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INTEROFFICE MEMORANDUM

SRR-CWDA-2020-00050
Revision 0

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To: K. H. Rosenberger, 705-1C

From: G. P. Flach, 705-1C GREGORY FLACH (Affiliate) Digitally signed by GREGORY FLACH (Affiliate) Date: 2020.09.24 13:40:43 -04'00'

Reviewed per SRR Procedure S4-ENG.51: S. P. Hommel, 705-1C Steve Hommel Digitally signed by Steve Hommel Date: 2020.09.24 13:48:55 -04'00'

Update to Projected Degradation of Saltstone Disposal Facility Cementitious Materials to Evaluate SDU Concrete Mix 3B and Cement-Free Saltstone

The Saltstone Disposal Facility (SDF) Performance Assessment (PA) considers degradation of cementitious materials through sulfate attack, corrosion of embedded steel (reinforcing bars) that is controlled by carbonation, and/or decalcification. [SRR-CWDA-2019-00001] The SDF cementitious materials analyzed are:

- Saltstone composed of 45% slag, 45% fly ash, and 10% cement mixed with decontaminated salt solution (45/45/10 saltstone) and
- The various concrete mixes used in Saltstone Disposal Unit (SDU) design-types 1, 2, 4, 6, and 7. [SRNL-STI-2018-00077]

Since then two new cementitious materials have been proposed for use in future SDF liquid waste solidification and SDU construction:

- Cement-free saltstone with a dry mix composed of 60% slag and 40% fly ash as described in SRR-CWDA-2019-00003 (60/40/0 saltstone), and
- High-quality concrete with a binder composed of cement, slag, and metakaolin for future SDUs (e.g., SDU 8) and identified as “Mix 3B” in mix design and testing report SRR-SDU-2019-00026 (SDU 8/Mix 3B concrete).

Purpose

This study expands the SDF PA degradation analysis (SRNL-STI-2018-00077) to include 60/40/0 saltstone and SDU 8/Mix 3B concrete. The degradation analysis has also been updated to reanalyze 45/45/10 saltstone and SDU 2/6/7 design-type concrete using alternative estimates of chemical reaction capacity for sulfate attack, carbonation, and decalcification.

Normative Mineral Analysis

Chemical reaction capacities in the SDF PA degradation analysis are based on normative mineral compositions of hydrated saltstone and SDU 2/6/7 concrete estimated by SIMCO Technologies, Inc. (2010, 2012). In this study, reaction capacities are based on an updated normative mineral composition analysis, SRR-CWDA-2020-00066, recently conducted for all four materials of interest: 45/45/10 saltstone, 60/40/0 saltstone, SDU 2/6/7 concrete, and SDU 8 (Mix 3B) concrete. SRR-CWDA-2020-00066 generated four normative mineral compositions for each cementitious material by combining two methods with two assumptions on binder reactivity (degree of hydration). One method is a slight modification of the SRNL-STI-2018-00586 / SRNL-TR-2008-00283 approach and the other method is that of Herfort and Lothenbach

(2017). The two reactivity assumptions are 100% hydration of all binders and partial hydration: 100% of cement, 70% of slag, and 40% for the remaining binders.

The other needed material properties are taken from SRR-CWDA-2020-00036 and SRR-CWDA-2020-00040. The physical properties of 45/45/10 saltstone and SDU 2/6/7 concrete are unchanged from the SDF PA, and the recommended physical properties of 60/40/10 saltstone for modeling are the same as 45/45/10 saltstone. The saturated hydraulic conductivity (K_{sat}) and effective diffusion coefficient (D_e) of SDU 8/Mix 3B concrete are slightly higher than those for SDU 2/6/7 concrete.

A normative mineral analysis uses general knowledge of cement hydration reactions, equilibrium constants and kinetics, and degrees of reaction to virtually react the mix dry ingredients with water to form a plausible set of hydrated minerals constituting the cured material. Stoichiometry is used to preserve the collective mass of each chemical element through the process, based on the specified proportions and metal oxide analyses of the dry ingredients and the water-to-cementitious materials (w/c) ratio. Tables 1 and 2 list the hydrated minerals considered in each normative mineral analysis using cement chemist notation. The SRNL method was modified primarily by adding Portlandite and gypsum to the previously assumed set of potential minerals present in hydrated material; these two minerals were added to consume any excess calcium and sulfur, respectively. Minerals in common to both sets are highlighted. [SRR-CWDA-2020-00066]

Table 1. Mineral set assumed in modified SRNL normative mineral composition analysis.

Potential Mineral	Cement Chemist Notation†	Molecular Formula
Portlandite	CH	$Ca(OH)_2$
Calcium Silicate Hydrate	CSH	$CaSiO_3 \cdot H_2O$
Hydrotalcite	M_4AH_{10}	$Mg_4Al_2O_7 \cdot 10H_2O$
Kaolinite	AS_2H_2	$Al_2Si_2O_5(OH)_4$
Gibbsite	$A_{0.5}H_{1.5}$	$Al(OH)_3$
Gypsum	CsH_2	$CaSO_4 \cdot 2H_2O$
Pyrrhotite	—	FeS
Unreacted Quartz	S	SiO_2
Unreacted Iron Oxide	F	Fe_2O_3
Unreacted H2O	H	H_2O

† Shorthand notation: A:Al_2O_3, c:CO_2, C:CaO, H:H_2O, M:MgO, s:SO_3, S:SiO_2

Table 2. Mineral set assumed by Herfort-Lothenbach (2017).

Potential Mineral	Cement Chemist Notation†	Potential Mineral	Cement Chemist Notation
Portlandite	CH	Calcite	Cc
High-Ca C-S-H	$C_{1.75}SH_4$	Monocarbonate	C_4AcH_{11}
High-Ca C-A-S-H	$C_{1.75}SA_{0.05}H_4$	Hemicarbonate	$C_4Ac_{0.5}H_{12}$
C-A-S-H	$C_{1.3}SA_{0.1}H_3$	OH-AFm	C_4AH_{13}
Low-Ca C-A-S-H	$C_{0.67}SA_{0.05}H_2$	Friedel’s salt	$C_4ACl_2H_{10}$
Low-Ca C-S-H	$C_{0.67}SH_2$	Kuzel’s salt	$C_4As_{0.5}Cl_2H_{12}$
Hydrotalcite	M_4AH_{10}	Strätlingite	C_2ASH_8
Gypsum	CsH_2	Katoite	C_3AH_6
Ettringite	$C_6As_3H_{32}$	Ca-stilbite	$C_{0.17}SA_{0.17}H_{1.04}$
Thaumasite	C_3SscH_{15}	Amorphous silica	S
Monosulfate	C_4AsH_{12}	Aluminum hydroxide	AH_3
Hemisulfate	$C_4As_{0.5}H_{12.5}$	Unreacted H2O	H

† Shorthand notation: A:Al_2O_3, c:CO_2, C:CaO, H:H_2O, M:MgO, s:SO_3, S:SiO_2

Although the two mineral sets are quite different, the impact on degradation predictions is much lower than might be expected because degradation reaction capacities are expressed in terms of total aluminum and calcium, regardless of the hydrated mineral(s) in which they appear. Total hydrated aluminum and calcium concentrations depend mostly on mix ingredients, ingredient proportions and compositions, assumed degree of hydration, and any calibration to measured properties (e.g., bulk density). The SRNL method calibrated the hydrated mineral set to measured bulk density and reduction capacity. No calibration was performed using the Herfort-Lothenbach method.

Reaction Capacities from the Normative Mineral Analysis

Table 3 presents reaction capacities from SRR-CWDA-2020-00066. Among the four normative mineral composition cases, the Herfort / Lothenbach method coupled with the partial hydration exhibits the lowest Al reaction capacity for concretes which controls sulfate attack, the dominant degradation phenomenon. For saltstone, the modified SRNL method coupled with partial hydration produces the lowest reaction capacity. The partial hydration assumption produces a lower reaction capacity and higher degradation rate than the complete hydration assumption for either material. As a conservatism, only the reaction capacities from the partial hydration cases are carried forward.

Table 3: Chemical reaction capacities from SRR-CWDA-2020-00066.

Parameter	45/45/10 Saltstone	60/40/0 Saltstone	SDU2/6/7 Concrete	Mix 3B Concrete
Modified SRNL method w/property adjustment, complete hydration				
Aluminum concentration, mol/g-solid	2.82E-03	3.04E-03	4.27E-04	4.90E-04
Calcium concentration, mol/g-solid	3.53E-03	4.60E-03	1.18E-03	1.59E-03
Calcium concentration, mol/cm^3	3.29E-03	4.29E-03	2.57E-03	3.58E-03
Modified SRNL method w/property adjustment, partial hydration				
Aluminum concentration, mol/g-solid	1.43E-03	1.73E-03	2.43E-04	3.11E-04
Calcium concentration, mol/g-solid	2.89E-03	3.21E-03	1.03E-03	1.44E-03
Calcium concentration, mol/cm^3	2.69E-03	2.99E-03	2.25E-03	3.23E-03
Herfort-Lothenbach method, complete hydration				
Aluminum concentration, mol/g-solid	2.59E-03	2.74E-03	4.26E-04	4.89E-04
Calcium concentration, mol/g-solid	3.27E-03	4.19E-03	1.19E-03	1.58E-03
Calcium concentration, mol/cm^3	4.11E-03	5.48E-03	2.69E-03	3.64E-03
Herfort-Lothenbach method, partial hydration				
Aluminum concentration, mol/g-solid	1.34E-03	1.64E-03	2.42E-04	3.08E-04
Calcium concentration, mol/g-solid	2.75E-03	3.05E-03	1.03E-03	1.41E-03
Calcium concentration, mol/cm^3	3.18E-03	3.51E-03	2.28E-03	3.20E-03

Degradation Rate Coefficients

Tables 4 and 5 summarize degradation rate coefficients calculated from the reaction capacities (Table 3) and using the same methods as described in SRNL-STI-2018-00077, for partial hydration and for each of the three analysis cases: Compliance Value (CV), Best Estimate (BE), and Conservative Estimate (CE). Figures 1 through 3 present the CV results in graphical form.

Cement-free 60/40/0 saltstone is projected to degrade slower than 45/45/10 saltstone (Figure 3). SDU 8/Mix 3B concrete is projected to degrade faster than SDU 2/6/7 concrete (Figures 1 and 2), primarily because of its higher effective diffusion coefficient rather than compositional differences. However, the rate coefficients used in the SDF PA are higher than those from this study, except for carbonation of SDU 8/Mix 3B concrete. Although SDU 8/Mix 3B concrete is projected to carbonate at a faster rate than assumed in the SDF PA, sulfate attack dominates concrete degradation such that the net degradation rate of SDU 8/Mix 3B concrete is projected to be slower than the rate assumed in the SDF PA. Because concrete degradation rates are more impactful to the SDF PA than saltstone rates within the 1000-year Compliance Period, only the Herfort-Lothenbach partial hydration rate coefficients are carried forward.

Table 4: Degradation rate coefficients for concrete.

Rate Coefficient (cm/√yr)	**Sulfate Attack**			**Carbonation-Controlled Corrosion**		
	PA Ref.	Mod. SRNL partial hydration	Herfort-Lothenbach partial hydration	PA Ref	Mod. SRNL partial hydration	Herfort-Lothenbach partial hydration
SDF PA Compliance Value (CV) case						
SDU 2/6/7 Concrete	0.223	0.110	0.110	0.120	0.101	0.101
SDU 8 Concrete	N/A	0.157	0.159	N/A	0.144	0.144
SDF PA Best Estimate (BE) case						
SDU 2/6/7 Concrete	0.182	0.089	0.090	0.023	0.082	0.082
SDU 8 Concrete	N/A	0.123	0.124	N/A	0.113	0.113
SDF PA Conservative Estimate (CE) case						
SDU 2/6/7 Concrete	0.238	0.117	0.117	0.199	0.108	0.107
SDU 8 Concrete	N/A	0.195	0.197	N/A	0.178	0.179

Table 5: Degradation rate coefficients for saltstone.

Rate Coefficient (cm/yr)	**Decalcification**		
	PA Ref.	Mod. SRNL partial hydration	Herfort-Lothenbach partial hydration
SDF PA Compliance Value (CV) case			
45/45/10 Saltstone	7.6E-05	3.5E-05	3.0E-05
60/40/0 Saltstone	N/A	3.2E-05	2.7E-05
SDF PA Best Estimate (BE) case			
45/45/10 Saltstone	5.1E-06	2.3E-06	2.0E-06
60/40/0 Saltstone	N/A	2.1E-06	1.8E-06
SDF PA Conservative Estimate (CE) case			
45/45/10 Saltstone	5.1E-04	2.3E-04	2.0E-04
60/40/0 Saltstone	N/A	2.1E-04	1.8E-04

Figure 1: Degradation rate coefficients for sulfate attack on concrete.

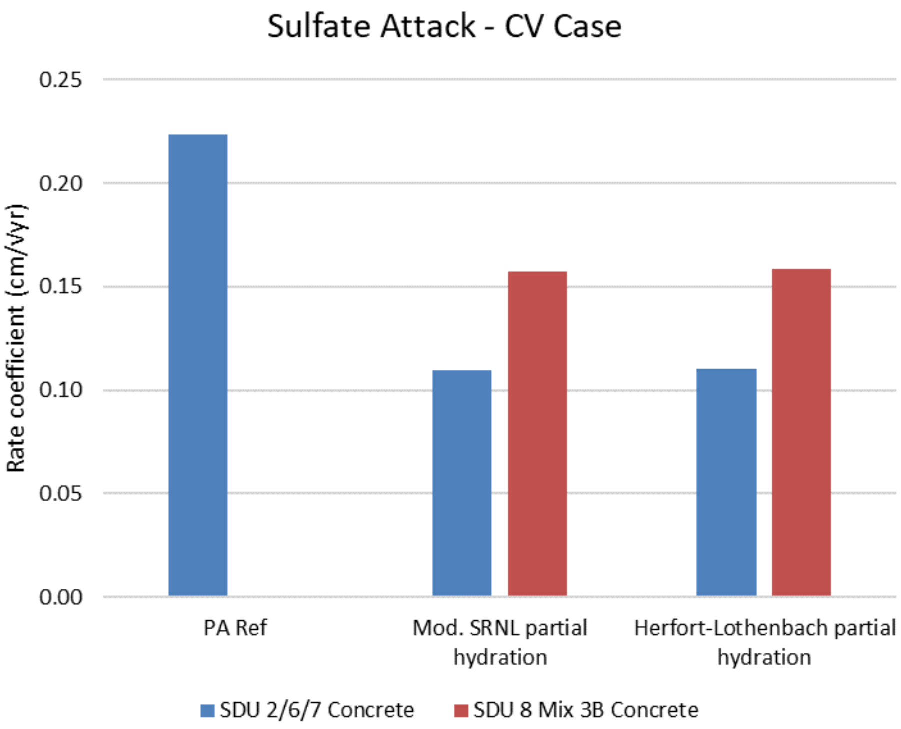


Figure 2: Degradation rate coefficients for carbonation of concrete.

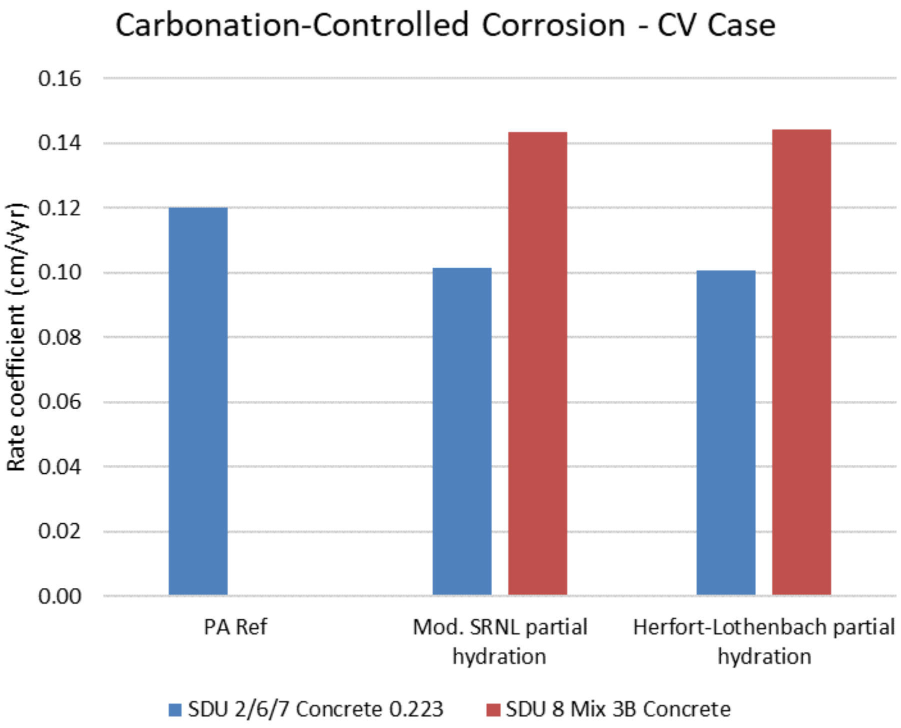
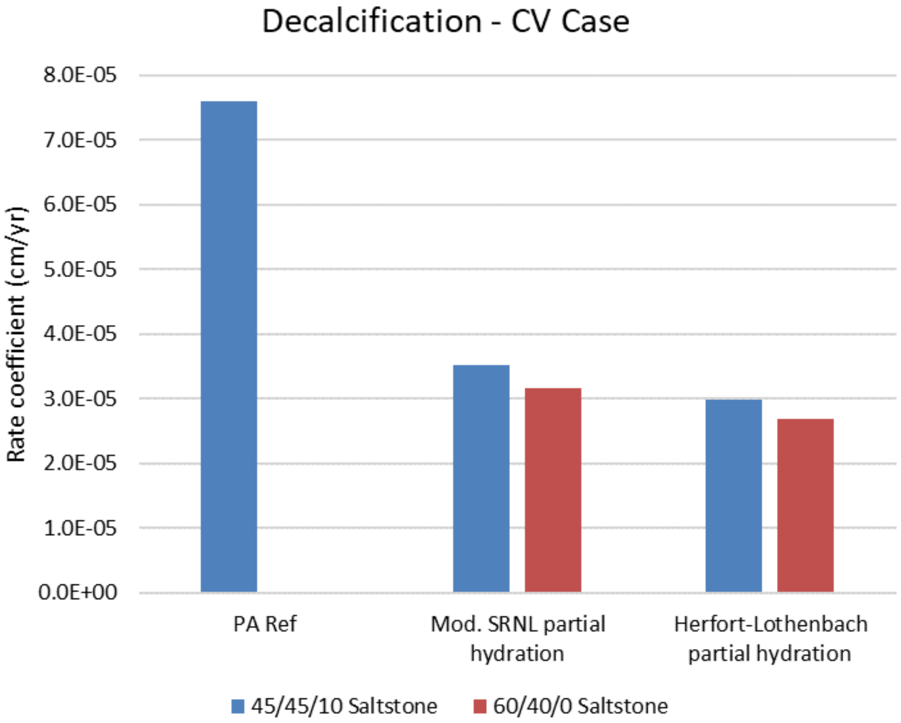


Figure 3: Degradation rate coefficients for advective decalcification of saltstone.



Updated Degradation Analysis Results

Table 6 summarizes the start and end times of physical degradation and associated saturated hydraulic conductivity end members for various cementitious materials and analyses. "SDU 7 Design" columns present degradation times and K_{sat} values for SDU 7 from the SDF PA for reference (SRNL-STI-2018-00077). "SDU 7 + 45/45/10" denotes degradation times from this study for SDU 7, that is, the SDU 7 geometry, SDU 2/6/7 concrete mix, and 45/45/10 saltstone. Hydraulic conductivities are not affected by reaction capacity assumptions, so "SDU 7 + 45/45/10" K_{sat} values are the same as the SDF PA ("SDU 7 Design") and not explicitly shown. "SDU 8 + 60/40/0" denotes the SDU 8 geometry (assumed same as SDU 7), Mix 3B concrete mix, and 60/40/0 saltstone. Further detail on degradation timing is provided in Tables 7 and 8.

Consistent with the earlier discussion of rate coefficients, degradation times from this study for all four cementitious materials (SDU 2/6/7 concrete, SDU 8/Mix 3B concrete, 45/45/10 saltstone, 60/40/0 saltstone) exceed those from the SDF PA, indicating relative conservatism in the PA. SDU 8/Mix 3B concrete has a higher initial K_{sat} than SDU 2/6/7 concrete per SRR-CWDA-2020-00036 (1.0E-09 cm/s versus 7.8E-10 cm/s), but the SDF PA determined that values as high as 1.0E-7 cm/s have minimal impact on SDF performance (Section 5.8.3.3 of SRR-CWDA-2019-00001). The initial K_{sat} is the same for 45/45/10 and 60/40/0 saltstone per SRR-CWDA-2020-00040.

Table 6: Summary of degradation times and saturated hydraulic conductivities.

Degradation start and end times

SDU 7 Design			SDU 7 + 45/45/10			SDU 8 + 60/40/0		
CE	**CV**	**BE**	**CE**	**CV**	**BE**	**CE**	**CV**	**BE**
(yr)	(yr)	(yr)	(yr)	(yr)	(yr)	(yr)	(yr)	(yr)
0	**0**	0	0	**0**	0	0	**0**	0
Roof	12	in	**Roof**	12	in	**Roof**	12	in
1371	**1552**	2306	3889	**4294**	6035	1933	**2545**	3597
0	**0**	0	0	**0**	0	0	**0**	0
Floor	24	in	**Floor**	24	in	**Floor**	24	in
2312	**2800**	4603	6912	**7745**	11251	3004	**4160**	6288
0	**0**	0	0	**0**	0	0	**0**	0
Wall ⑤	10.72	in	**Wall ⑤**	11.02	in	**Wall ⑤**	11.02	in
720	**1075**	2020	2818	**3190**	4831	1005	**1547**	2514
0	**0**	0	0	**0**	0	0	**0**	0
Wall ④	12.26	in	**Wall ④**	12.61	in	**Wall ④**	12.62	in
824	**1229**	2316	3225	**3651**	5529	1151	**1770**	2877
0	**0**	0	0	**0**	0	0	**0**	0
Wall ③	14.92	in	**Wall ③**	15.37	in	**Wall ③**	15.38	in
1002	**1496**	2829	3931	**4451**	6740	1403	**2158**	3507
0	**0**	0	0	**0**	0	0	**0**	0
Wall ②	17.62	in	**Wall ②**	18.17	in	**Wall ②**	18.18	in
1184	**1767**	3349	4648	**5262**	7968	1658	**2552**	4146
0	**0**	0	0	**0**	0	0	**0**	0
Wall ①	20.22	in	**Wall ①**	20.88	in	**Wall ①**	20.89	in
1358	**2028**	3851	5340	**6046**	9155	1906	**2932**	4764
1371	**1552**	2306	3889	**4294**	6035	1933	**2545**	3597
Grout	516	in	**Grout**	516	in	**Grout**	516	in
2.6E+06	**1.7E+07**	2.6E+08	6.6E+06	**4.4E+07**	6.6E+08	7.3E+06	**4.9E+07**	7.3E+08
0	**0**	0	0	**0**	0	0	**0**	0
Column	10.63	in	**Column**	10.63	in	**Column**	10.63	in
72	**92**	299	72	**92**	299	72	**92**	299

Hydraulic conductivity end-members

SDU 7 Design			SDU 8 + 60/40/0		
CE	**CV**	**BE**	**CE**	**CV**	**BE**
(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
9.1E-10	**7.8E-10**	6.4E-10	2.0E-09	**1.0E-09**	7.0E-10
Roof	12	in	**Roof**	12	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
9.1E-10	**7.8E-10**	6.4E-10	2.0E-09	**1.0E-09**	7.0E-10
Floor	24	in	**Floor**	24	in
9.1E-05	**9.1E-05**	9.1E-05	9.1E-05	**9.1E-05**	9.1E-05
9.10E-10	**7.80E-10**	6.40E-10	2.00E-09	**1.00E-09**	7.00E-10
Wall ⑤	10.72	in	**Wall ⑤**	10.98	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
9.10E-10	**7.80E-10**	6.40E-10	2.00E-09	**1.00E-09**	7.00E-10
Wall ④	12.26	in	**Wall ④**	12.56	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
9.10E-10	**7.80E-10**	6.40E-10	2.00E-09	**1.00E-09**	7.00E-10
Wall ③	14.92	in	**Wall ③**	15.31	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
9.10E-10	**7.80E-10**	6.40E-10	2.00E-09	**1.00E-09**	7.00E-10
Wall ②	17.62	in	**Wall ②**	18.09	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
9.10E-10	**7.80E-10**	6.40E-10	2.00E-09	**1.00E-09**	7.00E-10
Wall ①	20.22	in	**Wall ①**	20.79	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
2.0E-09	**5.0E-10**	1.0E-10	2.0E-09	**5.0E-10**	1.0E-10
Grout	516	in	**Grout**	516	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05
1.0E-08	**5.0E-09**	5.0E-09	1.0E-08	**5.0E-09**	5.0E-09
Column	10.63	in	**Column**	10.63	in
4.1E-05	**4.1E-05**	4.1E-05	4.1E-05	**4.1E-05**	4.1E-05

Table 7: Degradation timing detail for SDU 7 and 45/45/10 saltstone.

Degradation mechanism:			*SA*	*Carb*	*SA*	*Carb*	*SA*	*Carb*	**Sulfate attack**							**Carbonation**						
	Thickness:		CE	CE	CV	CV	BE	BE	**A (cm/√yr)**			**Time (yr)**			**max δ**	**A (cm/√yr)**			**Time (yr)**			**max δ**
Component	(in)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	CE	CV	BE	CE	CV	BE	(cm)	CE	CV	BE	CE	CV	BE	(cm)
Roof delay									*no clean grout:*			0	**0**	0		*HDPE-GCL:*			1800	1800	1700	
Roof degradation	12	30.48	21	9.45	20.5	9.96	19	11.4	0.117	0.110	0.090	3889	4294	6035	2.54	0.107	0.101	0.082	2089	2494	4335	2.54
Roof delay+degradation			0		0		0					3889	**4294**	6035					3889	**4294**	6035	
Floor delay									*immediate contact:*			0	**0**	0		*HDPE-GCL:*			1700	1750	1600	
Floor degradation	24	60.96	37.4	23.6	37	24	35.5	25.5	0.117	0.110	0.090	6912	7745	11251	2.54	0.107	0.101	0.082	5212	5995	9651	2.54
Floor delay+degradation			0		0		0					6912	**7745**	11251					6912	**7745**	11251	
Wall delay									*immediate contact:*			0	**0**	0		*no liner:*			0	**0**	0	
Wall degradation	11.02	27.99	15.2	12.7	15.2	12.7	15.2	12.7	0.117	0.110	0.090	2818	3190	4831	2.54	0.107	0.101	0.082	2818	3190	4831	2.54
Wall delay+degradation			0		0		0					2818	**3190**	4831					2818	**3190**	4831	
Wall delay									*immediate contact:*			0	**0**	0		*no liner:*			0	**0**	0	
Wall degradation	12.61	32.03	17.4	14.6	17.4	14.6	17.4	14.6	0.117	0.110	0.090	3225	3651	5529	2.54	0.107	0.101	0.082	3225	3651	5529	2.54
Wall delay+degradation			0		0		0					3225	**3651**	5529					3225	**3651**	5529	
Wall delay									*immediate contact:*			0	**0**	0		*no liner:*			0	**0**	0	
Wall degradation	15.37	39.05	21.3	17.8	21.3	17.8	21.3	17.8	0.117	0.110	0.090	3931	4451	6740	2.54	0.107	0.101	0.082	3931	4451	6740	2.54
Wall delay+degradation			0		0		0					3931	**4451**	6740					3931	**4451**	6740	
Wall delay									*immediate contact:*			0	**0**	0		*no liner:*			0	**0**	0	
Wall degradation	18.17	46.16	25.1	21	25.1	21	25.1	21	0.117	0.110	0.090	4648	5262	7968	2.54	0.107	0.101	0.082	4648	5262	7968	2.54
Wall delay+degradation			0		0		0					4648	**5262**	7968					4648	**5262**	7968	
Wall delay									*immediate contact:*			0	**0**	0		*no liner:*			0	**0**	0	
Wall degradation	20.88	53.04	28.9	24.2	28.9	24.2	28.9	24.2	0.117	0.110	0.090	5340	6046	9155	2.54	0.107	0.101	0.082	5340	6046	9155	2.54
Wall delay+degradation			0		0		0					5340	**6046**	9155					5340	**6046**	9155	
Grout delay																						
Grout degradation	516	1311																				
Grout delay+degradation																						
Column delay									*immediate contact:*			0	**0**	0								
Column degradation	10.63	27.0	27.0	0	27.0	0	27.0	0	0.977	0.863	0.479	72	92	299	2.54							
Column delay+degradation												72	**92**	299								

Table 7: Degradation timing detail for SDU 7 and 45/45/10 saltstone (continued).

Degradation mechanism:	**Decalcification**									**Limiting**		
	Thickness:		**A (cm/√yr)**			**Time (yr)**			**max δ**	**CE**	**CV**	**BE**
Component	(in)	(cm)	CE	CV	BE	CE	CV	BE	(cm)	(yr)	(yr)	(yr)
Roof delay					*HDPE-GCL:*	1800	1800	1700		**0**	**0**	**0**
Roof degradation	12	30.48	0.019	0.018	0.015	212368	240417	364060	2.54		Roof	
Roof delay+degradation						214168	242217	365760		**3889**	**4294**	**6035**
FloorUMM delay					*HDPE-GCL:*	1700	1750	1600		**0**	**0**	**0**
FloorUMM degradation	24	60.96	0.019	0.018	0.015	424737	480834	728120	2.54		Floor	
FloorUMM delay+degradation						426437	482584	729720		**6912**	**7745**	**11251**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	11.02	27.99	0.019	0.018	0.015	195003	220758	334291	2.54		Wall ⑤	
Wall delay+degradation						195003	220758	334291		**2818**	**3190**	**4831**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	12.61	32.03	0.019	0.018	0.015	223186	252664	382605	2.54		Wall ④	
Wall delay+degradation						223186	252664	382605		**3225**	**3651**	**5529**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	15.37	39.05	0.019	0.018	0.015	272049	307980	466369	2.54		Wall ③	
Wall delay+degradation						272049	307980	466369		**3931**	**4451**	**6740**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	18.17	46.16	0.019	0.018	0.015	321631	364110	551367	2.54		Wall ②	
Wall delay+degradation						321631	364110	551367		**4648**	**5262**	**7968**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	20.88	53.04	0.019	0.018	0.015	369539	418346	633496	2.54		Wall ①	
Wall delay+degradation						369539	418346	633496		**5340**	**6046**	**9155**
Grout delay				**A_U (cm/yr)**		3889	4294	6035		**3889**	**4294**	**6035**
Grout degradation	516	1311	2.0E-04	3.0E-05	2.0E-06	6598918	4.4E+07	6.6E+08			Grout	
Grout delay+degradation						6.6E+06	**4.4E+07**	6.6E+08		**6.6E+06**	**4.4E+07**	**6.6E+08**
Column delay										**0**	**0**	**0**
Column degradation	10.63	27.0									Column	
Column delay+degradation										**72**	**92**	**299**

Initial thickness		**t=0 thickness**		**Times:**		
				CE	**CV**	**BE**
(in)	(cm)	(in)	(cm)	(yr)	(yr)	(yr)
				-322	**-365**	**-553**
12.28	31.2	11.02	28.0		Wall ⑤	
				2818	**3190**	**4831**
				-343	**-389**	**-588**
13.95	35.4	12.61	32.0		Wall ④	
				3225	**3651**	**5529**
				-378	**-428**	**-647**
16.85	42.8	15.37	39.0		Wall ③	
				3931	**4451**	**6740**
				-411	**-465**	**-704**
19.78	50.2	18.17	46.2		Wall ②	
				4648	**5262**	**7968**
				-441	**-499**	**-756**
22.60	57.4	20.88	53.0		Wall ①	
				5340	**6046**	**9155**

Table 8: Degradation timing detail for SDU 8 (Mix 3B) and 60/40/0 saltstone.

Degradation mechanism:			*SA*	*Carb*	*SA*	*Carb*	*SA*	*Carb*	**Sulfate attack**							**Carbonation**						
	Thickness:		CE	CE	CV	CV	BE	BE	**A (cm/√yr)**			**Time (yr)**			**max δ**	**A (cm/√yr)**			**Time (yr)**			**max δ**
Component	(in)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	CE	CV	BE	CE	CV	BE	(cm)	CE	CV	BE	CE	CV	BE	(cm)
Roof delay											*no clean grout:*	0	**0**	0				*HDPE-GCL:*	1900	1900	1900	
Roof degradation	12	30.48	29.4	1.03	25.2	5.29	21.9	8.57	0.197	0.159	0.124	1933	2545	3597	2.54	0.179	0.144	0.113	33	645	1697	2.54
Roof delay+degradation			0		0		0					1933	**2545**	3597					1933	**2545**	3597	
Floor delay											*immediate contact:*	0	**0**	0				*HDPE-GCL:*	1800	1750	1800	
Floor degradation	24	60.96	45.8	15.2	41.2	19.8	38.3	22.7	0.197	0.159	0.124	3004	4160	6288	2.54	0.179	0.144	0.113	1204	2410	4488	2.54
Floor delay+degradation			0		0		0					3004	**4160**	6288					3004	**4160**	6288	
Wall delay											*immediate contact:*	0	**0**	0				*no liner:*	0	**0**	0	
Wall degradation	11.02	28	15.3	12.7	15.3	12.7	15.3	12.7	0.197	0.159	0.124	1005	1547	2514	2.54	0.179	0.144	0.113	1005	1547	2514	2.54
Wall delay+degradation			0		0		0					1005	**1547**	2514					1005	**1547**	2514	
Wall delay											*immediate contact:*	0	**0**	0				*no liner:*	0	**0**	0	
Wall degradation	12.62	32.05	17.5	14.5	17.5	14.5	17.5	14.5	0.197	0.159	0.124	1151	1770	2877	2.54	0.179	0.144	0.113	1151	1770	2877	2.54
Wall delay+degradation			0		0		0					1151	**1770**	2877					1151	**1770**	2877	
Wall delay											*immediate contact:*	0	**0**	0				*no liner:*	0	**0**	0	
Wall degradation	15.38	39.07	21.4	17.7	21.4	17.7	21.4	17.7	0.197	0.159	0.124	1403	2158	3507	2.54	0.179	0.144	0.113	1403	2158	3507	2.54
Wall delay+degradation			0		0		0					1403	**2158**	3507					1403	**2158**	3507	
Wall delay											*immediate contact:*	0	**0**	0				*no liner:*	0	**0**	0	
Wall degradation	18.18	46.19	25.3	20.9	25.3	20.9	25.3	20.9	0.197	0.159	0.124	1658	2552	4146	2.54	0.179	0.144	0.113	1658	2552	4146	2.54
Wall delay+degradation			0		0		0					1658	**2552**	4146					1658	**2552**	4146	
Wall delay											*immediate contact:*	0	**0**	0				*no liner:*	0	**0**	0	
Wall degradation	20.89	53.07	29	24	29	24	29	24	0.197	0.159	0.124	1906	2932	4764	2.54	0.179	0.144	0.113	1906	2932	4764	2.54
Wall delay+degradation			0		0		0					1906	**2932**	4764					1906	**2932**	4764	
Grout delay																						
Grout degradation	516	1311																				
Grout delay+degradation																						
Column delay											*immediate contact:*	0	**0**	0								
Column degradation	10.63	27.0	27.0	0	27.0	0	27.0	0	0.977	0.863	0.479	72	92	299	2.54							
Column delay+degradation												72	**92**	299								

Table 8: Degradation timing detail for SDU 8 (Mix 3B) and 60/40/0 saltstone (continued).

Degradation mechanism:	**Decalcification**									**Limiting**		
	Thickness:		**A (cm/√yr)**			**Time (yr)**			**max δ**	**CE**	**CV**	**BE**
Component	(in)	(cm)	CE	CV	BE	CE	CV	BE	(cm)	(yr)	(yr)	(yr)
Roof delay					*HDPE-GCL:*	1900	1900	1900		**0**	**0**	**0**
Roof degradation	12	30.48	0.032	0.026	0.020	76114	117099	190286	2.54		Roof	
Roof delay+degradation						78014	118999	192186		**1933**	**2545**	**3597**
FloorUMM delay					*HDPE-GCL:*	1800	1750	1800		**0**	**0**	**0**
FloorUMM degradation	24	60.96	0.032	0.026	0.020	152229	234198	380572	2.54		Floor	
FloorUMM delay+degradation						154029	235948	382372		**3004**	**4160**	**6288**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	11.02	28	0.032	0.026	0.020	69925	107577	174813	2.54		Wall ⑤	
Wall delay+degradation						69925	107577	174813		**1005**	**1547**	**2514**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	12.62	32.05	0.032	0.026	0.020	80033	123128	200083	2.54		Wall ④	
Wall delay+degradation						80033	123128	200083		**1151**	**1770**	**2877**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	15.38	39.07	0.032	0.026	0.020	97558	150090	243896	2.54		Wall ③	
Wall delay+degradation						97558	150090	243896		**1403**	**2158**	**3507**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	18.18	46.19	0.032	0.026	0.020	115343	177450	288357	2.54		Wall ②	
Wall delay+degradation						115343	177450	288357		**1658**	**2552**	**4146**
Wall delay					*no liner:*	0	0	0		**0**	**0**	**0**
Wall degradation	20.89	53.07	0.032	0.026	0.020	132527	203888	331318	2.54		Wall ①	
Wall delay+degradation						132527	203888	331318		**1906**	**2932**	**4764**
Grout delay				**A_U (cm/yr)**		1933	2545	3597		**1933**	**2545**	**3597**
Grout degradation	516	1311	1.8E-04	2.7E-05	1.8E-06	7300615	4.9E+07	7.3E+08			Grout	
Grout delay+degradation						7.3E+06	**4.9E+07**	7.3E+08		**7.3E+06**	**4.9E+07**	**7.3E+08**
Column delay										**0**	**0**	**0**
Column degradation	10.63	27.0									Column	
Column delay+degradation										**72**	**92**	**299**

Initial thickness		**t=0 thickness**		**Times:**		
				CE	**CV**	**BE**
(in)	(cm)	(in)	(cm)	(yr)	(yr)	(yr)
				-114	**-176**	**-286**
12.28	31.2	11.02	28.0		Wall ⑤	
				1005	**1547**	**2514**
				-122	**-187**	**-305**
13.95	35.4	12.62	32.0		Wall ④	
				1151	**1770**	**2877**
				-134	**-206**	**-335**
16.85	42.8	15.38	39.1		Wall ③	
				1403	**2158**	**3507**
				-145	**-224**	**-364**
19.78	50.2	18.18	46.2		Wall ②	
				1658	**2552**	**4146**
				-156	**-240**	**-390**
22.60	57.4	20.89	53.1		Wall ①	
				1906	**2932**	**4764**

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