples from a field-emplaced saltstone monolith. The DOE designed a Sampling and Analyses Plan (SRR-SPT-2012-00049, Rev. 1) to determine how representative laboratory-produced samples are of field-emplaced samples (i.e., to address MF 3.03). The DOE Sampling and Analyses Plan included samples representing various combinations of laboratory and field components, processing, and curing. Therefore, if there was a difference between the results of laboratory-made and cores of field-emplaced saltstone, then the source of any deviation could be determined by evaluating the intermediate samples. The DOE Sampling and Analysis Plan was not intended to evaluate all nine sample sets initially; but, rather to compare the results of laboratory-made samples and cores from field-emplaced saltstone and to evaluate the intermediate sample sets only if there was a need to determine what aspect of the process (e.g., salt solution properties, mixing conditions, curing conditions) caused a deviation between the laboratory-made samples and cores of field-emplaced saltstone. The nine sample types are described in Table 1 below.

Table 1. Sample types created per the DOE Saltstone Sampling and Analyses Plan (reproduced from Table 1 of the DOE document SRR-SPT-2012-00049, Rev. 1.

Sample Type	Sample Set	Dry Feeds	Salt Solution	Salt Solution/Dry Feed Ratio	Grout Preparation	Grout Curing
A	*1*	Nominal 45/45/10 (FA/BFS/OPC)‡	Non-radioactive simulant based on average Tank 50 composition	Nominal w/c+ ratio 0.6	Mixed in laboratory	Ambient laboratory environment
	2	Simulated field composition	Non-radioactive simulant based on Tank 50 composition†	Simulated field composition	Mixed in laboratory	Ambient laboratory environment
	3	Simulated field composition	Non-radioactive simulant based on Tank 50 composition†	Simulated field composition	Mixed in laboratory	Simulated field curing profile in laboratory
B	*4*	Nominal 45/45/10 (FA/BFS/OPC)‡	Tank 50 salt solution	Nominal w/c+ ratio 0.6	Mixed in laboratory	Ambient laboratory environment
	5	Simulated field composition	Tank 50 salt solution	Simulated field composition	Mixed in laboratory	Ambient laboratory environment
	6	Simulated field composition	Tank 50 salt solution	Simulated field composition	Mixed in laboratory	Simulated field curing profile in laboratory
C	*7*	Processed in field	Processed in field	Processed in field	Processed in field	Ambient laboratory environment
	8	Processed in field	Processed in field	Processed in field	Processed in field	Simulated field curing profile in laboratory
D	*9*	Processed in field	Processed in field	Processed in field	Processed in field	Cured in field

‡ FA = fly ash; BFS = blast furnace slag; OPC = ordinary Portland cement

\+ w/c = water to cementitious materials ratio

† Tank 50 simulant shall be based on composition of actual Tank 50 sample utilized for Sample Sets 4-6.

As reported in SRR-CWDA-2016-00053, in April and May of 2015, the DOE collected a total of five core samples from three ports from SDS 2A (i.e., two core samples from two ports and one core sample from a third port). Lower and upper sections of one of the cores were sampled separately, resulting in a total of 18 subsamples (i.e., three from each of four of the cores and six from one of the cores). The DOE measured the physical and hydraulic properties of the SDS 2A core samples and compared them to the properties of laboratory-prepared saltstone simulant samples made with simulated salt waste with the results summarized in Tables 2 and 3 below. Saturated hydraulic conductivity measurements from six samples, which included cores from each of the ports and at several different elevations from within the saltstone monolith, ranged from <1.0×10^{-9} cm/s to 4.4×10^{-9} cm/s, with a mean of <1.6×10^{-9} cm/s. Several samples had reported saturated hydraulic conductivity values less than the method detection limit of 1.0×10^{-9} cm/s and additional testing at SREL indicated that the hydraulic conductivity values of two additional core samples were between 7×10^{-11} cm/s and 6×10^{-10} cm/s at the time the DOE document (SRR-CWDA-2016-00053) was issued. The hydraulic conductivity results for the two core samples are shown in Figure 9 in SREL Doc. R-16-0003. Generally, the hydraulic conductivity values decrease with additional pore volumes and become more stable. The DOE plans to conduct additional research to determine the cause of the changing hydraulic conductivity with time (ML16354A116; SRNL-CWDA-2016-0019).

Table 2. Density, Porosity, and Water Content (adapted from SRR-CWDA-2016-00053)

Sample ID	Approximate Pour Date and SDS[a] Height	Bulk Density [standard deviation][a] (g/cm^3)	Total Porosity [standard deviation] (%)	Permeable Porosity [standard deviation] (%)	Water Content [standard deviation] (%)
SDU2A-0931-A-1-L-5	08-12-2013 16.0 ft	1.72 [0.01]	64.3	45.0 [0.4]	29.8 [0.2]
SDU2A-0931-A-2-L-5	08-12-2013 16.0 ft	1.74 [0.00]	63.6	41.9 [0.1]	29.0 [0.2]
SDU2A-0931-B-1-L-1	08-16-13 17.0 ft	1.72 [0.01]	67.3	43.2 [0.2]	31.2 [1.2]
SDU2A-0931-C-1-L-5	08-12-2013 16.0 ft	1.76 [0.02]	64.5	42.0 [0.3]	29.1 [0.6]
SDU2A-0931-C-2-L-6	08-11-2013 15.5 ft	1.75 [0.04]	66.6	43.3 [1.4]	30.5 [0.9]
SDU2A-0931-C-2-L-8	08-10-2013 15.0 ft	1.71 [0.06]	68.8	46.6 [2.1]	32.1 [0.1]
Mean (SDS 2A)		**1.73 [0.03]**[b]	**65.8 [2.0]**	**43.7 [1.8]**	**30.3 [1.2]**
Mean (Laboratory)		**1.76 [0.01]**[c]	**59.8 [0.8]** [c]	**40.8 [0.7]** [c]	**30.4 [0.1]** [c]

[a] mean and standard deviation of three subsamples, except where noted
[b] mean and standard deviation of 18 subsamples (3 subsamples from 4 cores and 6 subsamples from core SDU2A-0931-C-2-L).
[c] mean and standard deviation of nine subsamples (three subsamples from each of three laboratory-prepared samples).

Table 3. Saturated Hydraulic Conductivity (adapted from SRR-CWDA-2016-00053)

Sample ID	Approximate Pour Date and SDS Height	Saturated Hydraulic Conductivity (cm/s)	Comments on Sample Integrity
SDU2A-0931-A-1-L-3	08-14-2013 16.5 ft	$1.2x10^{-9}$	Side defects that could not be excluded when sample sectioned to 2" length
SDU2A-0931-A-2-L-2	08-16-2013 17.0 ft	$<1.0x10^{-9}$	No observable surface defects
SDU2A-0931-B-1-L-2	08-14-2013 16.5 ft	$4.4x10^{-9}$	Difficult to section without fracturing
SDU2A-0931-C-1-L-2	08-16-2013 17.0 ft	$<1.0x10^{-9}$	No observable surface defects
SDU2A-0931-C-2-L-1	08-16-2013 17.0 ft	$<1.0x10^{-9}$	No observable surface defects
SDU2A-0931-C-2-L-5	08-11-2013 15.5 ft	$<1.0x10^{-9}$	No observable surface defects
Mean (SDS 2A)		**$<1.6x10^{-9}$**	4 of 6 samples with no visible surface defects
Mean (Laboratory)		**$<1.0x10^{-9}$**	Demolded samples without surface defects

As reported in SREL Doc. R-16-0003, following U.S. Environmental Protection (EPA) Method 1315, SREL measured the release rate of several constituents from three core samples, which had been cured for approximately 20 months in SDS 2A with the results in Table 4 below. The authors determined that the release was consistent with a diffusion-controlled mechanism and reflected a combination of both chemical and physical transport properties.

Table 4. Summary of Apparent[4] Diffusivities (adapted from SREL Doc. R-16-0003)

Sample ID	NO_3^-	^{99}Tc	^{137}Cs	^{129}I
SDU-A (SDU2A-0931-C-1-U-2)	$1.3x10^{-8}$	$6.4x10^{-11}$	$4.2x10^{-10}$	TBD[a]
SDU-B (SDU2A-0931-C-1-U-5)	$4.4x10^{-9}$	$5.8x10^{-11}$	$1.1x10^{-10}$	TBD[a]
SDU-C (SDU2A-0931-C-2-U-2)	$5.5x10^{-9}$	$5.2x10^{-11}$	$4.9x10^{-10}$	TBD[a]
[a] I-129 data is pending analysis				

NRC Evaluation

In the 2013 SDF Monitoring Plan, the NRC was primarily concerned with saltstone saturated hydraulic conductivity and diffusivity because the NRC based its conclusions in the 2012 TER on the DOE Case K, which assumed the degree of saturation did not affect the hydraulic conductivity (i.e., the MCC is such that the relative permeability has a value of 1 at all saturations). The DOE included revised MCCs in the FY 2013 and FY 2014 Special Analysis

[4] In SREL Doc. R-16-0003, those values were referred to as effective diffusivities. For consistency with the SRNL terminology (see Footnote 3), those values are referred to as apparent diffusivities in this TRR because they include both chemical and physical transport properties.

documents. Because the NRC had anticipated that the MCCs would not be revised until the DOE revised its 2009 PA, the MF for the MCCs was included in the 2013 SDF Monitoring Plan under MA 10, “Performance Assessment Model Revisions” in MF 10.05 *“Moisture Characteristic Curves”*. However, because the MCCs are directly relevant to saltstone hydraulic performance and were revised by DOE in the FY 2013 and FY 2014 Special Analysis documents, the MCCs are discussed in this TRR.

The Evaluation Cases in both the FY 2013 and FY 2014 Special Analysis documents assumed the initial hydraulic conductivity of saltstone to be 6.4×10^{-9} cm/s with an effective diffusion coefficient of 1×10^{-8} cm^2/s, which are representative of an intact matrix. The DOE assumed that degradation of the saltstone does not occur until the complete degradation of the roofs of the disposal structures. This includes the time since placement of the saltstone in the disposal structures. As the NRC described in Section 2.6.4.2 of the 2012 SDF TER, that assumption was inconsistent with observations of cracks in SDS 4 saltstone, which occurred prior to closure (SRNL-ESB-2008-00017, SRR-CWDA-2011-00105). The NRC concern of additional degradation mechanisms affecting hydraulic properties (e.g., shrinkage cracking, settlement) is ultimately related to degradation, is a separate MF under MA 4 (Waste Form Physical Degradation), and is not a basis to hold open any MFs under MA 3. A separate TRR will address the NRC concerns related to MA 4.

Diffusivity of saltstone is discussed in this section because it is addressed generally under MA 3 in the 2013 SDF Monitoring Plan, although it is not addressed specifically as a MF. The revised effective diffusion coefficient of 1×10^{-8} cm^2/s in the FY 2013 and FY 2014 Special Analysis documents was based on laboratory measurements for a simulated non-radioactive saltstone simulant cured for 28 days (SRNL-STI-2010-00515). Diffusivity tests were also conducted on additional simulated saltstone samples prepared at SREL and on three saltstone core samples taken from SDS 2A (SREL Doc. R-16-0003). For the simulant samples, which were cured for 6 months, the effective diffusivity for nitrate[5] from two tests averaged 1.6×10^{-8} cm^2/s (SREL Doc. R-15-0003). For the three SDS 2A core samples, the nitrate results ranged from 4.4×10^{-9} cm^2/s to 1.3×10^{-8} cm^2/s as shown in Table 3 above. The effective diffusion coefficient is then coupled with radionuclide-specific sorption coefficients to allow the DOE to model the transport of individual radionuclides, such as Tc-99.

SREL conducted the diffusivity experiments on the simulated and SDS 2A samples according to EPA Method 1315 and used the calculation outlined in American National Standards Institute/American Nuclear Society (ANSI/ANS) 16.1 to calculate diffusivity. The NRC verified that the calculation of diffusivity for Tc-99 and Cesium (Cs)-137 using EPA Method 1315 and ANSI/ANS 16.1 produced the same results. The concentration data for nitrate, which were assumed to reflect a diffusional release and were used to develop an effective diffusion coefficient, were not provided in the report (SREL Doc. R-15-0003). However, NRC verified the diffusivity values calculated for Tc-99 and Cs-137 using the same method that was used for nitrate.

Based on the test results from carefully controlled saltstone simulants and actual saltstone samples from SDS 2A, the NRC determined that the assumed initial diffusivity values are well supported and are therefore reasonable.

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[5] The “effective diffusion coefficient” in the SREL report includes the effects of porosity, tortuosity, sorption, and dissolution. As described in WSRC-STI-2006-00198, that value would be characterized as an apparent diffusion coefficient. However, for nitrate the effects of sorption and dissolution should not be significant. Accordingly, the effective and apparent diffusion coefficients for nitrate should be equivalent.

MF 3.01 – "Hydraulic Conductivity of Field-Emplaced Saltstone"

In Case A in the 2009 PA and in the Evaluation Cases for the FY 2013 and FY 2014 Saltstone Special Analysis documents, the DOE relied on measurements of laboratory-prepared samples to support the assumed initial hydraulic conductivity of saltstone. Although the initial hydraulic conductivity value was based on realistic conditions (e.g., realistic curing temperatures and humidity, inclusion of admixtures) (SRNL-STI-2012-00558), there is still uncertainty inherent in relying on laboratory samples instead of field-emplaced samples. This is described in more detail in MF 3.03 below.

Prior to 2015, the only available field data were those obtained from SDS 4 Cell E, which yielded hydraulic conductivity values that were two orders of magnitude greater than the Case A value in the 2009 PA. As previously described, when the NRC issued the 2012 SDF TER, it was not clear to the NRC whether the field-coring technique was responsible for the discrepancy between laboratory-prepared and field-emplaced saltstone, as the DOE had hypothesized. Based on the details below, the NRC has now determined that the assumed initial hydraulic conductivity value of saltstone in the FY 2013 and FY 2014 Special Analysis documents is adequately supported.

Measurements of the SDS 2A core samples provided the most compelling support for the initial saturated hydraulic conductivity of field-emplaced saltstone. Those measurements showed that all of the core samples had hydraulic conductivity values less than the assumed value of 6.4×10^{-9} cm/s from the FY 2013 and FY 2014 Saltstone Special Analysis documents. That included the six core samples tested at SRNL and the two core samples tested at SREL. Both tests used at SRNL and at SREL used a falling head permeameter. The results are reported for when the hydraulic conductivity values of the samples approached steady state conditions, which is consistent with the American Society for Testing and Materials (ASTM) method ASTM-D5084-10. However, it is not clear if the change in hydraulic conductivity with pore volumes shown in the SREL data in Figure 9 of SREL Doc. R-16-0003 is due to mineralogical changes occurring in the core samples (ML16354A116) or sample equilibration. Although there is not sufficient information currently available to discern whether the change in hydraulic conductivity was due to normal sample equilibration or from secondary mineral formation, the NRC determined that the data from those core samples can still be used to support the DOE-assumed initial hydraulic conductivity value for the following reasons:

- The initial saturated hydraulic conductivity of the two SDS 2A core samples in Figure 9 (SREL Doc. R-16-0003) at the start of the test was approximately 2×10^{-9} cm/s and 1×10^{-8} cm/s, which is in the range of the DOE-assumed initial hydraulic conductivity of saltstone of 6.4×10^{-9} cm/s.

- Any mineralogical changes that occurred during the test are reasonably expected to occur under field conditions (i.e., any mineralogical changes that may have occurred are not likely to be an experimental artifact).

- The DOE provided sensitivity cases that provide insight into the effects of higher initial saltstone hydraulic conductivity values.

- The DOE is planning on conducting additional research in FY 2017 to help resolve the cause of apparent change in hydraulic conductivity with pore volumes passed through the samples.

In addition to the direct evidence of the hydraulic conductivity of saltstone from the recent research with core samples, the DOE conducted additional studies and analyses to support the assumed hydraulic conductivity value. Recent laboratory studies from VSL and SREL (VSL-14R3210-1, SREL Doc. R-14-0007), which yielded hydraulic conductivity values that were consistent with the assumed values in the FY 2013 and FY 2014 Special Analysis documents, were conducted under more realistic curing conditions than the previous research studies. Lastly, the NRC determined that the analysis in SRR-CWDA-2014-00118, described above, provided a reasonable explanation for anomalously high saturated hydraulic conductivity values observed in earlier studies, such as SRNL-STI-2010-00745.

The 2013 SDF Monitoring Plan includes the following:

> *NRC expects to close MF 3.01 (Hydraulic Conductivity of Field-Emplaced Saltstone) under [10 CFR Part 61 Performance Objective (PO)] §61.41 after NRC determines that model support for the saturated hydraulic conductivity of field-emplaced saltstone is sufficient.*

and

> *NRC expects to close MF 3.01 (Hydraulic Conductivity of Field-Emplaced Saltstone) under PO §61.42 after NRC determines that model support for the saturated hydraulic conductivity of field-emplaced saltstone is sufficient.*

Based on the above information, the PAB staff recommends closing MF 3.01 under both PO §61.41 and PO §61.42.

MF 3.02 – "Variability of Field-Emplaced Saltstone"

MF 3.02 focuses on the variability in the hydraulic properties of saltstone. Variations can result from changes in process feeds (e.g., dry feed component percentages, dry feed sources and storage conditions, salt waste composition, liquid-to-premix ratio) or saltstone production, emplacement, and curing processes (e.g., method of mixing, method of emplacement, flush water volume used, curing conditions).

Measured properties of the core samples from SDS 2A (SRR-CWDA-2016-00053) provide direct evidence of some types of variability in field-emplaced saltstone. Sample density, porosity, permeable porosity, and water content are all related to the hydraulic properties of saltstone. As shown in Table 2 above, measurements from different cores were generally within a few percent of the mean of the measurements from all of the SDS 2A cores. As shown in Table 3 above, the variability in the measured saturated hydraulic conductivity was more difficult to determine because many of the samples had saturated hydraulic conductivity values less than the limit of detection. However, all of the emplaced saltstone samples had measured saturated hydraulic conductivity values that were lower than the value assumed in the FY 2014 Special Analysis document, which was 6.4×10^{-9} cm/s. Diffusivity data was provided in report SREL Doc. R-16-0003 for three saltstone core samples. For nitrate, which should not be affected by solubility or sorption, the three diffusivity measurements ranged from 4.4×10^{-9} to 1.3×10^{-8} cm^2/s.

Potential sources of saltstone variability within the SDF that were not represented in measurements taken of the SDS 2A core samples include: (1) differences between saltstone emplacement in the 150-ft and 375-ft disposal structures, such as thinner lifts and increased drop height in the 375-ft structures, (2) effects at lift boundaries, which were avoided in the sub-samples used for measurements in the core sample report, and (3) potential future changes to saltstone additives, premix ingredients, or salt waste characteristics. Those additional sources of variability and studies done to address them are discussed below.

Process Feeds

As described in Section 2.6.4.1 of the 2012 SDF TER, the NRC determined that the DOE had an adequate quality assurance program for verifying that the dry bulk grout materials conform to applicable ASTM standards. The NRC described a DOE study of batch-to-batch variability in the fraction of dry feeds supplied to saltstone and determined that the DOE had adequate control of the dry feeds to the SPF. The NRC also described additional potential sources of variation in saltstone performance due to variability in the treated salt solution from batch to batch (e.g., aluminate concentrations) or changes in saltstone processing (e.g., addition of anti-foaming agents).

The DOE Unresolved Waste Management Question Evaluation (UWMQE) process was designed to evaluate the potential effects of changes in saltstone processing. The UWMQE process is described in more detail in the DOE's *Unreviewed Waste Management Question (UWMQ) Requirements Document for Saltstone Facility* (SRR-CWDA-2011-00196). In that report, three of the screening criteria are directly related to the hydraulic performance of saltstone: (1) dry feeds nominal premix ratios remain unchanged, (2) nominal cementitious material ratio (0.6 water to premix) for saltstone is not increased, (3) SPF will receive and mix the salt solution with cement, fly ash, and slag to form a homogeneous grout mixture or slurry. The DOE recently conducted a UWMQE on the effect of adding process water flushes into the mixer discharge (SRR-UWMQE-2016-00002), as the proposed activity exceeded the aforementioned nominal cementitious material ratio screening criteria. In that UWMQE, the DOE determined that the additional flush water would increase the effective water-to-premix ratio from 0.612 to 0.616, which is within the acceptable range of values (i.e., 0.59 to 0.64) (SRR-UWMQE-2016-00002; SRR-CWDA-2014-00006). The NRC staff agrees that the proposed process change does not significantly increase the water-to-premix ratio.

In addition, other process changes can indirectly affect hydraulic properties. For example, DOE recently completed a UWMQE document addressing the effects of changes in slag vendor and grade. In that UWMQE, the DOE explicitly addressed changes in heat production because of the importance of curing temperature (SRR-CWDA-2015-00088; SRR-CWDA-2015-00057). The NRC reviewed the UWMQE and supporting references as part of its normal monitoring activities (ML16147A197). In that review, the NRC described several studies that DOE conducted to evaluate the effects of other variables, such as curing temperatures, liquid-to-premix ratios, aluminate concentrations in salt waste, and the presence of admixtures. Based on those studies, the NRC determined that the DOE identified the types of variables that would be expected to influence saltstone performance (e.g., any variable affecting heat generation or liquid-to-premix ratio). The NRC monitors changes in those types of significant process variables as part of its normal monitoring activities at the SDF. Significant changes in treated salt waste composition are specifically mentioned in Table 1-2 of the 2013 SDF Monitoring Plan as events about which the DOE should keep the NRC informed.

Differences between Emplacement in the 150-ft and 375-ft Disposal Structures

Because all of the core samples were taken from a 150-ft disposal structure, the evaluation of saltstone variability at the SDF must also consider potential sources of variation between saltstone in a 150-ft disposal structure and in a 375-ft disposal structure. The DOE expects that saltstone in a 375-ft disposal structures will be placed in thinner lifts than saltstone in a 150-ft disposal structures (SRNL-STI-2012-00522). In addition, saltstone emplaced in a 150-ft disposal structure is expected to experience different ranges of drop height during emplacement and horizontal travel distances before the saltstone sets compared to saltstone emplaced in a 375-ft disposal structure.

The main effects of the thinner lifts are expected to be decreased curing temperature and effects due to the increased frequency of lift boundaries. The effects of lift boundaries also could cause saltstone variability within a disposal structure, as described below. Based on thermocouple data from saltstone emplaced in SDS 2B (SRR-CWDA-2013-00012), the NRC determined that the DOE evaluated the variations in curing temperature that occur during saltstone emplacement in a 150-ft disposal structure. The NRC expects that the curing temperatures in a 150-ft disposal structure should bound the peak curing temperatures in the 375-ft disposal structure if the same saltstone formulation is used because heat will dissipate more quickly from a thinner lift. Therefore, the effects of the thinner lifts on curing temperature are not expected to degrade saltstone performance in a 375-ft disposal structure more than saltstone emplaced in a 150-ft disposal structure. The NRC expects that the DOE would evaluate any other variables affecting cure temperature (e.g., change in the dry premix components) through the UWMQE process.

Saltstone emplaced in a 375-ft disposal structure could experience a greater range of drop heights than saltstone emplaced in a 150-ft disposal structure. A 150-ft disposal structure has an interior height of 6.7 m (22 ft) whereas a 375-ft disposal structure has an interior height of 13.1 m (43 ft). The DOE has not performed physical experiments with saltstone grout to study the effects of that difference in drop heights. However, the DOE used fluid dynamics modeling to project the effects of increased drop height on saltstone properties (SRNL-STI-2012-00454). That report indicated that the modeling results should be considered “preliminary scoping analyses” because they had not been benchmarked with physical experiments. The models projected that increasing the drop height from 1.5 m to 13.1 m (5 feet to 43 feet) would not affect the amount of air entrained in the grout, which could affect the grout porosity and hydraulic properties, for pouring times of 30 minutes or longer.

Although the DOE has not performed physical experiments with saltstone grout to study the effects of drop height on saltstone performance, the DOE studied the effects of drop height on the properties of the grout used to fill the waste tanks (RPT-5539-EG-0016). Tank fill grout differs from saltstone grout in significant ways, including the liquid-to-premix ratio and the inclusion of aggregate, so the applicability of that report to saltstone grout is uncertain. In that study, the DOE evaluated the difference between samples dropped 12.8 m (42 ft) in free fall, and grout dropped the same distance but dropped through a tremie (i.e., a tube used to convey grout) that terminated 1.5 m (5 ft) above an unyielding surface. The DOE evaluated the effects of drop height on hydraulic conductivity, compressive strength, and aggregate segregation.

In that study, the results of the hydraulic conductivity measurements were complicated by drilling artifacts, different aging times after drilling, and different lateral distances from the grout drop impact area. In samples of grout dropped either with or without a tremie, DOE observed higher hydraulic conductivities in samples measured shortly after drilling than they did in samples stored in a moist environment from 90 days to 126 days after drilling. The DOE attributed that effect to self-healing of damage caused by drilling. Samples measured shortly after drilling also showed a significant (i.e., one to two orders of magnitude) increase in hydraulic conductivity as the lateral distance from the impact area increased from 0.30 m to 2.7 m (1 ft to 9 ft). However, for both drop heights, if samples were allowed to self-heal after drilling, that effect was no longer seen. The NRC determined that the result most applicable to saltstone was that, if the samples were allowed to self-heal in a moist environment after drilling for 90 days or 126 days, then the hydraulic conductivity of samples of grout dropped entirely in free fall was not significantly different from the hydraulic conductivity of the samples of grout dropped through a tremie.

The results for the compressive strength tests showed that after 28 days of curing, samples of grout dropped without a tremie had slightly higher compressive strength than samples dropped through a tremie. Results for grout dropped either with or without a tremie showed a trend of decreasing compressive strength as the lateral distance from the impact area increased from 0.30 m to 2.7 m (1 ft to 9 ft). The DOE determined that all samples met the compressive strength requirements for tank fill grout.

The NRC determined that the potential concern about aggregate segregation is not expected to be applicable to saltstone because there is no aggregate in saltstone. Therefore, results related to aggregate segregation are not further discussed in this TRR.

In addition to the larger range of drop heights, grout also could potentially have a longer radial flow distance in a 375-ft disposal structure compared to a 150-ft disposal structure because of the larger radius of a 375-ft disposal structure. Experiments with a variety of grout formulations (SRNL-L3100-2012-00161) provided evidence that long-radius pours did not produce low quality grout. The DOE indicated that grout representative of saltstone flowed 29 m (95 feet) and that pour locations in SDS 6 would be located so that the pour radius would be 24 m (80 feet) or less. That distance is very similar to the 23 m (75 ft) maximum flow distance in a 150-ft disposal structure (i.e., the radius of a disposal structure with grout poured through a central port (WB00001K-004)). Based on that information, the NRC determined that increased flow distance in a 375-ft disposal structure compared to a 150-ft disposal structure is not expected to affect saltstone variability at the SDF.

Based on the above information, the NRC determined that geometrical differences between a 150-ft disposal structure and a 375-ft disposal structure, including thinner saltstone lifts, increased drop height, and different saltstone pouring locations, are unlikely to cause significant variability in saltstone performance.

Effects at Lift Boundaries: Cold Joints

Joints between lifts (i.e., cold joints) could cause variation in saltstone properties within a disposal structure because of drying and oxidation of exposed surfaces, as well as salt deposition on exposed surfaces. Oxidation at exposed surfaces could affect saltstone chemical performance, but is not expected to cause variability in hydraulic properties, and will be addressed in a future TRR. Cold joints could potentially cause differences between saltstone performance in a 150-ft disposal structure compared to a 375-ft disposal structure because of the thinner lifts and relatively larger number of cold joints in a 375-ft disposal structure. To address the potential effects of cold joints on saturated hydraulic conductivity, the DOE studied the effects using laboratory samples. The DOE prepared samples with varying numbers of lifts and cured them for 28 days. The DOE created 7.5-cm (3-inch(in)) diameter, 15-cm (6-in) long cylindrical samples, with lifts ranging from 1.3 cm to 15 cm (0.5 in to 6 in) thick, resulting in samples ranging from monoliths (i.e., samples with no cold joints) to samples made with 12 lifts (i.e., 11 joints) (SRNL-STI-2012-00522). The DOE tested the effect of the number of joints on the hydraulic conductivity of samples and tested the effects of the orientation of the joints with respect to flow direction on sample hydraulic conductivity. In that study (SRNL-STI-2012-00522), the DOE observed no trend in hydraulic conductivity as a function of the number of joints for samples with a flow direction perpendicular to the joints. However, the DOE determined that samples made with joints parallel to the direction of flow showed increased hydraulic conductivity with an increasing number of joints. The direction of water flow through saltstone is expected to be primarily vertical (i.e., perpendicular to the lift boundaries) (SRR-CWDA-2016-00060). Therefore, the physical experiments documented in SRNL-STI-2012-00522 support the DOE determination that cold joints will not significantly affect saltstone hydraulic performance.

The modeling results in the DOE response to the NRC RAI Question SP-1 on the FY 2014 Special Analysis document provide another line of evidence supporting the determination that cold joints are not expected to have a significant effect on flow through saltstone. The DOE evaluated the effect of considering degradation as a progressing front instead of a homogeneous increase in saltstone hydraulic conductivity, as was modeled in the FY 2014 Special Analysis document Evaluation Case. Although the DOE response to RAI Question SP-1 was developed to respond to an NRC concern about modeling decalcification, the fundamental nature of the issue as a horizontal layer with potentially increased conductivity could be applicable to the consideration of cold joints as well.

The DOE response to RAI Question SP-1 included the following statement:

> *With respect to a more spatially rigorous simulation of radionuclide migration in a nonlinear two-layered system, water entering the saltstone from above would be diverted from vertical flow to horizontal flow, allowing mass to bleed out the sides of the [saltstone disposal structure], which would be expected to reduce the rate of decalcification and slow releases relative to the Evaluation Case (which is dominated by vertical/downward flow and release). However, the horizontal release mechanism would tend to provide earlier releases (at lower magnitudes) which are spread out over time, thus providing results that are similar to those represented by the mass-transfer model described in Section 5.6.6.2 of the [FY 2014 Special Analysis document].*

Based on the experiments described in SRNL-STI-2012-00522, which demonstrated that cold joints have little effect on water flow perpendicular to the joints, the NRC determined that cold joints are not expected to cause significant variability in saltstone hydraulic performance. The modeling results described in the DOE response to RAI Question SP-1 also support that determination that cold joints are not anticipated to have significant adverse effects on saltstone hydraulic performance.

Effects at Lift Boundaries: Flush Water Addition

Saltstone at lift boundaries experiences more flush-water addition than saltstone in the interior of the lift. Ordinary cementitious materials are sensitive to the water-to-cement ratio. Because saltstone is made with treated liquid salt waste, the analogous property in saltstone is called the liquid-to-premix ratio. Because of the sensitivity of properties of cementitious material to the water-to-cement ratio, the NRC monitors the liquid-to-premix ratio of saltstone. As discussed during a 2008 NRC OOV to the SDF (ML081290367), actual liquid-to-premix ratios in saltstone may vary in part because of the addition of flush water to the disposal structures, introducing an additional source of variability into emplaced saltstone.

The NRC reiterated that concern in RAI Comment SP-6 on the FY 2013 Special Analysis document. In the DOE response to RAI Comment SP-6, the DOE described that flush water is added to both the dry feeds hopper and the grout mixer. Two different types of additions are made to the hopper: (1) small periodic additions during saltstone production (~60 gallons every 30 minutes); and (2) larger volumes of water (~600-900 gallons) at the beginning and end of production for the day. A large volume of water (~200-300 gallons) also is added to the mixer at the start and end of production for the day (see Figure 1 below). The DOE described that while the smaller flushes added to the hopper during production are expected to be incorporated into saltstone, a significant fraction of water added to the hopper and mixer at the beginning and end of the production runs is expected to exit the disposal structure through the drain system.

In addition, the DOE analyzed water additions to the SPF hopper and mixer as well as subsequent withdrawals of water from the drain system. From that analysis, the DOE determined that during the time period analyzed, which covered two production days, a total of 3,810 gallons was added to the hopper and mixer (combined), of which 2,160 gallons (56%) remained in the disposal structure and 1,650 gallons (44%) exited through the drain system. The data do not differentiate between the water added during processing and the larger volume of water added at the end of the day of processing.

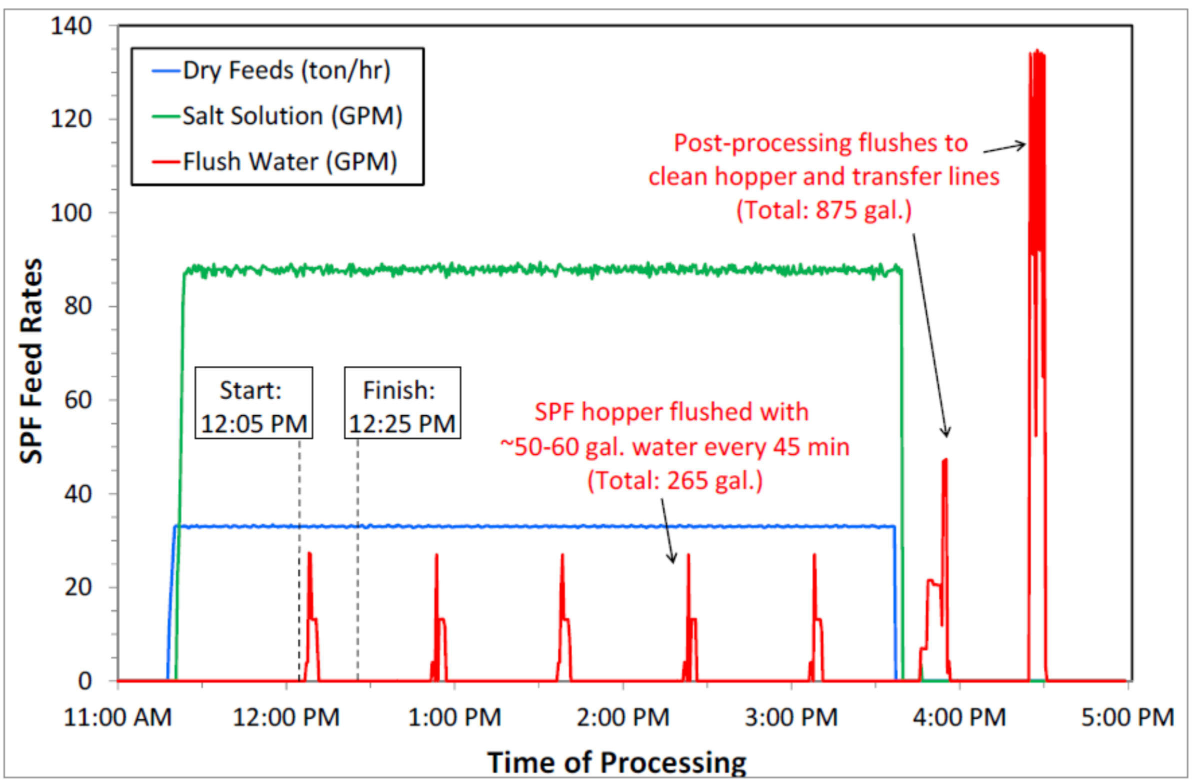

Figure 1. Feed Rates for Saltstone Processed on 8/12/2013 (reproduced from Figure 5.1 in SRR-CWDA-2016-00051)

The DOE also provided data showing that an increase in liquid-to-premix ratio from 0.59 to 0.73 appeared to cause: (1) increased saltstone porosity (from 63.8 to 66.1) and (2) increased hydraulic conductivity (from 2.9×10^{-9} cm/s to 8.5×10^{-9} cm/s) (SRR-CWDA-2014-00099). However, the DOE did not present evidence that the liquid-to-premix ratio in emplaced saltstone would be limited to 0.73. As shown in Figure 2 below, the DOE expected flush water to cause temporary excursions of the liquid-to-premix ratio that could be significantly greater than 0.73. Although Figure 2 below shows excursions as high as 1.8, the limit of the liquid-to-premix ratios in emplaced saltstone is expected to be less than that value because a significant fraction of the flush water is removed through the drain system instead of being incorporated into saltstone. The precise values are not known because, although the DOE understands generally how much flush water is incorporated into saltstone from analyzing flush water additions and water removed from the drainage system, it is unclear how much saltstone the water is incorporated into.

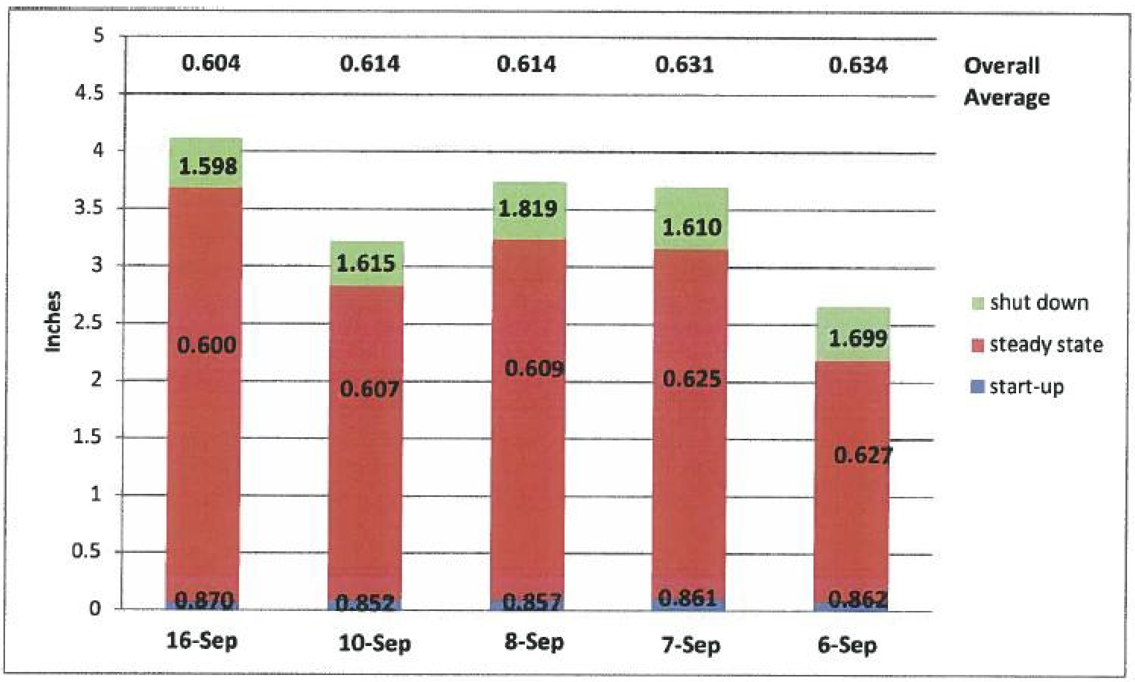

Figure 2. DOE estimated upper bounds of liquid-to-premix ratio during several days of processing including the effects of flush-water additions (reproduced from Figure 4.2-2 in the FY 2013 Special Analyis document).

Some evidence of the effects of flush water additions on saltstone properties is provided by data from the core samples taken from SDS 2A. In recent reports (SRR-CWDA-2016-00051; SRNL-STI-2016-00106), the DOE compared three types of samples that had different flush-water additions: (1) samples made in the laboratory with simulated salt waste (see Table 1, Set 3 above), (2) samples processed in the field and cured in the laboratory (see Table 1, Set 8 above), and (3) cores from emplaced saltstone (see Table 1, Set 9 above). Samples made in the laboratory (see Table 1, Set 3 above) contain no flush water. For samples processed in the field and cured in the laboratory (see Table 1, Set 8 above), two samples were taken. The dashed vertical lines in Figure 1 above show the window in which the samples were taken relative to the flush water additions. However, in the report SRR-CWDA-2016-00051, the DOE indicated that it was unclear precisely when during the sampling window the two samples were taken. Therefore, it was not clear to the NRC how much the flush additions affected the samples. The DOE indicated that the mean density and permeable porosity of that sample set was equivalent to the mean density and permeable porosity of the samples prepared in the laboratory. The DOE hypothesized that may mean the samples were not collected during the flush water additions.

The third sample group consisted of cores taken from SDS 2A (see Table 1, Set 9 above). As shown in Table 2 above, the SDS 2A core samples had lower densities, higher porosities, and higher permeable porosities than the laboratory-produced samples. Those data are consistent with the anticipated effects of a higher liquid-to-premix ratio. Those properties also could be explained by higher saturated hydraulic conductivity. However, as shown in Table 3 above, because many of the hydraulic conductivity measurements for all of the sample groups were below the lower limit of detection, it is difficult for the NRC to determine whether the core samples did have higher hydraulic conductivities than the other two sample groups without further testing.

The SDS 2A cores include the smaller flush water made during processing. However, it is not clear to the NRC how much the cores reflect the larger flush-water additions that occurred at the beginning and end of a processing day. SDS 2A cores included grout poured during multiple processing days between August 10 and 16, 2013, representing multiple lifts. As shown in Figure 2 above, samples used for density, porosity, and water content included sample boundaries that could include lift boundaries, while samples taken for saturated hydraulic conductivity measurements and Tc leaching were taken from sample interiors. The sample interiors were not expected to include lift boundaries because (1) core samples often separated at lift boundaries and (2) sample boundaries were chosen to correspond to the beginning and end of daily pours (SRNL-STI-2016-00106). Samples used for density, porosity, and water content measurements were taken from the ends of core samples, which were then broken into 2 to 25 gram sub-samples with a hammer. Thus, it is likely, although not certain to the NRC, that some of the sub-samples measured for density, porosity, and water content represented the larger flush-water additions at the beginning and end of the processing day.

Although the amount of water added during post-processing was larger than the amount of flush water added during grout emplacement, the effect on saltstone properties was not likely to increase linearly with the volume of flush water added because a significant fraction of the post-processing water probably left the disposal structure immediately through the drain water system without being incorporated into the grout. In addition, some of the water that was initially taken up by the saltstone may subsequently bleed from the grout during initial curing and exit the system through the drain water system.

Saturated hydraulic conductivity measurements were taken of samples cut from core interiors (see Figure 3 below) to avoid artifacts of core drilling. That approach was necessary because of the difficulty of field-drilling cores. The DOE indicated that, although the density and porosity of the SDS 2A core samples varied from the density and porosity of the laboratory-prepared samples, the difference was not of practical importance because there was not a significant difference between the measured saturated hydraulic conductivities of the SDS 2A cores and that of laboratory-prepared samples. That could occur if the samples' densities and porosities did not change enough to significantly affect the saturated hydraulic conductivity. Another possible explanation could be that, because many of the samples had a hydraulic conductivity below the detection limit, the experiment could not detect the difference between the SDS 2A cores and laboratory-prepared samples. A third possible explanation could be that, because the density and porosity were measured in sub-samples taken from the sample ends and the saturated hydraulic conductivity was measured in sub-samples taken from sample interiors, the density and porosity measurements reflected the effects of flush-water addition while the saturated hydraulic conductivity measurements did not.

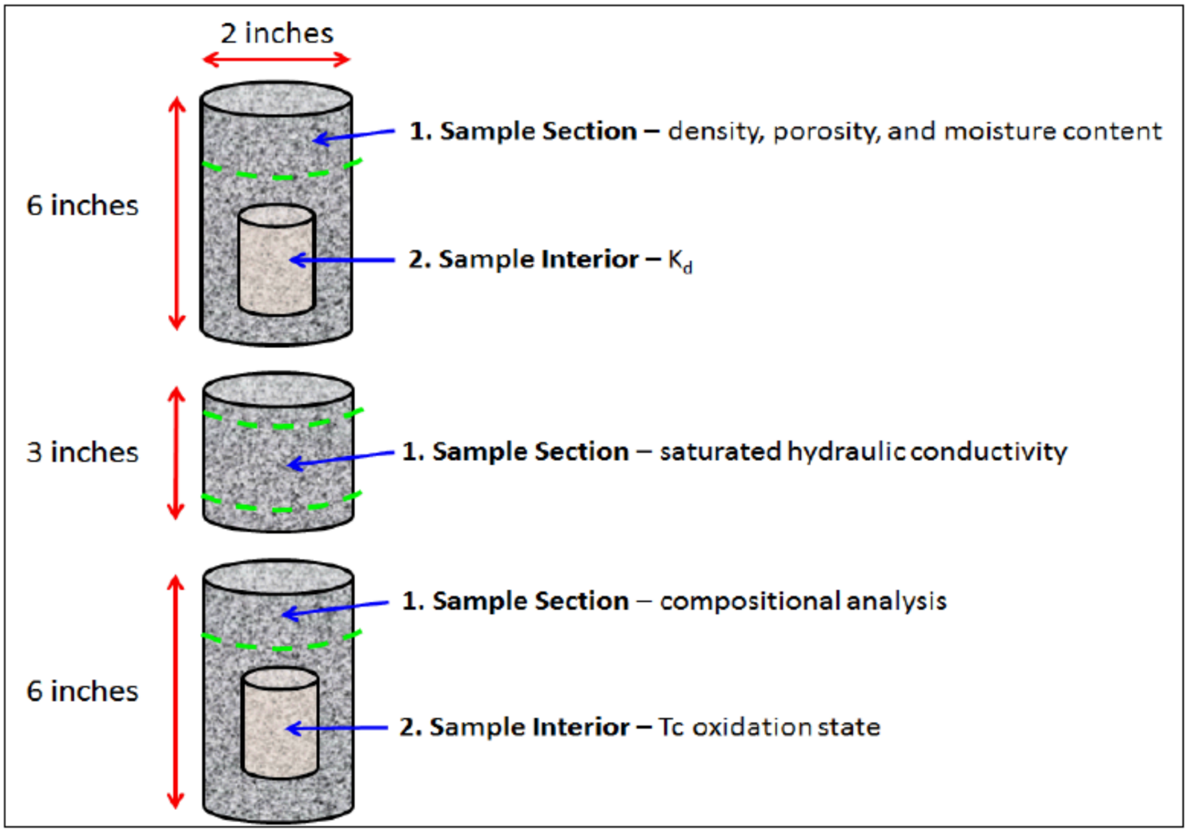

Figure 3. DOE plan for cutting sub-samples from the SDS 2A cores. The DOE indicated that section lengths were approximated and based on estimated depths of daily pours to SDS 2A between August 11-16, 2013 (from Figure 2-1 in SRNL-STI-2016-00106).

The third possible explanation would imply that bands of lower-density, higher-porosity, and potentially higher-saturated hydraulic conductivity saltstone at lift boundaries were not represented by the SDS 2A core data. In the DOE response to RAI Comment SP-6 of the NRC RAI on the DOE FY2013 Special Analysis, DOE indicated that saltstone affected by flush water " … potentially forms thin, discrete horizontal sections that are separated by thicker saltstone sections with the desired [water-to-cement] ratio of 0.6 …" (SRR-CWDA-2014-00099). The DOE indicated that the measured hydraulic conductivity of samples with a liquid-to-premix ratio of 0.59 was 2.9×10^{-9} cm/sec (SRNL-STI-2012-00558). That value was lower than the value assumed in the Evaluation Case of the FY 2014 Special Analysis document, which was 6.4×10^{-9} cm/sec. The DOE qualitatively claimed that the higher hydraulic conductivity assumed in the FY 2014 Special Analysis document helped to account for bands of higher hydraulic-conductivity saltstone. The NRC estimated the resulting effective hydraulic conductivity for a hypothetical system containing alternating horizontal layers of saltstone with nominal characteristics and saltstone with higher porosity and higher hydraulic conductivity. The NRC used a weighted harmonic average, which has been used widely to estimate an effective hydraulic conductivity perpendicular to layers with differing hydraulic conductivity. Specifically, the NRC used the following equation:

$$K_{H_{effective}} = \frac{\sum_1^n b_i}{\sum_1^n \frac{b_i}{K_{H,i}}}$$

where $K_{H,i}$ is the hydraulic conductivity of horizontal layer i and b_i is the thickness of horizontal layer i. For this screening calculation, a range of thicknesses was considered. First, the layer thicknesses were estimated based on the layer thicknesses in Figure 2. In this calculation, the layer with the intended liquid-to-premix ratio was estimated to be 250 cm thick and the layer affected by flush water additions was estimated to be 60 cm thick. A hypothetical hydraulic conductivity of 1.6×10^{-9} cm/s was used to represent saltstone in the interior of lifts to be consistent with the value used in the FY 2014 Special Analysis document. An extreme value of 1×10^{-6} cm/s for saltstone at lift boundaries was used to bound the effects of large flush-water additions. Based on these assumptions, adding a layer affected by flush water additions only increased the effective vertical hydraulic conductivity by a factor of 1.3. Using hydraulic conductivity values in the range of 1×10^{-12} cm/s to 1×10^{-8} cm/s to represent the hydraulic conductivity of the layers with the intended liquid-to-premix ratio did not appreciably affect the results.

To test the sensitivity of the screening calculation to the assumed layer thicknesses, NRC staff also performed the calculation based on the assumption that the layer with the intended liquid-to-premix ratio was the same thickness as the layer affected by the flush water additions (i.e., 60 cm). Based on this assumption, the vertical effective hydraulic conductivity increased by a factor of two. If the effective vertical hydraulic conductivity of saltstone was increased from the value measured in the SDS 2A cores (i.e., 1.6×10^{-9} cm/s) by a factor of 2 because of horizontal layers with higher hydraulic conductivities, then the effective vertical hydraulic conductivity would still be lower than then nominal value of 6.4×10^{-9} cm/s used in the FY 2014 Special Analysis document. That result supports the DOE qualitative claim that the nominal hydraulic conductivity value of 6.4×10^{-9} cm/s used in the Evaluation Case accounts for potential increases in the effective vertical hydraulic conductivity of saltstone due to potential horizontal layers of saltstone with higher hydraulic conductivity.

Horizontal layers with increased hydraulic conductivity could also increase lateral water flow from saltstone. As described above with respect to cold joints, the effect should be similar to the modeling results described in the DOE response to RAI Question SP-1 for the FY 2014 Special Analysis document. Specifically, the DOE indicated that increased lateral flow through some layers of saltstone would be likely to cause a more gradual release at earlier times, and the effect was likely to be represented by the mass-transfer model described in Section 5.6.6.2 of the FY 2014 Special Analysis document.

In summary, the DOE provided results for the potential effects of flush water additions on saltstone properties. The SDS 2A cores had lower density and higher porosity than laboratory-made samples, which could be explained by a higher liquid-to-premix ratio due to flush water addition. Those measurements included the effects of smaller flush-water additions made during processing and may have included some effect of the larger-flush water additions made at the beginning and end of the processing day because they were taken from the ends of lifts. Hydraulic conductivity measurements of the SDS 2A cores only reflected the smaller flush-water additions made during processing, because hydraulic conductivity measurements were made on sub-samples taken from the interior of the cores. All of the hydraulic conductivity measurements on the SDS 2A cores were below the initial saturated hydraulic conductivity value used in the FY 2014 Special Analysis document. Although the sub-samples used for the hydraulic conductivity measurements did not include saltstone at the ends of the lifts, which would reflect the larger flush-water additions made at the beginning and the end of the day of processing, independent NRC calculations supported the qualitative DOE claim that the nominal hydraulic conductivity value of $6.4x10^{-9}$ cm/s used in the FY 2014 Special Analysis document accounted for potential increases due to potential horizontal layers with increased hydraulic conductivity. In addition, modeling results described by DOE in response to RAI Question SP-1 for the FY 2014 Special Analysis document supported the DOE determination that horizontal layers with higher hydraulic conductivity should not significantly adversely affect saltstone performance. Based on the above information, the NRC determined that flush-water additions were adequately controlled and should not have a significant adverse effect on saltstone performance.

Conclusion for MF 3.02

The 2013 SDF Monitoring Plan includes the following:

> *NRC expects to close MF 3.02 (Variability of Field-Emplaced Saltstone) under PO §61.41 after NRC determines that saltstone production, placement, and curing conditions that significantly affect saltstone hydraulic properties are well controlled.*

and

> *NRC expects to close MF 3.02 (Variability of Field-Emplaced Saltstone) under PO §61.42 after NRC determines that saltstone production, placement, and curing conditions that significantly affect saltstone hydraulic properties are well controlled.*

Based on the above information, the PAB staff recommends closing MF 3.02 under both PO §61.41 and PO §61.42. The NRC will monitor the effects of any future process changes as part of its normal monitoring role at the SDF.

MF 3.03 "Applicability of Laboratory Data to Field-Emplaced Saltstone"

As reported in the DOE document SRR-CWDA-2014-00018, the DOE conducted a large number of laboratory studies investigating the hydraulic conductivity of saltstone with results spanning five orders of magnitude, ranging from 10^{-11} cm/s to 10^{-6} cm/s (ML053010250, SRR-CWDA-2014-00018). Although the value in the Evaluation Case was based on saltstone simulants produced under realistic conditions (e.g., curing temperatures and humidity levels consistent with field conditions, inclusion of admixtures) (SRNL-STI-2012-00558), there was still uncertainty due to potential differences between laboratory and field-emplaced saltstone. As indicated in the 2013 SDF Monitoring Plan:

> *"Specifically, it is unclear to NRC staff whether or not laboratory samples reflect the composition (e.g., actual water-to-cement ratios, admixtures, variations in aluminate concentrations in treated salt waste) and curing conditions (e.g., actual curing temperature, humidity) of field-emplaced saltstone. Also, it is unclear to NRC staff whether or not laboratory samples adequately capture the effects of scale (e.g., effects of fractures or interfaces between saltstone lifts)."*

As reported in recent DOE documents (SRNL-STI-2016-00106; SRR-CWDA-2016-00053), the DOE investigated the properties of SDS 2A core samples relative to laboratory-prepared samples. That SRNL research provided insight into the applicability of laboratory data to field-emplaced saltstone, including bulk density, total and permeable porosity, water content, and saturated hydraulic conductivity. During the April 2016 OOV to the SDF (ML16147A197), the DOE presented those recent results, which indicated that the physical and hydraulic properties of carefully-controlled laboratory-prepared samples were reasonably consistent with the field-emplaced core samples from the SDS 2A, as shown above in Tables 2 and 3 (SRR-CWDA-2016-00053). Although the laboratory-prepared and field-emplaced samples were reasonably consistent, there was a small systematic difference between some of the properties of laboratory-prepared samples and field-emplaced cores, which may be due to flush-water additions, as discussed previously in this TRR under MF 3.02.

Research was also recently conducted at SREL on laboratory-prepared and field-emplaced saltstone core samples (SREL Doc. R-16-0003). Figure 9 in that report showed a significant difference between the hydraulic conductivity of the laboratory-prepared and field-emplaced saltstone samples. The difference in hydraulic conductivity between the samples appears to have resulted in a difference in contaminant release rates due to a residence time effect. As described in the DOE report SRR-CWDA-2016-00119, the DOE is planning in FY 2017 to investigate the mechanism(s) responsible for the differences between the laboratory-prepared and field-emplaced saltstone samples.

Also under MF 3.02 in the SDF Monitoirng Plan, the NRC described that the features and processes that could result in a scale effect (e.g., differences in curing temperature, lift height, relative number of cold joints, increased drop height, and increased flow distance) were not expected to cause significant variability. Fracturing of saltstone will be addressed under a future TRR on saltstone degradation.

With respect to diffusion, the revised effective diffusion coefficient of 1×10^{-8} cm^2/s in the FY 2013 and FY 2014 Saltstone Special Analysis documents was based on laboratory measurements for a simulated non-radioactive saltstone cured for 28 days (SRNL-STI-2010-00515). Additional simulated saltstone samples were prepared at SREL (SREL Doc. R-16-0003). Following EPA Test Method 1315, a sample cured for 6 months had an effective diffusion coefficient[6] for nitrate of 1.6×10^{-8} cm^2/s. In Table 3 above, the effective diffusion coefficient for nitrate from three saltstone core samples ranged from 4.4×10^{-9} cm^2/s to 1.3×10^{-8} cm^2/s, using EPA Test Method 1315. The lower effective diffusivities observed for the actual core samples may correspond to a longer cure time. Accordingly, diffusion results from carefully-controlled laboratory-prepared samples appear to be conservative relative to the diffusivity of actual saltstone. Therefore, the NRC determined that the diffusivities of carefully-controlled laboratory-prepared samples are an acceptable basis for the initial diffusivity of field-emplaced samples.

Conclusion for MF 3.03

The 2013 SDF Monitoring Plan includes the following:

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[6] The "effective diffusion coefficient" in SREL Doc. R-16-0003 includes the effects of porosity, tortuosity, sorption, and dissolution. As described in WSRC-STI-2006-00198, that value would be characterized as an apparent diffusion coefficient. However, for nitrate the effects of sorption and dissolution should not be significant. Accordingly, the effective and apparent diffusion coefficients for nitrate should be equivalent.

NRC expects to close MF 3.03 (Applicability of Laboratory Data to Field-Emplaced Saltstone) under PO §61.41 after NRC determines that representing the hydraulic properties of field-emplaced saltstone with the hydraulic properties of laboratory-produced samples is adequate. That assessment should account for the range of expected disposal conditions of field-emplaced saltstone as well as effects of scale. Alternately, MF 3.03 may be closed if NRC determines that DOE bases the hydraulic properties of saltstone on the properties of an appropriate range of samples of field-emplaced saltstone, rather than on measurements of laboratory-produced samples.

and

NRC expects to close MF 3.03 (Applicability of Laboratory Data to Field-Emplaced Saltstone) under PO §61.42 after NRC determines that representing the hydraulic properties of field-emplaced saltstone with the hydraulic properties of laboratory-produced samples is adequate. That assessment should account for the range of expected disposal conditions of field-emplaced saltstone as well as effects of scale. Alternately, MF 3.03 may be closed if NRC determines that DOE bases the hydraulic properties of saltstone on the properties of an appropriate range of samples of field-emplaced saltstone, rather than on measurements of laboratory-produced samples.

Leaching behavior is addressed under MA 5. However, it appears that differences in the observed leaching of Tc from laboratory-prepared and field-emplaced samples may be due to differences in hydraulic properties and residence time effects. For the above reasons, the PAB staff recommends narrowing the scope of MF 3.03 to understanding of the short-term (i.e., within the first several pore volumes) changes in the hydraulic conductivity between laboratory-prepared and field-emplaced saltstone samples.

If laboratory data are relied on in the future (e.g., to investigate potential effects of variability on field-emplaced saltstone), then the NRC will review the experimental procedures and the applicability of the experimental conditions to verify that the laboratory data are reasonably representative of field-emplaced saltstone.

The previous and planned research on the SDS 2A core samples provides a robust line of evidence for the properties of intact portions of the saltstone grout. However, the bulk grout will include fractures, which could significantly affect the effective hydraulic properties of the bulk emplaced saltstone. Because that concern is ultimately related to degradation, the NRC will address fracturing under *Monitoring Area 4 -Waste Form Physical Degradation* and it is not being used to hold open any MFs in MA 3.

<u>*MF 3.04 "Effect of Curing Temperature on Saltstone Hydraulic Properties"*</u>

The results of several DOE studies (SRNL-STI-2010-00419, SRNL-STI-2010-00745, SRNL-STI-2011-00665) appeared to indicate that higher curing temperatures could result in significantly greater saltstone hydraulic conductivity than what the DOE assumed in Case A in the 2009 PA and in the Evaluation Case in both the FY 2013 and FY 2014 Special Analysis documents. Accordingly, the NRC was concerned that field-emplaced saltstone, which is subjected to greater-than-ambient curing temperatures, may have hydraulic conductivity values exceeding those assumed by the DOE in the 2009 PA. However, several recent studies indicated that the effects of curing temperature were adequately accounted for in the assumed initial hydraulic conductivity value in both the FY 2013 and FY 2014 Special Analysis documents, including:

- Research conducted in 2012 (SRNL-STI-2012-00558) which was relied upon for both the FY 2013 and FY 2014 Special Analysis documents, includes realistic curing temperatures and profiles, admixtures, and varying liquid-to-premix ratios. The results from that study showed saturated hydraulic conductivity values ranging from $1.4x10^{-9}$ cm/s to $3.2x10^{-8}$ cm/s with a mean of $6.4x10^{-9}$ cm/s.

- An analysis in 2015 (SRR-CWDA-2014-00118) provided a hypothesis to explain the elevated hydraulic conductivities that were reported in SRNL-STI-2010-00745. A combination of rapid thermal ramping and short cure duration may have been responsible for the elevated values. That explanation seems reasonable to the NRC, especially in light of the recent data from cores of emplaced saltstone.

- The 2015 saltstone data from cores of saltstone from SDS 2A provides direct evidence for the effect of curing temperature, as well as other variables, on the hydraulic properties of saltstone (SRR-CWDA-2016-00053, SREL Doc. R-16-0003).

As described in MF 3.03, the revised effective diffusion coefficient of $1x10^{-8}$ cm^2/s in both the FY 2013 and FY 2014 Special Analysis documents is based on laboratory measurements for a simulated non-radioactive saltstone cured for 28 days (SRNL-STI-2010-00515). Those simulated saltstone samples were cured at a constant temperature of 24^oC. Recent research was conducted at SREL to evaluate the diffusivity of simulated and cored saltstone samples from SDS 2A (SREL Doc. R-16-0003) under realistic field conditions. The simulated saltstone samples followed a curing profile that mimicked the temperature and humidity profile of the conditions within SDS 2B. Following EPA Method 1315, a sample cured for 6 months had an effective diffusion coefficient[7] for nitrate of $1.6x10^{-8}$ cm^2/s. For three saltstone core samples from SDS 2A, the effective diffusion coefficient for nitrate ranged from $4.4x10^{-9}$ cm^2/s to $1.3x10^{-8}$ cm^2/s (see Table 3 above) following the same EPA Method 1315. The lower effective diffusivities observed for the actual core samples relative to the simulated samples may correspond to a longer cure time. Because both the simulated and actual saltstone samples from the SREL study included realistic curing temperatures and humidity, the NRC determined that the diffusivity values assumed in both the FY 2013 and FY 2014 Special Analysis documents reasonably accounted for the effect of curing temperature.

The 2013 SDF Monitoring Plan includes the following:

> *NRC expects to close MF 3.04 (Effect of Curing Temperatures on Saltstone Hydraulic Properties) under PO §61.41 after NRC determines that projected SDF performance is based on estimates of the hydraulic properties of saltstone (e.g., hydraulic conductivity and diffusivity) that are well-supported. That support should account for the range of curing conditions (i.e., temperatures values, humidity values) experienced by field-emplaced saltstone.*

and

> *NRC expects to close MF 3.04 (Effect of Curing Temperatures on Saltstone Hydraulic Properties) under PO §61.42 after NRC determines that projected SDF performance is*

[7] The "effective diffusion coefficient" in the SREL report includes the effects of porosity, tortuosity, sorption, and dissolution. As described in WSRC-STI-2006-00198, that value would be characterized as an apparent diffusion coefficient. However, for nitrate the effects of sorption and dissolution should not be significant. Accordingly, the effective and apparent diffusion coefficients for nitrate should be equivalent.

based on estimates of the hydraulic properties of saltstone (e.g., hydraulic conductivity and diffusivity) that are well-supported. That support should account for the range of curing conditions (i.e., temperatures values, humidity values) experienced by field-emplaced saltstone.

The NRC determined that the DOE has the data to account for the effects of curing temperatures on field-emplaced saltstone. That support included both laboratory measurements and measurements of samples of field-emplaced saltstone. For the above reasons, the PAB staff recommends closing MF 3.04 under both PO §61.41 and PO §61.42.

MF 10.05: Moisture Characteristic Curves

In the 2012 SDF TER, the NRC raised concerns related to the DOE assumed MCCs in the 2009 PA Base Case. However, in Case K in the 2009 PA RAI comment responses (SRR-CWDA-2011-00044, Rev.1), the DOE revised the approach to unsaturated flow through saltstone and assumed that the relative permeability was 1.0 independent of saltstone saturation (i.e., the DOE assumed a MCC that did not diminish the hydraulic conductivity from the saturated hydraulic conductivity). In both the FY 2013 and FY 2014 Special Analysis documents, the DOE included a revised MCC for saltstone that was not equal to 1.0 and which varied in time according to the assumed extent of degradation (SRR-CWDA-2014-00006). The NRC will address MCCs that were used to simulate saltstone degradation under *Monitoring Area 4 - Waste Form Physical Degradation* and disposal structure degradation under *Monitoring Area 6 – Disposal Structure Performance*. For all of the disposal structures described in the FY 2014 Special Analysis document, the initial MCC for saltstone grout (i.e., prior to saltstone degradation[8]) is shown in Figure 4 below. The relative permeability does not decrease as rapidly with saturation in the FY 2014 Special Analysis document as it did in the 2009 PA. The NRC determined that the risk significance of the MCC used in the FY 2014 Special Analysis document for saltstone grout prior to degradation is limited because of the high initial saturation of saltstone.

The DOE predicted that the saturation for saltstone grout prior to degradation for SDS 1, SDS 4, the 150-ft disposal structures, and the 375-ft disposal structures was always greater than 99.95%. At those saturation values, the assumed MCC designates that the relative permeability would be no less than 87% of the saturated hydraulic conductivity. That allowed the NRC to determine that the resultant relative permeability for saltstone grout prior to degradation is of limited risk significance. However, changes to assumptions in the modeling of saltstone could result in lower predicted saturation levels and consequently lower relative permeabilities, which could be risk significant. If the DOE relies on the same MCCs in future revisions to the PORFLOW model and the model predicts lower saturation levels prior to degradation, then the DOE may need to provide additional support for the assumed MCCs if the model results indicate a significant degree of risk reduction.

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[8] As shown in Tables 4.2-9 through 4.2-12 of the FY 2014 Special Analysis document, the DOE assumed the following delays in degradation of saltstone: 486 years for SDS 1; 2,112 years for SDS 4; 961 years for the 150-ft diameter disposal structures; and 1,413 years for the 375-ft diameter disposal structures (SRR-CWDA-2014-00006).

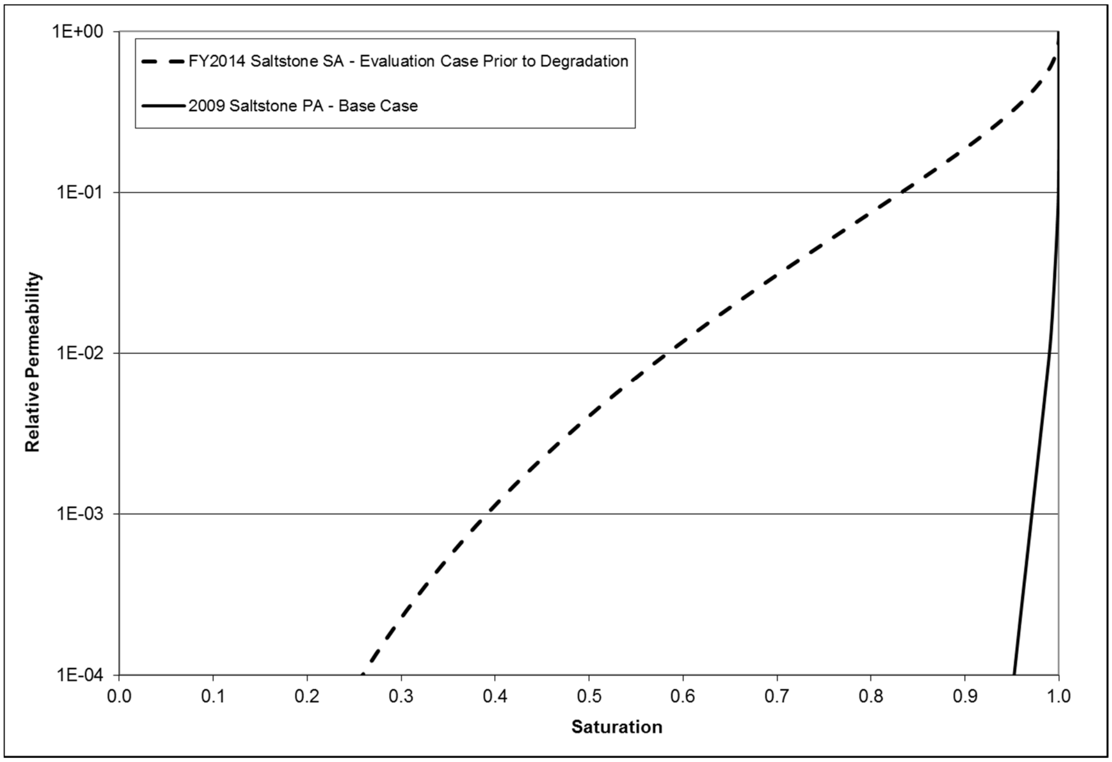

Figure 4. Comparison of moisture characteristic curves from the 2009 PA and FY 2014 Special Analysis document.

The 2013 SDF Monitoring Plan includes the following:

> *NRC expects to close MF 10.05 (Moisture Characteristic Curves) under PO §61.41 after DOE updates the PA and NRC determines that the MCCs are well-supported. Alternatively, MF 10.05 may be closed if, in an updated PA, DOE assumes the relative permeability is 1, which means that DOE does not use MCCs in the updated PA.*

and

> *NRC expects to close MF 10.05 (Moisture Characteristic Curves) under PO §61.42 after DOE updates the PA and NRC determines that the MCCs are well-supported. Alternatively, MF 10.05 may be closed if, in an updated PA, DOE assumes the relative permeability is 1, which means that DOE does not use MCCs in the updated PA.*

The NRC determined that the DOE support for the assumed initial MCC (i.e., prior to saltstone degradation) is adequate based on the limited risk significance of the initial MCC used in the FY 2014 Special Analysis document. However, future changes to modeling assumptions and parameterization may result in this MCC becoming more risk significant and additional support may be needed for future analyses. Accordingly, the NRC will continue to review the risk significance and support for MCCs. For the above reasons, the PAB staff recommends keeping MF 10.05 open under both PO §61.41 and PO §61.42.

<u>Follow-up Actions</u>

There are no Follow-up Actions related to the saltstone waste form hydraulic properties.

Open Issues

There are no Open Issues related to the saltstone waste form hydraulic properties.

Conclusions

During the NRC review of the 2009 PA, the NRC identified several concerns related to the hydraulic performance of saltstone, which were documented in the 2012 SDF TER (ML121020140). Those concerns were captured under two MAs in the 2013 SDF Monitoring Plan (ML13100A076):

- *MA 3 – Waste Form Hydraulic Performance* with four MFs: MF *3.01 "Hydraulic Conductivity of Field-Emplaced Saltstone", MF 3.02 "Variability of Field-Emplaced Saltstone", MF 3.03 "Applicability of Laboratory Data to Field-Emplaced Saltstone", MF 3.04 "Effect of Curing Temperature on Saltstone Hydraulic Properties"*

- *MA 10 – Performance Assessment Model Revisions under one MF: MF 10.05 "Moisture Characteristic Curves"*

In the Evaluation Cases for both the FY 2013 and FY 2014 Special Analysis documents, the DOE revised several key assumed hydraulic properties of saltstone based on recent research conducted since the issuance of the 2009 PA. The initial saturated hydraulic conductivity used in the model was increased from the 2009 PA value of 2.0×10^{-9} cm/s to 6.4×10^{-9} cm/s. The modeled effective diffusion coefficient for intact saltstone was decreased from 1×10^{-7} cm^2/s to 1×10^{-8} cm^2/s. In addition to the revised saturated hydraulic conductivity and effective diffusivity, the DOE revised the assumed MCC for saltstone.

The revised effective diffusion coefficient of 1×10^{-8} cm^2/s in the FY 2013 and FY 2014 Special Analysis documents was based on laboratory measurements for a simulated non-radioactive saltstone simulant. The DOE also conducted diffusivity tests on additional simulated saltstone samples and actual saltstone core samples collected from SDS 2A. For the simulant samples, the effective diffusivity for nitrate averaged 1.6×10^{-8} cm^2/s. For the saltstone core samples, the effective diffusivity averaged 7.6×10^{-9} cm^2/s. Based on those tests of controlled simulated samples and actual saltstone core samples, the NRC determined that the assumed effective diffusion coefficient in the FY 2013 and FY 2014 Special Analysis documents was well supported.

In the Evaluation Cases for both the FY 2013 and FY 2014 Special Analysis documents, the DOE revised the initial saturated hydraulic conductivity of saltstone upwards from the 2009 PA value of 2.0×10^{-9} cm/s to 6.4×10^{-9} cm/s. To support the assumed initial hydraulic conductivity of saltstone, the DOE conducted additional laboratory studies and testing on actual saltstone core samples since the 2009 PA. The measurements of the saltstone core samples provided the most compelling support for the initial saturated hydraulic conductivity of field-emplaced saltstone. That included six core samples tested at SRNL and two core samples tested at SREL. The hydraulic conductivity measurements from the core samples were all less than the assumed value of 6.4×10^{-9} cm/s in the FY 2013 and FY 2014 Saltstone Special Analysis documents. In addition to the direct evidence of the hydraulic conductivity of saltstone from the core sample research, the DOE conducted additional studies and analyses to support the assumed hydraulic conductivity value. Research from the Vitreous State Laboratory at The Catholic University of America for simulated saltstone samples prepared under realistic curing conditions yielded hydraulic conductivity values that were consistent with the assumed values in the FY 2013 and FY 2014 Special Analysis documents. For the above reasons, the PAB staff recommends closing MF 3.01 under both PO §61.41 and PO §61.42,

In the 2013 SDF Monitoring Plan, the NRC described concerns related to the variability in the hydraulic properties of saltstone (MF 3.02 – *Variability of Field-Emplaced Saltstone*). This variability can result from changes in process feeds (e.g., dry feed component percentages, dry feed sources and storage conditions, salt waste composition, liquid-to-premix ratio) or saltstone production, emplacement, and curing processes (e.g., method of mixing, method of emplacement, flush water volume used, curing conditions). The recent DOE research results, in particular the measured properties of saltstone core samples, provided significant insight into to variability in field-emplaced saltstone. The NRC determined that the production, placement, and curing conditions that could cause significant variability in saltstone performance were well-controlled and were not expected to result in significant variability. In addition, the NRC determined that the DOE process to evaluate the effects of potential process changes allowed DOE to assess and control saltstone variability. For the above reasons, the PAB staff recommends closing MF 3.02 under both PO §61.41 and PO §61.42. The NRC will monitor the effects of any future process changes as part of the NRC monitoring role at the SDF.

In the 2009 PA, the DOE relied on laboratory data to support assumptions related to the hydraulic performance of saltstone. In the 2013 SDF Monitoring Plan, the NRC described concerns about relying solely on laboratory data without sufficient evidence that the laboratory data reflects the properties of field-emplaced saltstone (i.e., MF 3.03 – *Applicability of Laboratory Data to Field-Emplaced Saltstone*). Recent DOE research results on the physical and hydraulic properties of saltstone core samples provided support for use of laboratory data in representing field-emplaced saltstone, as long as key field conditions (e.g., temperature, humidity, liquid-to-premix ratio) were replicated. However, differences in recently observed leaching behavior between laboratory-prepared and field-emplaced samples may be due to differences in hydraulic properties. For the reasons above, the PAB staff recommends narrowing the scope of MF 3.03 (Applicability of Laboratory Data to Field-Emplaced Saltstone) under both PO §61.41 and PO §61.42 to understanding of the short-term (i.e., within the first several pore volumes) changes in the hydraulic conductivity between laboratory-prepared and field-emplaced saltstone samples..

In the 2012 SDF TER, the NRC described that, based on then available DOE research results, the curing conditions (i.e., temperature and humidity) appear to have a significant effect on the hydraulic properties of saltstone. In the 2013 SDF Monitoring Plan, the NRC developed a MF to describe that concern (MF 3.04 – *Effect of Curing Temperature on Saltstone Hydraulic Properties*). Since the 2009 PA, the DOE developed several new lines of evidence, including: (1) research results that indicated that unrealistic curing conditions were responsible for anomalously high hydraulic properties in previous studies, (2) laboratory studies of simulated saltstone produced under realistic conditions, and (3) research results from actual saltstone core samples. The NRC determined that the DOE research results demonstrated that the effects of curing conditions were adequately accounted for in the assumed initial hydraulic conductivity and effective diffusivity values in both the FY 2013 and FY 2014 Special Analysis documents. For the above reasons, the PAB staff recommends closing MF 3.04 under both PO §61.41 and PO §61.42.

In the 2012 SDF TER, the NRC raised concerns related to the DOE assumed MCCs in the 2009 PA Base Case. In the 2013 SDF Monitoring Plan, the NRC developed a MF to describe that concern (MF 10.05 – *Moisture Characteristic Curves*). However, in a sensitivity case (Case K), the DOE revised the approach to unsaturated flow through saltstone and assumed that the relative permeability was 1.0 – independent of saltstone saturation (i.e., the DOE assumed a MCC that did not diminish the hydraulic conductivity from the saturated hydraulic conductivity). In both the FY 2013 and FY 2014 Special Analysis documents, the DOE again included a MCC for saltstone that was not equal to 1.0, but it was revised from the curve in the 2009 PA. Because of the assumed saturation of saltstone in the hydrologic model supporting the FY 2014 Special Analysis document, the MCC does not reduce the hydraulic conductivity significantly compared to the saturated hydraulic conductivity. Therefore, based on its limited risk significance because of the assumed high initial saltstone saturation, the NRC determined that the DOE support for the initial MCC (i.e., prior to saltstone degradation) in the FY 2014 Special Analysis document was adequate. However, future changes to modeling assumptions and parameterization may result in this MCC becoming more risk significant and additional support may be needed for future analyses. For the above reasons, the PAB staff recommends keeping MF 10.05 open under both PO §61.41 and PO §61.42.

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