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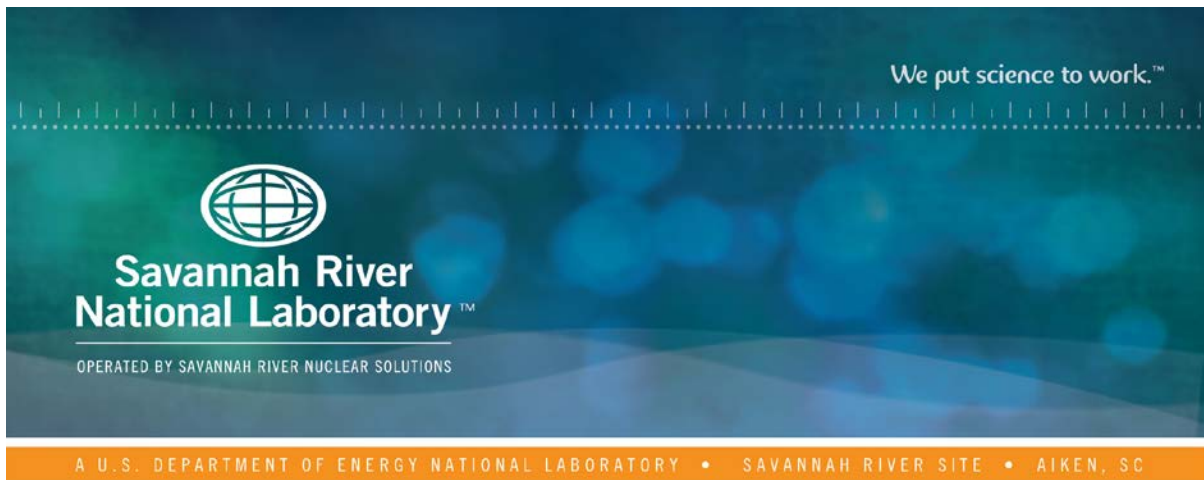
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# Degradation Of Cementitious Materials Associated with Saltstone Disposal Units

G. P. Flach  
F. G. Smith, III

September 2014

SRNL-STI-2013-00118, Rev. 2



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## **DEGRADATION OF CEMENTITIOUS MATERIALS ASSOCIATED WITH SALTSTONE DISPOSAL UNITS**

**G. P. Flach**  
**F. G. Smith III**

**September 2014**

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contract number DE-AC09-08SR22470.

## REVIEWS AND APPROVALS

G. P. Flach, Author, Radiological Performance Assessment	Date
F. G. Smith III, Author, Process Modeling & Computational Chemistry	Date
G. A. Taylor, Design Check, Radiological Performance Assessment	Date
J. E. Laurinat, Design Check, Process Modeling & Computational Chemistry	Date
D. A. Crowley, Manager, Radiological Performance Assessment	Date
M. B. Gorenssek, Manager, Process Modeling & Computational Chemistry	Date
R. S. Aylward, Manager, Environmental Restoration Technology	Date
M. K. Harris, Manager, Computational Sciences	Date
K. H. Rosenberger, Manager, Closure & Disposal Assessment	Date

## EXECUTIVE SUMMARY

The Saltstone facilities at the DOE Savannah River Site (SRS) stabilize and dispose of low-level radioactive salt solution originating from liquid waste storage tanks at the site. The Saltstone Production Facility (SPF) receives treated salt solution and mixes the aqueous waste with dry cement, blast furnace slag, and fly ash to form a grout slurry which is mechanically pumped into concrete disposal cells that compose the Saltstone Disposal Facility (SDF). The solidified grout is termed “saltstone”.

Cementitious materials play a prominent role in the design and long-term performance of the SDF. The saltstone grout exhibits low permeability and diffusivity, and thus represents a physical barrier to waste release. The waste form is also reducing, which creates a chemical barrier to waste release for certain key radionuclides, notably Tc-99. Similarly, the concrete shell of a saltstone disposal unit (SDU) represents an additional physical and chemical barrier to radionuclide release to the environment. Together the waste form and the SDU compose a robust containment structure at the time of facility closure. However, the physical and chemical state of cementitious materials will evolve over time through a variety of phenomena, leading to degraded barrier performance over Performance Assessment (PA) timescales of thousands to tens of thousands of years. Previous studies of cementitious material degradation in the context of low-level waste disposal have identified sulfate attack, carbonation influenced steel corrosion, and decalcification (primary constituent leaching) as the primary chemical degradation phenomena of most relevance to SRS exposure conditions.

In this study, degradation time scales for each of these three degradation phenomena are estimated for saltstone and concrete associated with each SDU type under conservative, nominal, and best estimate assumptions. The nominal value (NV) is an intermediate result that is more probable than the conservative estimate (CE) and more defensible than the best estimate (BE). The combined effects of multiple phenomena are then considered to determine the most limiting degradation time scale for each cementitious material. Degradation times are estimated using a combination of analytic solutions from literature and numerical simulation codes provided through the DOE Cementitious Barriers Partnership (CBP) Software Toolbox. Task Technical Requests HLW-SSF-2013-0001 Rev. 3, HLW-SSF-TTR-2013-0021 Rev. 2, and G-TTR-Z-00007 Rev. 0 define the scope of the analysis and certain input data.

For the SDU 2 design with a clean cap fill, the roof, wall, and floor components are projected to become fully degraded under Nominal conditions at 3855, 922, and 1413 years, respectively. For SDU 4 the roof and floor are estimated to be fully degraded under Nominal conditions after 1106 and 1404 years, respectively; the wall is assumed to be fully degraded at time zero in the most recent PA simulations. Degradation of these concrete barriers generally occurs from combined sulfate attack and corrosion of embedded steel following carbonation. Saltstone is projected to degrade very slowly by decalcification, with complete degradation occurring in excess of 200,000 years for any SDU type. Complete results are provided in Table 5-1 through Table 5-3. Additional results for the SDU 2 and SDU 6 designs are provided in Table 5-5 through Table 5-7 assuming the absence of the traditional clean cap fill and column degradation by carbonation-influenced steel corrosion. For the SDU 6 design, the roof and floor components are projected to fully degrade by 1413 years while the tapered wall fully degrades at 815 years for the thinnest section and 1822 years for the thickest section. Additional degradation results are presented in Table 5-12 through Table 5-16 for SDU 2 and 6 assuming column degradation by sulfate attack.

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## **LIST OF ACRONYMS**

ACI	American Concrete Institute
BE	Best Estimate
CBP	Cementitious Barriers Partnership
CE	Conservative Estimate
CSH	Calcium-Silicate-Hydrate
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
DOE	Department of Energy
NV	Nominal Value
PA	Performance Assessment
SDF	Saltstone Disposal Facility
SDU	Saltstone Disposal Unit
SPF	Saltstone Production Facility
SRS	Savannah River Site
SRR	Savannah River Remediation
SRNL	Savannah River National Laboratory

## 1.0 INTRODUCTION

The Saltstone facilities at the DOE Savannah River Site (SRS) stabilize and dispose of low-level radioactive salt solution originating from liquid waste storage tanks at the site. The Saltstone Production Facility (SPF) receives treated salt solution and mixes the aqueous waste with dry cement, blast furnace slag, and fly ash to form a grout slurry which is mechanically pumped into concrete Saltstone Disposal Units (SDUs) that compose the Saltstone Disposal Facility (SDF). The solidified grout is termed “saltstone”. The *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site* (SRR 2009) and supporting documents provide further information about the general design and operation of the SDF.

Cementitious materials play a prominent role in the design and long-term performance of the SDF. Saltstone exhibits low permeability and diffusivity, and thus represents a physical barrier to waste release. The waste form is also reducing, which creates a chemical barrier to waste release for certain key radionuclides, notably Tc-99. Similarly, the concrete shell of an SDU represents an additional physical and chemical barrier to radionuclide release to the environment. Together the waste form and disposal cell compose a robust containment structure at the time of facility closure.

However, the physical and chemical state of cementitious materials will evolve over time through a variety of phenomena, leading to degraded barrier performance over Performance Assessment (PA) timescales of thousands to tens of thousands of years. Previous studies of cementitious material degradation in the context of low-level waste disposal have identified sulfate attack, carbonation-influenced steel corrosion, and decalcification (primary constituent leaching) as the primary chemical degradation phenomena of most relevance to SRS exposure conditions (Walton et al. 1990, Langton 2007, 2010a, Samson et al. 2009).

In this study, degradation time scales for each of these three degradation phenomena are estimated for saltstone and the SDU concrete associated with each SDU type under conservative, nominal, and best estimate assumptions. The nominal value (NV) is an intermediate result that is more probable than the conservative estimate (CE) and more defensible than the best estimate (BE). The combined effects of multiple phenomena are then considered to determine the most limiting degradation time scale for each cementitious material. Degradation times are estimated using a combination of analytic solutions from literature and numerical simulation codes provided through the DOE Cementitious Barriers Partnership (CBP) Software Toolbox (<http://cementbarriers.org>). Task Technical Requests HLW-SSF-2013-0001 Rev. 3, HLW-SSF-TTR-2013-0021 Rev. 2, and G-TTR-Z-00007 Rev. 0 define the scope of the analysis and certain input data.

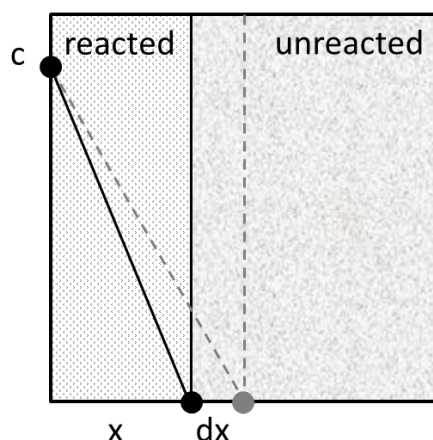
Revision 1 (Flach and Smith 2013b) of this report differs from Revision 0 (Flach and Smith 2013a) in four aspects. First, the carbonation analysis was revised to account for the primary dissolved carbon species being bicarbonate ( $HCO_3^-$ ) at the elevated  $pH$  associated with cement pore water, rather than carbonic acid ( $H_2CO_3$ ) assumed in Revision 0. The practical impact is insignificant to NV results because gas phase  $CO_2$  diffusion dominates liquid phase carbon transport. Second, the moisture characteristic curve (van Genuchten 1980) parameters for saltstone were revised to implement the 20°C cure temperature ARP/MCU saltstone properties

recommended by SRR (Sheppard 2013b). In Revision 0 values for 60°C ARP/MCU saltstone were inadvertently used. The impact is again insignificant to the NV analysis. Third, degradation times were estimated for the anticipated SDU 6 design that will supersede SDU 2. The SDU 6 design utilizes the same concrete formulation as SDU 2, so degradation analyses of the latter generally apply to SDU 6 except for geometrical differences. “Design” and “Design w/Margin” cases were analyzed. Finally, the absence of clean grout filling the upper interior volume was considered for SDU 2 and SDU 6. The direct effect is earlier degradation of the concrete roof, because sulfate attack begins immediately when saltstone is in contact with the underside of the roof. Contact is assumed to occur at the time of facility closure; that is, any contact time prior to closure, up to approximately 20 years, is considered minimal and neglected in the degradation analysis.

The current Revision 2 includes added discussion of passive steel corrosion and biodegradation, defines time zero for the degradation analysis as the time of facility closure, corrects a minor molecular weight error embedded in the SDU 6 estimates of initial ( $t = 0$ ) wall degradation, and augments the Revision 1 SDU 2/6 analysis of column degradation to consider the presence of sulfate attack on these reinforced concrete components.

### 1.1 Generic moving reaction front

The degradation mechanisms under consideration share the same basic functional form when the chemical reaction zone moves slowly as a sharp front across the porous medium and diffusion with constant diffusivity is the dominant transport mode for the fluid (gas or liquid) phase reactant, as shown in Figure 1-1.



**Figure 1-1. Generic moving reaction front controlled by diffusion.**

The differential molar balance for this generic moving front system is

$$Sn\tau D_m \frac{c}{x} dt = R(1-n)\rho_s dx \quad (1.1)$$

where

$S$  = saturation of fluid phase delivering reactant to moving front  
[cm<sup>3</sup> phase / cm<sup>3</sup> void]

$n$  = porosity [cm<sup>3</sup> void / cm<sup>3</sup> total]

$\tau$  = tortuosity, defined here as the ratio of effective to molecular diffusion coefficient (< 1) [-]

$D_m$  = molecular diffusion coefficient for fluid phase [cm<sup>2</sup>/yr]

$x$  = penetration depth [cm]

$t$  = elapsed time [yr]

$c$  = concentration of fluid phase reactant [mol / cm<sup>3</sup> phase]

$R$  = reaction capacity of solid [mol / g solid], i.e., moles of fluid phase reactant consumed per mass of solid

$\rho_s$  = solid / mineral density [g/cm<sup>3</sup> solid]

Integration of Equation (1.1) yields the following analytic expression for penetration depth

$$x = \left[ \frac{2Sn\tau D_m c t}{(1-n)\rho_s R} \right]^{1/2} \quad (1.2)$$

Inspection of Equation (1.2) indicates that movement of the reaction front is proportional or inversely proportional to the square root of all quantities except porosity. Equation (1.2) can be used to define the relative effect of a parameter change compared to a baseline result. For example, a modified exposure concentration ( $c_2$ ) produces an altered penetration depth ( $x_2$ ) given by

$$x_2 = \left[ \frac{c_2}{c_1} \right]^{1/2} x_1 \quad (1.3)$$

where  $c_1$  and  $x_1$  are the baseline conditions.

The effective reaction capacity of a numerical reactive transport model can be derived using Equation (1.2) for a selected penetration depth ( $x_0$ ) and time ( $t_0$ ) as

$$R = \frac{2Sn\tau D_m c t_0}{(1-n)\rho_s x_0^2} \quad (1.4)$$

Equation (1.4) is useful for translating numerical simulation results into the equivalent analytic form given by Equation (1.2), assuming the numerical model exhibits the underlying behavior implied by Equation (1.2). Alternatively, Equation (1.2) can be written as

$$x = At^{1/2} \quad (1.5)$$

where the rate constant  $A$  is defined by

$$A = \left[ \frac{2Sn\tau D_m c}{(1-n)\rho_s R} \right]^{1/2} \quad (1.6)$$

and empirically derived from a numerical simulation result  $(t_0, x_0)$  as

$$A = \frac{x_0}{t_0^{1/2}} \quad (1.7)$$

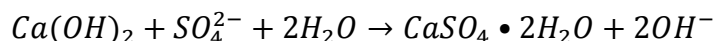
The time  $t_0$  associated with a certain penetration depth  $x_0$  is

$$t_0 = \frac{x_0^2}{A^2} \quad (1.8)$$

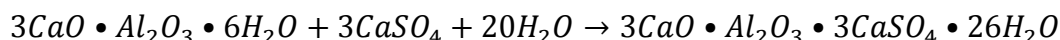
Equations (1.2) through (1.8) are generally applicable to all three degradation mechanisms being considered in this study (provided that the diffusion coefficient is fixed), although the particulars differ. In the case of sulfate attack, sulfate dissolved in the liquid phase diffuses into the porous medium, and reacts with the solid forming ettringite. In the case of carbonation, carbon dioxide in the gas phase diffuses in, reacts with the solid forming calcite, and the pH is lowered. In the case of decalcification, the 'reaction' is calcium in the solid dissolving into the liquid phase; the dissolved calcium then diffuses out of the porous medium. The report sections that follow address the specific analyses performed for sulfate attack, carbonation, and decalcification.

## 2.0 SULFATE ATTACK

Pore water in the saltstone waste form is expected to contain on the order of 0.1 M sulfate. Over time, as sulfate ions migrate into the cement barrier surrounding the waste and react with calcium hydroxide (Portlandite) to form calcium sulfate (gypsum) according to the reaction:



Calcium sulfate reacts with calcium/aluminum oxide minerals to form calcium aluminum sulfates such as ettringite according to the overall reaction:



These reactions alter the mineral content of the concrete. Products of the sulfate reactions have a greater volume than the reactants. The resulting expansion of the solid phase leads to cracking which has a deleterious impact on structural integrity and the ability of the cementitious barrier to contain the radioactive waste. Sulfate attack has been identified as one of the primary mechanisms for the degradation of Saltstone concrete (SRR 2009, Samson et al. 2009, Sarkar, et al., 2010a).

The Cementitious Barriers Partnership (CBP) Project is a multi-disciplinary, multi-institutional collaboration supported by the United States Department of Energy (US DOE) Office of Tank Waste Management with the objective of developing a set of tools to improve understanding and prediction of the long-term performance of cementitious barriers used in nuclear applications. The CBP is a partnership of federal, academic, private sector, and international expertise. In addition to the US DOE, the CBP partners are the Savannah River National Laboratory (SRNL), Consortium for Risk Evaluation with Stakeholder Participation (CRESP) at Vanderbilt University (VU), Energy Research Center of the Netherlands (ECN), and SIMCO Technologies, Inc. The Nuclear Regulatory Commission (NRC) is providing support under a Memorandum of Understanding. The National Institute of Standards and Technology (NIST) is providing research under an Interagency Agreement.

The CBP Project has released a Software Toolbox that includes two models that can be used to assess sulfate attack on SDUs (Brown, et al., 2013b). One model is a version of the STADIUM code developed by SIMCO (Samson, 2010) which models the transport of chemical ions and water through porous materials and reactions between the chemical and mineral species. The model solves a set of coupled differential equations describing one dimensional transport processes while simultaneously evaluating local diffusion coefficients and equilibrium chemical and mineral compositions in the materials. STADIUM can model systems with one (concrete), two (concrete and saltstone) or three (concrete, saltstone and soil) layers of materials. One limitation of STADIUM modeling is that structural changes and damage to the concrete have no direct impact on the diffusion and transport properties.

The other model included in the CBP Toolbox is a sulfate attack module based on LeachXS/Orchestra (LXO) developed at the ECN and Vanderbilt University with CRESP funding (Sarkar et al. 2010a, b, 2011; Meeussen, et al., 2010). Similar to STADIUM, LXO calculates transport rates of species through porous media and chemical equilibria between local

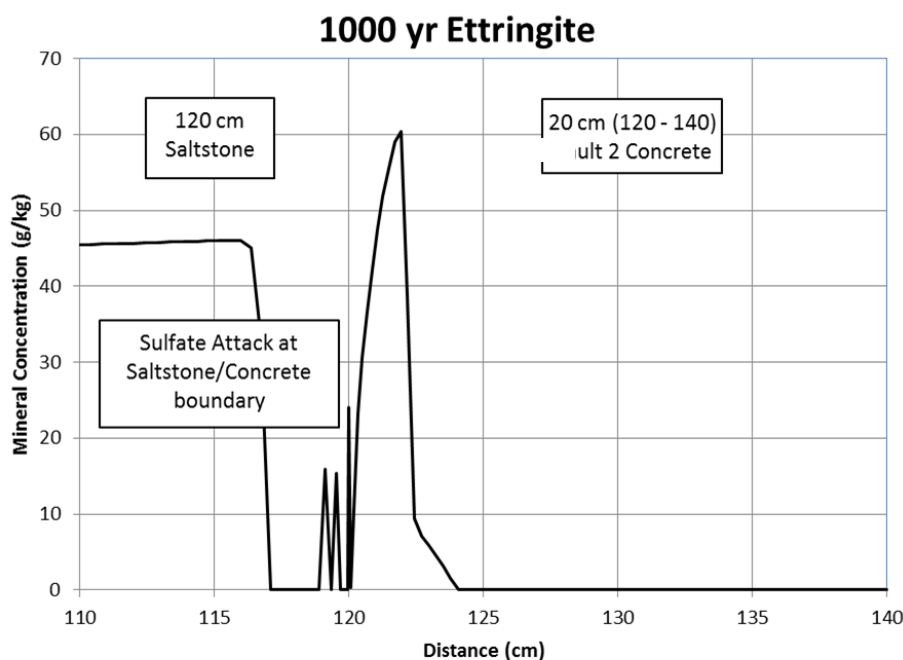


chemical and mineral phases. However, the LXO sulfate attack module also performs a damage calculation and modifies transport properties where damage is predicted. LXO models the material as a network of interconnected cells within which chemical equilibrium is maintained while transport of chemical species between cells occurs by diffusion and convection. The version of LXO released with the initial CBP Toolbox only allows modeling a single material.

## 2.1 STADIUM Sulfate Attack

Simulations of SDU 2 and SDU 1/4 concrete degradation were performed using the STADIUM code through the CBP Toolbox interface. The SDU 6 conceptual design utilizes the same concrete mix as SDU 2, so the SDU 2 simulations are applicable to the future SDU 6 design. For quality assurance, a preliminary run was made to confirm that the STADIUM model in the CBP Toolbox reproduced results for SDU 2 concrete as reported by Samson (2010) and again by Protiere et al. (2012). Using the data and parameters in the CBP Toolbox, the STADIUM model was run to simulate 1,000 years of concrete degradation for SDU 2 concrete. The concrete thickness was 20 cm (8 in) which is representative of the SDU 2 wall and roof thickness. Results from this trial calculation are plotted in Figure 2.1 which shows that, after 1,000 years of exposure, an ettringite mineral front has penetrated to a depth of approximately 2.5 cm from the saltstone interface (the concrete layer is from 120 cm to 140 cm in the plot). The shape of the ettringite front is consistent with that shown in the previous reports and the front depth is in agreement with the value reported at 1000 years in the cited publications. Using a simple linear extrapolation, this result would predict a concrete life of approximately 8,000 years.

However, in June 2010 SIMCO published a revised saltstone composition (SIMCO, 2010) which corrected an error in previous formulations and which produced a wasteform significantly more resistant to chemical attack. In March 2012, SIMCO also published a document (SIMCO, 2012) revising the SDU concrete compositions and properties based on better characterization of the constituent materials. The revised SDU 2 saltstone and revised concrete compositions were run using the STADIUM model with the CBP Toolbox. The simulations used a sulfate concentration in the pore fluid of 0.1 M resulting from a mixing solution concentration of 0.05 M. As points of reference, a recent WAC (Waste Acceptance Criteria) sample from Tank 50 had a sulfate concentration of 0.05 M (Bannochie 2011) and the sulfate concentration in feedwater to the SPF assumed in the Saltstone PA is 0.10 mol/L (Dean 2009). Results of the STADIUM calculations are shown in Figure 2.2 for simulations of 1,000 and 5,000 years. The revised compositions yielded significantly reduced ettringite penetration into the concrete, and suggest SDU 2 concrete is highly resistant to sulfate attack compared to ordinary concrete. Physical properties of the SDU 2 concrete have not changed significantly from previous values. Therefore, the reduced ettringite formation appears to derive from changes in the concrete chemistry. The revised ionic concentrations in SDU 2 concrete pore water reported by SIMCO (2012) are much lower than previous values and the concrete mineral composition has also changed significantly.



**Figure 2-1. STADIUM prediction of sulfate attack on SDU 2 concrete at saltstone/concrete interface using default CBP Toolbox parameters.**

The revised SIMCO saltstone and cement compositions were also used to perform a 1000 year STADIUM simulation of sulfate attack on 45 cm (18 in) of SDU 1/4 cement. The 45 cm thickness is representative of the SDU 1/4 wall. Results from this simulation are shown in Figure 2.3. The predicted ettringite front for this system is more similar to that obtained by previous STADIUM analyses, as shown in Figure 2.1.

Results from the STADIUM analyses using the latest SIMCO concrete and saltstone waste compositions are listed in Table 2.1. The ettringite penetration depth is conservatively defined as the furthest point of ettringite presence indicated by Figures 2.1 and 2.2. In comparison, SIMCO (2010) used the vertical face of the ettringite peak. STADIUM does not predict whether damage will occur, and thus does not alter transport properties in response to damage. To estimate degradation times, physical damage (e.g., cracking, spalling) is assumed to coincide with the presence of ettringite in STADIUM simulations. To approximately account for the effect of physical damage on transport, the estimated time for complete concrete degradation is calculated using a simple linear extrapolation of the model calculated results at 1000 years assuming no degradation at time zero. That is, no credit is taken for the possibility that ettringite may penetrate as a diffusion front obeying Equation (1.5), which would lead to longer times for complete penetration.

**Table 2-1. Results from STADIUM concrete degradation simulations.**

Concrete	Ettringite front depth* at 1000 years (a)	Ettringite front depth* at 5000 years (a)	Thickness	Estimated Time for Complete Degradation
SDU 2	0.5 cm	1.5 cm	20 cm	40,000 yr
SDU 1/4	5.5 cm	-	45 cm	8,200 yr

\* based on furthest point of ettringite penetration

In the 2009 Saltstone PA, the following empirical relationship was derived to calculate sulfate attack penetration depth, based on previous STADIUM calculations:

$$x = Ac^B t^{1/2} \quad (2.1)$$

In Equation (2.1),  $c$  is the molar concentration of sulfate in pore water and the coefficients  $A$  and  $B$  are 0.412 and 0.380 for SDU 1/4 and 0.626 and 0.467 for SDU 2, respectively. These calculations involved a single layer of concrete with approximate properties based on a surrogate material. Application of this equation predicts degradation times of approximately 8,800 years for 20 cm of SDU 2 concrete and 69,000 years for 45 cm of SDU 1/4 concrete. These results are almost the converse of those obtained with STADIUM using the revised saltstone and concrete compositions. These differences indicate the sensitivity of sulfate attack predictions to initial mineral composition (Samson 2010) and transport properties. The results presented in Figures 2.1 and 2.2 and Table 2.1 are considered more reliable because they involve a more realistic two-layer system and material properties have been updated using the best available characterization studies.

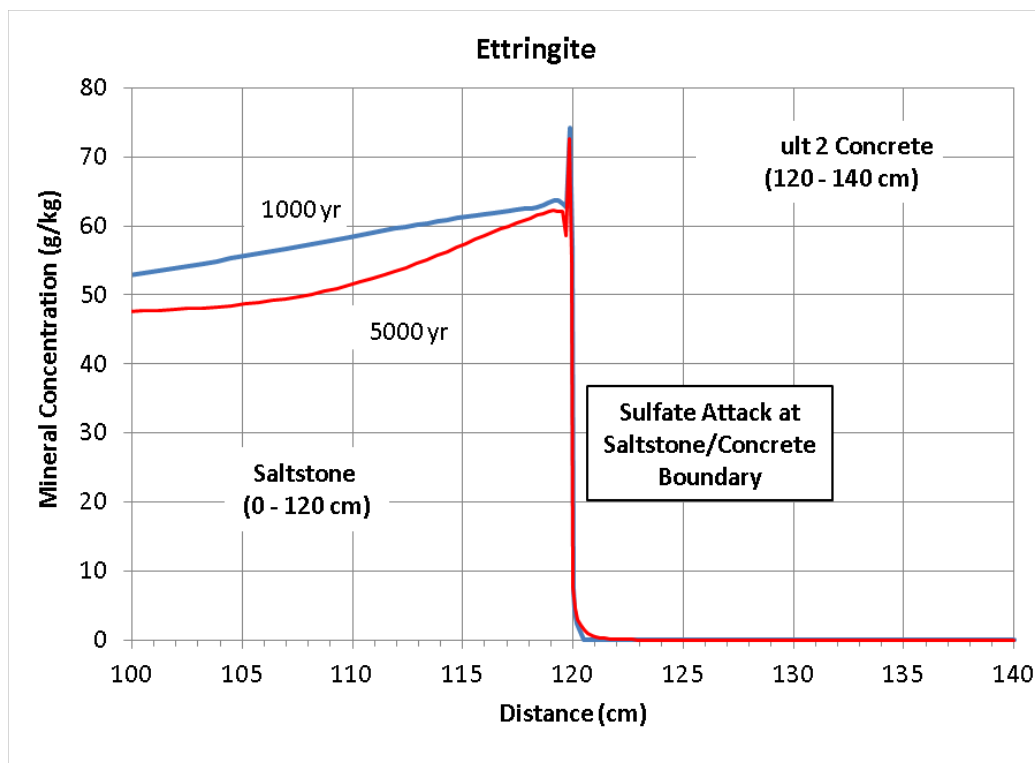


Figure 2-2. STADIUM prediction of sulfate attack on SDU 2 concrete at 1000 and 5000 years.

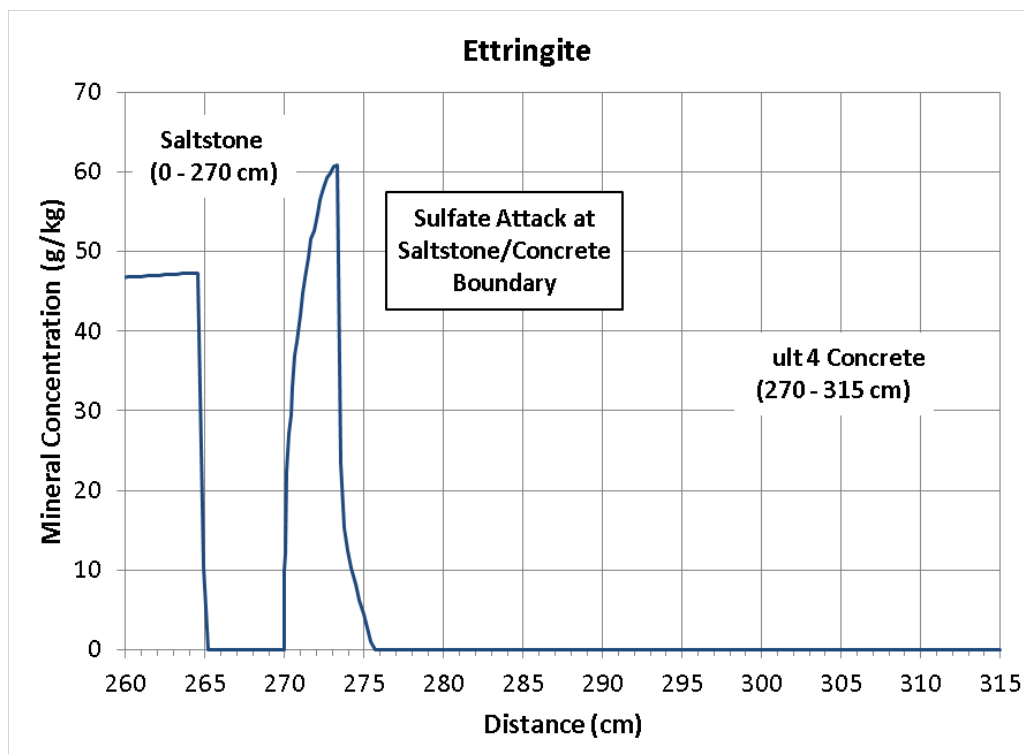


Figure 2-3. STADIUM prediction of sulfate attack on SDU 1/4 concrete at 1000 years.

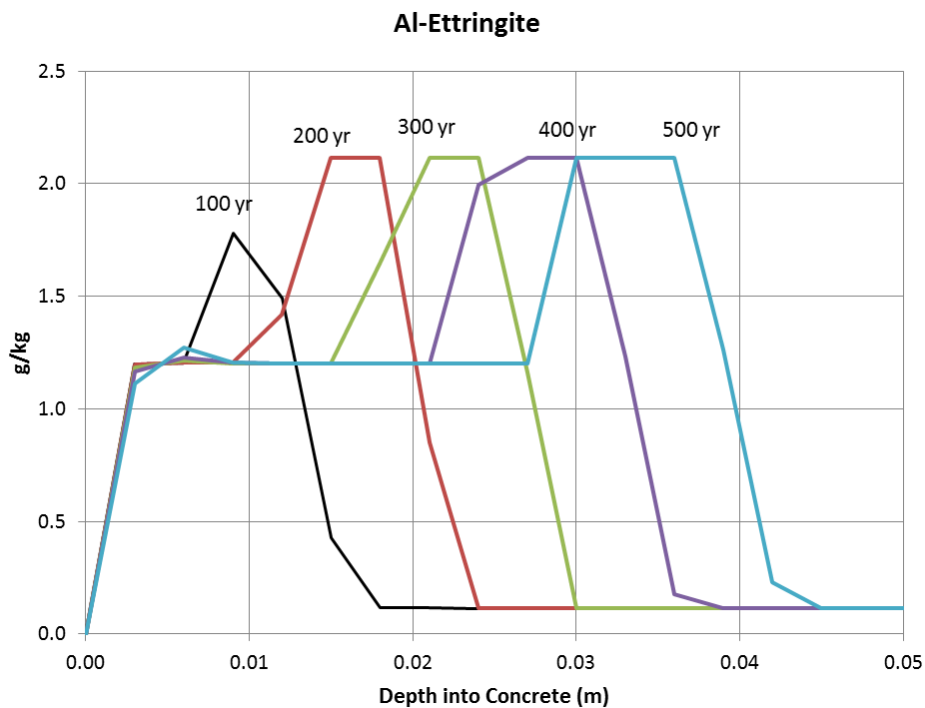
## 2.2 LXO Sulfate Attack

Several sets of calculations were also performed using the LXO module in the CBP Toolbox to predict sulfate attack on SDU 1/4 concrete at thicknesses of 45 and 60 cm and SDU 2 concrete at thicknesses of 20 and 30 cm. The smaller concrete thickness was representative of SDU 2 wall thickness while the larger value was representative of SDU 1/4 floor thickness. The LXO calculations used the default concrete chemical compositions in the CBP Toolbox and revised mineral compositions based on the recent SIMCO analysis (SIMCO, 2012). Except as noted below, the concrete parameters contained in the initial CBP Toolbox release such as thermal conductivity, specific heat, and rate of hydration were also used in the analysis. The initial sulfate concentration in the fluid phase was set to 0.1 M.

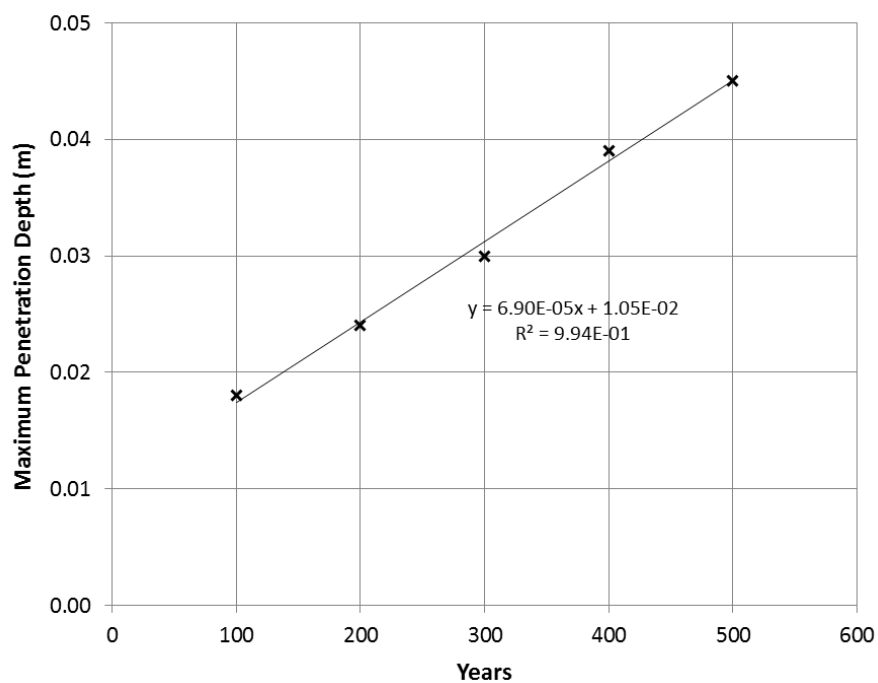
The use of Orchestra (the modeling part of LXO) to model sulfate attack on cementitious material is discussed in detail by Sarkar et al. (2009). The model uses a parameter designated as the “fractional porosity” ( $b$ ) which is defined to be the fraction of the pore volume that must be filled with mineral products from the chemical reactions that occur during concrete aging before cracking and concrete damage occur. The larger the fractional porosity the more pore volume is available for solid product deposition and the less damage occurs. Results are very sensitive to this parameter.

Sarkar et al. (2009) concluded that in general the optimal value for fractional porosity is  $b = 0.3$  based on model calibration and literature review. The main effect of fractional porosity in the model is to cause an increase in the diffusion coefficient, which accelerates delivery of sulfate to the reaction front and ettringite penetration. The model implicitly assumes saturated conditions (i.e. pores in the concrete are filled with water) for this calculation. However, any cracks that form during sulfate attack are expected to be unsaturated under Saltstone conditions, based on Equation (3.10) and surrounding discussion in Section 3.0. Such “dry” cracks would likely cause a smaller increase in diffusion coefficient compared to saturated cracks, or even impede diffusion (Seol et al. 2003). Unsaturated cracks and slower diffusion compared to saturated conditions can be approximately accounted for by increasing fractional porosity above 0.3. Based on engineering judgment, the current study was performed using a fractional porosity of 0.45 as the nominal value representative of *unsaturated* conditions with minimum (conservative estimate) and maximum (best estimate) values of 0.3 and 0.6, respectively.

The progression of an ettringite mineral front into the concrete coincides with the extent of concrete damage according to the LXO sulfate attack model. The ettringite front also coincides with a decrease in concrete porosity as predicted by the LXO model which would be indicative of concrete damage. After an initial period of rapid penetration, the rate of progression of the ettringite front predicted by LXO was found to be approximately linear, in contrast to a square root of time dependence indicated by Equations (1.2) and (1.5) for fixed diffusivity. Results showing ettringite mineralization in the concrete for the case of 30 cm of SDU 2 concrete with a fractional porosity of 0.6 at 100 year intervals are shown in Figure 2.4. The maximum ettringite penetration depth is plotted as a function of time in Figure 2.5 where the linear progression between 100 and 500 years is apparent. LXO simulations were performed for either 350 years or 500 years. Based on the results shown in Figure 2.5, the time for complete concrete degradation was estimated from the penetration depth predicted at the end of the simulation using linear extrapolation.



**Figure 2-4. Ettringite front penetration as a function of time for 30 cm of SDU 2 concrete with a fractional porosity of 0.6.**



**Figure 2-5. Maximum ettringite front penetration as a function of time for 30 cm of SDU 2 concrete with a fractional porosity of 0.6.**

### 2.2.1 LXO Simulation of Sulfate Attack on SDU 2 Concrete

SDU 2 calculations were performed for a concrete thickness of 20 cm, which is representative of the SDU 2 wall thickness, and for a concrete thickness of 30 cm, representative of the SDU 2 floor. An initial concrete porosity of 0.115 was used in these calculations and the VCT (“Vault Concrete Two”, SDU 2 mix) concrete composition was selected through the CBP user interface. Results for the 20 cm concrete thickness are shown in Figure 2.6 for the three values of fractional porosity specified and results for the 30 cm thickness are shown in Figure 2.7. It was intended to run all of the simulations for 500 years; however, when the front progressed beyond 50% of the concrete thickness, the LXO code had difficulty converging. Therefore, to obtain a consistent set of results, all SDU 2 calculations for 20 cm thickness were performed for only 350 years.

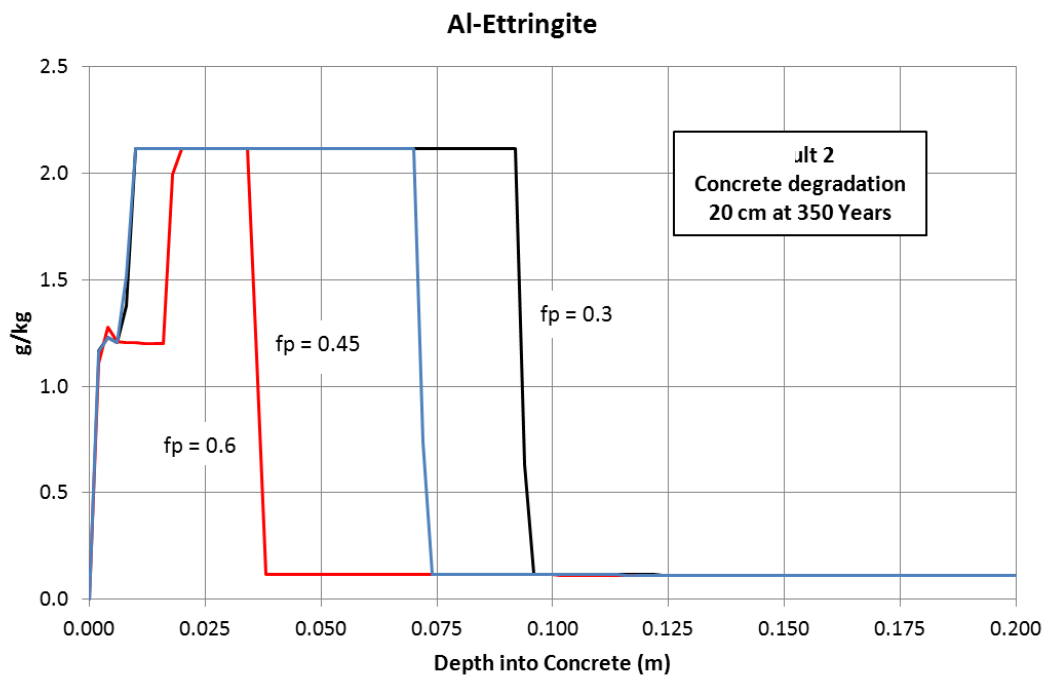
Linear extrapolation was used to estimate a time for complete concrete degradation from the front penetration times shown in Figures 2.6 and 2.7. Results of these calculations are listed in Table 2.2 and 2.3 for the 20 cm and 30 cm concrete thickness, respectively. The degradation times were then plotted as a function of fractional porosity and fit to a polynomial function. The fitting function was used to interpolate degradation times at intermediate values of the fractional porosity with the results plotted in Figure 2.8. The results shown in Figure 2.8 illustrate the sensitivity of the estimate of degradation to the fractional porosity. Beyond a fractional porosity of 0.5, the curves increase sharply.

**Table 2-2. SDU 2 LXO sulfate attack calculations for 20 cm of concrete.**

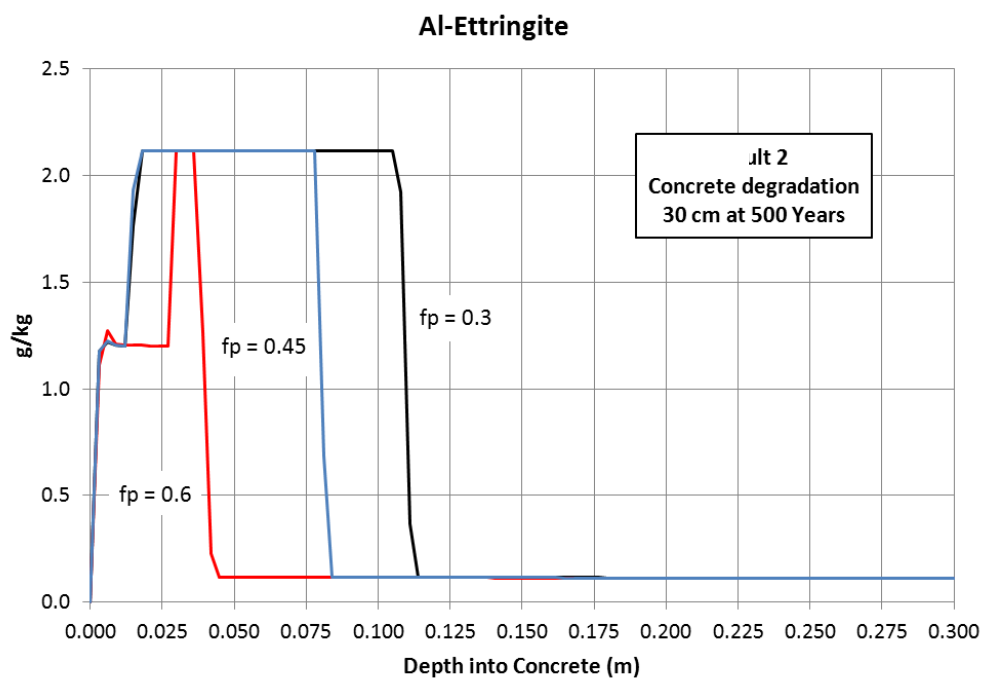
Fractional Porosity	Years	Front Depth (cm)	Fraction Degraded	Estimated Time for Complete Degradation
0.60	350	3.8	0.190	1842
0.45	350	7.4	0.370	946
0.30	350	9.4	0.470	745

**Table 2-3. SDU 2 LXO sulfate attack calculations for 30 cm of concrete.**

Fractional Porosity	Years	Front Depth (cm)	Fraction Degraded	Estimated Time for Complete Degradation
0.60	500	4.5	0.150	3333
0.45	500	8.4	0.280	1786
0.30	500	11.1	0.370	1351

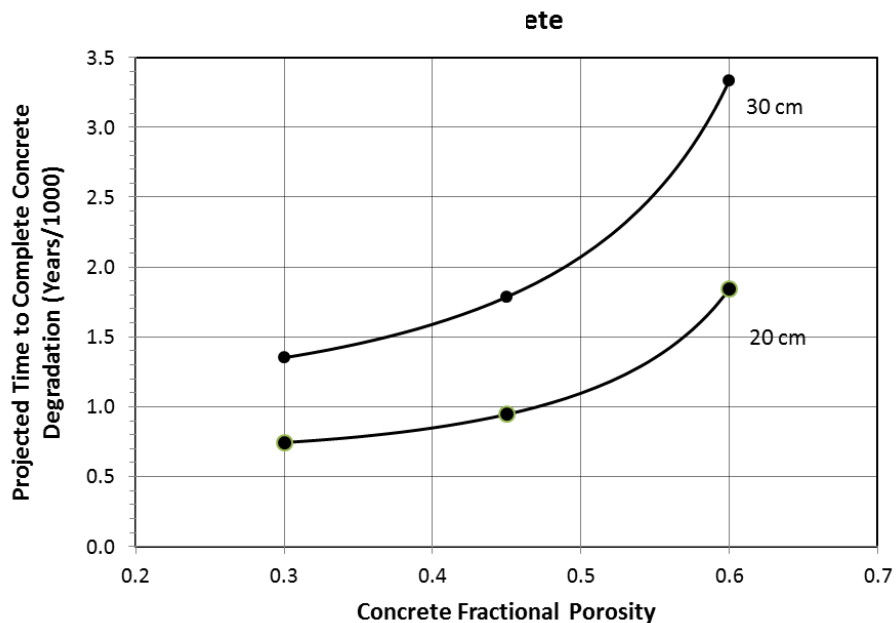


**Figure 2-6. Ettringite front penetration as a function of concrete fractional porosity for 20 cm SDU 2 concrete.**



**Figure 2-7. Ettringite front penetration as a function of concrete fractional porosity for 30 cm SDU 2 concrete.**





**Figure 2-8. Predicted times for 100% SDU 2 concrete degradation as a function of fractional porosity.**

### 2.2.2 LXO Simulation of Sulfate Attack on SDU 1/4 Concrete

SDU 1/4 calculations were performed for a concrete thickness of 45 cm, which is representative of the SDU 1/4 wall thickness, and for a concrete thickness of 60 cm, representative of the SDU 1/4 floor. An initial concrete porosity of 0.12 was used in these calculations and the VCO (“Vault Concrete One”, SDU 1/4 mix) concrete composition was selected through the CBP Toolbox user interface. Results for the 45 cm concrete thickness are shown in Figure 2.9 for the three values of fractional porosity specified and results for the 60 cm thickness are shown in Figure 2.10. All simulations were performed to simulate 500 years.

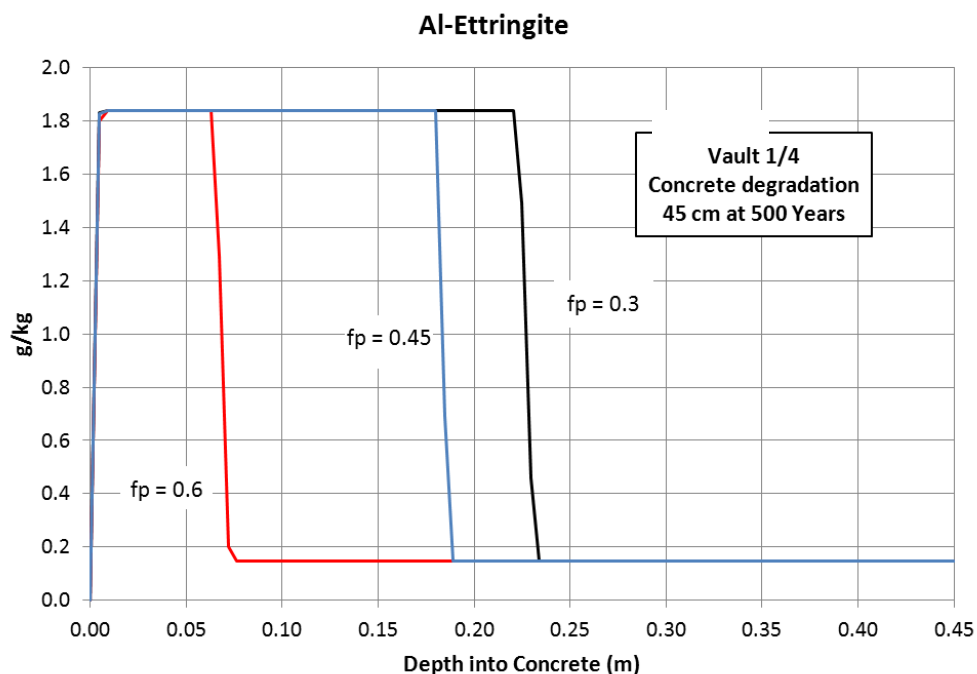
Linear extrapolation was used to calculate a time for complete concrete degradation from the front penetration times shown in Figures 2.9 and 2.10. Results from these calculations are listed in Table 2.4 and 2.5 for the 45 cm and 60 cm concrete thickness, respectively. As was done with the SDU 2 results, the degradation times were then plotted as a function of fractional porosity and fit to a smooth polynomial function. This fitting function was used to interpolate degradation times at intermediate values of the fractional porosity with the results plotted in Figure 2.11.

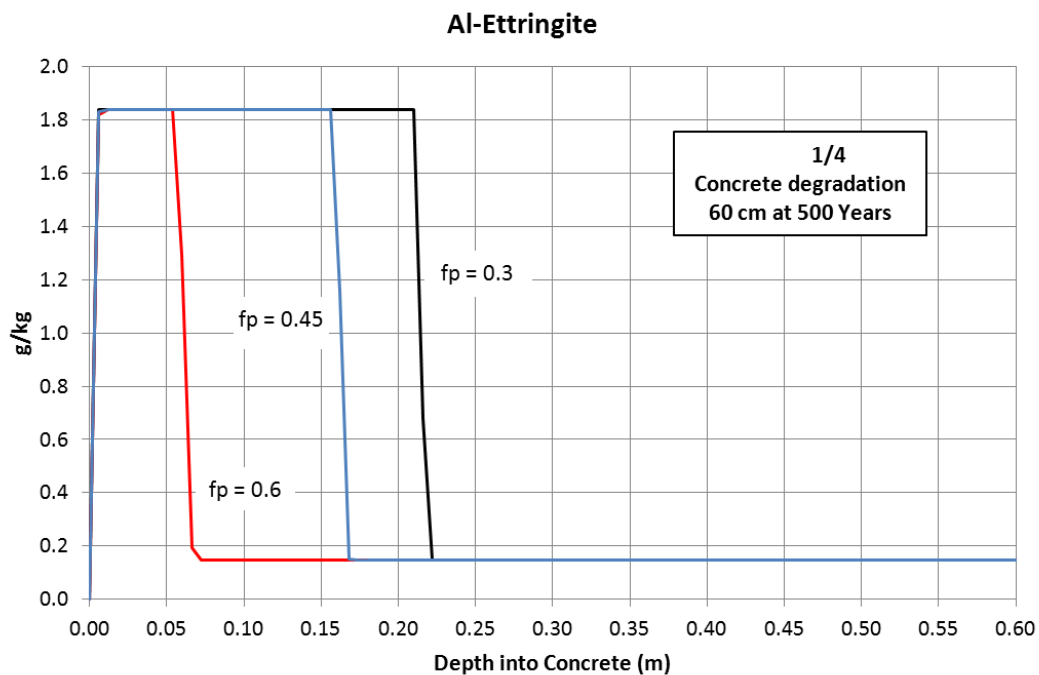
**Table 2-4. SDU 1/4 LXO sulfate attack calculations for 45 cm of concrete.**

Fractional Porosity	Years	Front Depth (m)	Fraction Degraded	Estimated Time for Complete Degradation
0.60	500	0.076	0.170	2941
0.45	500	0.189	0.420	1190
0.30	500	0.230	0.510	980

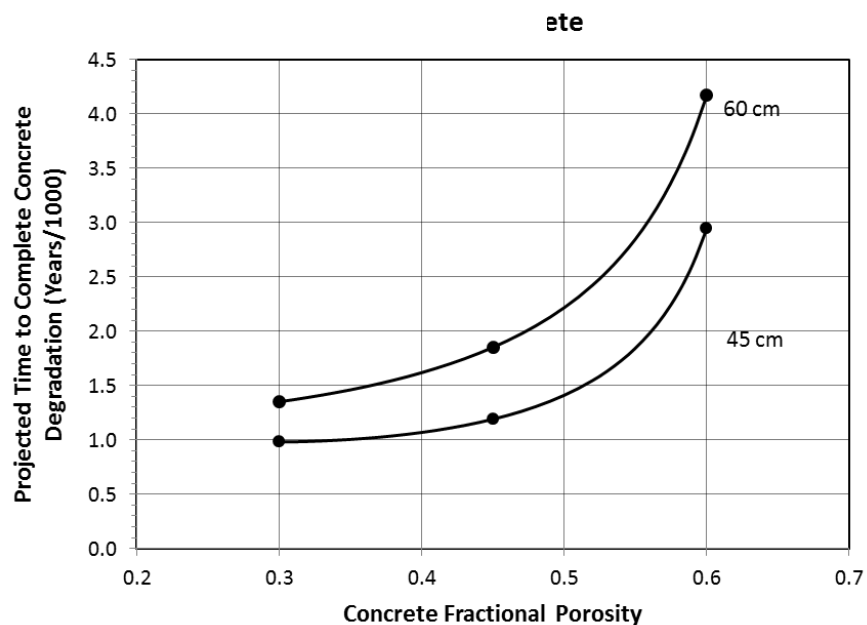
**Table 2-5. SDU 1/4 LXO sulfate attack calculations for 60 cm of concrete.**

Fractional Porosity	Years	Front Depth (m)	Fraction Degraded	Estimated Time for Complete Degradation
0.60	500	0.072	0.120	4167
0.45	500	0.162	0.270	1852
0.30	500	0.222	0.370	1351

**Figure 2-9. Ettringite front penetration as a function of concrete fractional porosity for 45 cm SDU 1/4 concrete.**



**Figure 2-10. Ettringite front penetration as a function of concrete fractional porosity for 60 cm SDU 1/4 concrete.**



**Figure 2-11. Predicted time for 100% SDU 1/4 concrete degradation as a function of fractional porosity.**

### 2.3 Sulfate Attack Results

From the analyses described in the preceding sections, the LXO model was found to predict faster concrete degradation from sulfate attack than was seen in the STADIUM simulations, in part because the model modifies transport properties based on predicted damage. LXO incorporates mineral availabilities that are generally less than 100%, which leads to faster depletion of solid reactants. STADIUM and LXO also assume different initial chemical compositions, which affects the results (Sarkar et al. 2011). Therefore, lacking long term experimental data to confirm either model, the more conservative LXO results shown in Tables 2.2 through 2.5 are recommended for estimating concrete degradation from sulfate attack.

Degradation times obtained using a fractional porosity of 0.45 represent nominal values while the degradation times obtained with fractional porosities of 0.3 and 0.6 represent conservative and best estimate values, respectively. With this approach, the best estimate of the degradation time is approximately twice the nominal, while the nominal and conservative values differ less. Therefore, a large variation in the estimated degradation time is not introduced into the analysis by choosing a fractional porosity of 0.45 for the nominal value compared to 0.3 for fully saturated conditions.

While degradation times are presented in the summary tables for the thicknesses involved in the simulations, degradation times for other thicknesses will be needed in Section 5.0, in which degradation times are defined for the various SDU 1, 2, and 4 concrete components. To this end, general degradation rates are defined from simulation results using the linear relationship

$$A_\ell = \frac{x_0}{t_0} \quad (2.2)$$

instead of Equation (1.7), which was found to be not applicable to LXO simulation results. Here  $(t_0, x_0)$  represents a selected penetration time and depth from a numerical simulation and the subscript  $\ell$  denotes a linear rate constant to distinguish it from the square of time rate constants defined by Equations (1.6) and (1.7). The time  $t_0$  associated with another penetration depth  $x_0$  is then

$$t_0 = \frac{x_0}{A_\ell} \quad (2.3)$$

Somewhat faster degradation rates were observed for a thinner model domain (e.g. 20 versus 30 cm), so Table 2.2 and Table 2.4 are used to generate linear degradation rates, which are presented in Table 2.6.

Calculation of specific degradation times is provided in Section 5.0. SDU 6 is expected to be constructed with the same concrete mix as the SDU 2. Therefore the SDU 2 rates are used to predict degradation times for the SDU 6 design.

**Table 2-6. Sulfate attack rates for SDU 2 and SDU 1/4 concrete.**

Parameter	SDU 2 CE <sup>1</sup>	SDU 2 NV <sup>2</sup>	SDU 2 BE <sup>3</sup>	SDU 1/4 CE <sup>1</sup>	SDU 1/4 NV <sup>2</sup>	SDU 1/4 BE <sup>3</sup>
Fractional porosity, $b$	0.3	0.45	0.6	0.3	0.45	0.6
Penetration depth, $x_0$ (cm)	9.4	7.4	3.8	23	18.5	7.7
Penetration time, $t_0$ (yr)	350	350	350	500	500	500
Linear rate constant, $A_\ell$ (cm/yr)	0.027	0.021	0.011	0.046	0.037	0.015

<sup>1</sup>CE – Conservative Estimate

<sup>2</sup>NV – Nominal Value

<sup>3</sup>BE – Best Estimate

### 3.0 CARBONATION

Carbonation, more properly termed carbonatation, commonly refers to the reaction of carbon dioxide with calcium hydroxide (Portlandite) to form calcium carbonate (calcite):



More generally, carbonation in the context of concrete may include other reactions of carbon dioxide with calcium-bearing minerals, such as calcium-silicate-hydrate (CSH). Carbonation increases mechanical strength and decreases alkalinity to a pH around 8.5 in cementitious materials. While the former is generally beneficial, corrosion of embedded steel accelerates as pH approaches carbonated conditions, approximately  $pH < 10$ . The volume of the corrosion products far exceeds that of the uncorroded steel, which typically introduces sufficient internal pressure to cause cracking and spalling of the surrounding concrete. Most concrete components of the various SDUs contain reinforcing steel, notable exceptions being the upper and lower mudmats in the SDU 2 design. Saltstone also contains embedded steel in the form of support columns (SDU 2 and 4) and roof trusses (SDU 4).

Papadakis et al. (1989) developed an analytical solution for carbonation penetration depth with the same basic form as Equation (1.2). Using the nomenclature of this report, the expression is

$$x = \left[ \frac{2\theta D_e c_{CO_2} t}{c_{Ca(OH)_2} + 3c_{CSH}} \right]^{1/2} \quad (3.1)$$

where

$x$  = penetration depth [cm]

$\theta$  = gas content,  $Sn$  [ $cm^3$  phase /  $cm^3$  total]

$D_e$  = effective diffusion coefficient for gas phase,  $\tau D_m$  [ $cm^2/yr$ ]

$c_{CO_2}$  = carbon dioxide concentration [ $mol / cm^3$  gas]

$t$  = elapsed time [yr]

$c_{Ca(OH)_2}$  = Portlandite concentration [ $mol / cm^3$  total]

$c_{CSH}$  = CSH concentration,  $CSH \equiv 3CaO \cdot 2SiO_2 \cdot 3H_2O$  [ $mol / cm^3$  total].

In the context of Equation (1.6),  $c_{Ca(OH)_2} + 3c_{CSH} = (1 - n)\rho_s R$ . Equation (3.1) considers only transport of carbon dioxide through the gas phase, which is appropriate for unsaturated concrete in typical applications. However, fully saturated conditions are also of interest for the SDF and Equation (3.1) can be generalized to include delivery of dissolved carbon dioxide to the reaction front as follows

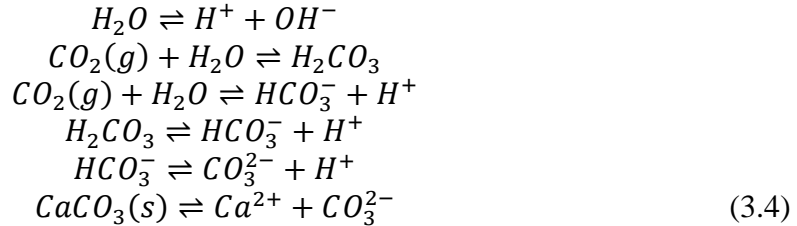
$$x = \left[ \frac{2(\theta_g D_{e,g} c_{CO_2,g} + \theta_\ell D_{e,\ell} c_{CO_2,\ell})t}{c_{Ca}} \right]^{1/2} = At^{1/2} \quad (3.2)$$

where the subscripts  $g$  and  $\ell$  denote the gas and liquid phases, respectively, and

$$A \equiv \left[ \frac{2(\theta_g D_{e,g} c_{CO_2,g} + \theta_\ell D_{e,\ell} c_{CO_2,\ell})}{c_{Ca}} \right]^{1/2} \quad (3.3)$$

Also, the denominator of Equation (3.1) is equivalent to the cumulative molar concentration of  $Ca$  in  $Ca(OH)_2$  and  $CSH$ , and denoted by  $c_{Ca}$  in these equations. Equation (3.2) is used to predict carbonation depth under saturated and unsaturated conditions in this study.

Millings (2012) estimated the average and median partial pressure of  $CO_2$  in the vadose zone to be roughly 0.01 atm at the Savannah River Site, compared to an atmospheric partial pressure of 0.00039 atm. Using the ideal gas law at 20°C, the molar concentration of carbon dioxide in the vadose zone becomes 4.16E-07 mol/cm<sup>3</sup> gas. The concentration of dissolved  $CO_2$  in cement pore water at the cement-soil interface can be estimated by analyzing a calcium carbonate (calcite) system in equilibrium with gaseous  $CO_2$ :



For a partial pressure of 0.01 atm,  $pH=7.3$  and the dominant form of dissolved carbon is  $HCO_3^-$  at a concentration  $c_{aq} = 3.07E-06$  mol/ cm<sup>3</sup> liquid. The total concentration of dissolved carbon is  $c_{aq} = 3.41E-06$  mol/ cm<sup>3</sup> (Table 3-1). The transport properties and solid phase concentrations for the SDU 1/4 floor and wall concrete and SDU 2 concrete are available from the Saltstone PA (SRR 2009) and a more recent characterization report, SIMCO (2012). Similar data for the Saltstone grout are provided in SRR (2009) and SIMCO (2010). These input data to Equations (3.2) and (3.3) are summarized in Table 3-2. The solid phase concentration of calcium in SDU 1 and 4 roof concrete is approximated by scaling the SDU 1/4 floor/wall concrete value using the  $CaO$  ratios computed in Table 3-3 based on the composition (SIMCO 2012, Table 3; SRR 2009, Tables 3.2-1 and 3.2-2) of the unhydrated binders. The SDU 2 concrete mix will also be in the SDU 6 design.

**Table 3-1. Chemical equilibrium for calcium carbonate (calcite) at 0.01 atm  $CO_2$ .**

<b>Calcium Carbonate (Calcite) System</b>					See, for example, p. 180, Stumm and Morgan, <u>Aquatic Chemistry</u> , Wiley, 1970
	<b>Reactions</b>				
1)	$H_2O \leftrightarrow H^+ + OH^-$				
2)	$CO_2(g) + H_2O \leftrightarrow H_2CO_3$				
3)	$CO_2(g) + H_2O \leftrightarrow HCO_3^- + H^+$				
4)	$H_2CO_3 \leftrightarrow HCO_3^- + H^+$				
5)	$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$				
6)	$CaCO_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-}$				
	<b>Specifications</b>				
1)	$p_{CO_2}$	0.010000	atm	2.00	Millings, M. <i>Summary of Carbon Dioxide in Water Table Wells and the Vadose Zone at SRS</i> , SRNL-L3200-2012-00017. Mar 30, 2012.
	<b>Equations</b>	@25C		-log10K	
1)	$K_w = [H^+][OH^-]$	1.00E-14	$M^2$	14	e.g. Table 3.4 (25C), R. A. Freeze and J. A. Cherry, <u>Groundwater</u> , Prentice-Hall, 1979
2)	$K_{CO_2} = [H_2CO_3]/p_{CO_2}$	3.39E-02	M/atm	1.47	Table 4-1, J. I. Drever, <u>The Geochemistry of Natural Waters</u> , 2nd edition, Prentice-Hall, 1988
3)	$K_1 = [H^+][HCO_3^-]/[H_2CO_3]$	4.47E-07	M	6.35	Table 4-1, J. I. Drever, <u>The Geochemistry of Natural Waters</u> , 2nd edition, Prentice-Hall, 1988
	$K_1 = [H^+][HCO_3^-]/p_{CO_2}$		$M^2/atm$	7.82	same as Table 5-1, Stumm and Morgan, <u>Aquatic Chemistry</u> , Wiley, 1970
4)	$K_2 = [H^+][CO_3^{2-}]/[HCO_3^-]$	4.68E-11	M	10.33	Table 5-1, Stumm and Morgan, <u>Aquatic Chemistry</u> , Wiley, 1970
5)	$K_{s0} = [Ca^{2+}][CO_3^{2-}]$	4.47E-09	$M^2$	8.35	Table 5-1, Stumm and Morgan, <u>Aquatic Chemistry</u> , Wiley, 1970
6)	$2*[Ca^{2+}] + [H^+] = [HCO_3^-] + 2*[CO_3^{2-}] + [OH^-]$				Charge balance
	<b>Variables</b>				
1)	$[H_2CO_3]$	3.39E-04	M	3.39E-07	mol/cm <sup>3</sup>
2)	$[H^+]$	4.93E-08	M	7.31	pH
3)	$[OH^-]$	2.03E-07	M	6.69	pOH
4)	$[HCO_3^-]$	3.07E-03	M	3.07E-06	mol/cm <sup>3</sup>
5)	$[CO_3^{2-}]$	2.91E-06	M	2.91E-09	mol/cm <sup>3</sup>
6)	$[Ca^{2+}]$	1.54E-03	M	1.54E-06	mol/cm <sup>3</sup>
	$[H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]$	3.41E-03	M	3.41E-06	mol/cm <sup>3</sup>

Notes: (a) All equilibrium constant calculations assume that the solution is ideal with respect to carbonates, i.e., that all activity coefficients are equal to one in Equations 1) through 5). (b) Equilibrium expressions are written without explicitly indicating the activity of  $H_2O$ .



**Table 3-2. Input data and rate constants for carbonation calculations.**

<i>Parameter</i>	<i>SDU 2</i>	<i>SDU 1/4</i>	<i>SDU 4 Roof</i>	<i>SDU 1 Roof</i>	<i>Saltstone</i>	<i>Units</i>
$p_{CO_2}$ (a)	0.01	0.01	0.01	0.01	0.01	atm
$c_{CO_2,g}$ (b)	4.16e-7	4.16e-7	4.16e-7	4.16e-7	4.16e-7	mol/cm <sup>3</sup> gas
$c_{CO_2,\ell}$ (c)	3.41e-6	3.41e-6	3.41e-6	3.41e-6	3.41e-6	mol/cm <sup>3</sup> liquid
$n$ (d)	0.11	0.12	0.136	0.145	0.58	cm <sup>3</sup> void / cm <sup>3</sup> total
$\rho_b$ (d)	2.22	2.24	2.21	2.20	1.01	g/cm <sup>3</sup> total
$D_{m,g}$ (e)	0.165	0.165	0.165	0.165	0.165	cm <sup>2</sup> /s
$\tau$ (f,g)	0.005 (f)	0.008 (f)	0.008 (f)	0.008 (f)	0.014 (g)	-
$D_{e,g}$ (h)	8.25e-4	1.32e-3	1.32e-3	1.32e-3	2.31e-3	cm <sup>2</sup> /s
$D_{e,\ell}$ (d,i)	5.0e-8 (d)	5.0e-8 (d)	1.0e-7 (d)	1.0e-7 (d)	1.0e-8 (i)	cm <sup>2</sup> /s
$[Ca(OH)_2]$ (f,g)	0 (f)	7.2 (f)	-	-	0 (g)	g/kg
$M_{Ca(OH)_2}$ (j)	74	74	-	-	74	g/mol
$c_{Ca(OH)_2}$ (k)	0	2.18e-4	-	-	0	mol/cm <sup>3</sup> total
$[CSH]$ (f,g)	81.2 (f)	118.8 (f)	-	-	147.4 (g)	g/kg
$M_{CSH}$ (l)	182.1	182.1	-	-	182.1	g/mol
$c_{CSH}$ (m)	9.90e-4	1.46e-3	-	-	8.18e-4	mol/cm <sup>3</sup> total
$c_{Ca}$ (n,o)	1.63e-3 (n)	2.63e-3 (n)	2.11e-3 (o)	1.82e-3 (o)	1.35e-3 (n)	mol/cm <sup>3</sup> total
<i>Best estimate</i>	<i>BE</i>	<i>BE</i>	<i>BE</i>	<i>BE</i>	<i>BE</i>	
$S_g$ (p)	6.6e-6 (~0)	6.6e-6 (~0)	6.6e-6 (~0)	6.6e-6 (~0)	0.0004	cm <sup>3</sup> gas / cm <sup>3</sup> void
$S_\ell$ (q)	1	1	1	1	0.9996	cm <sup>3</sup> liquid / cm <sup>3</sup> void
$\theta_g$ (r)	7.2e-7	7.9e-7	9.0e-7	9.6e-7	2.1e-4	cm <sup>3</sup> gas / cm <sup>3</sup> total
$\theta_\ell$ (s)	0.110	0.120	0.136	0.145	0.580	cm <sup>3</sup> liquid / cm <sup>3</sup> total
$A$ (t)	0.027	0.022	0.037	0.042	0.10	cm/ $\sqrt{yr}$
<i>Nominal value</i>	<i>NV</i>	<i>NV</i>	<i>NV</i>	<i>NV</i>	<i>NV</i>	
$S_g$ (u)	0.02	0.02	0.02	0.02	0.02	cm <sup>3</sup> gas / cm <sup>3</sup> void
$S_\ell$ (q)	0.98	0.98	0.98	0.98	0.98	cm <sup>3</sup> liquid / cm <sup>3</sup> void
$\theta_g$ (r)	0.0022	0.0024	0.0027	0.0029	0.0116	cm <sup>3</sup> gas / cm <sup>3</sup> total

<i>Parameter</i>	<i>SDU 2</i>	<i>SDU 1/4</i>	<i>SDU 4 Roof</i>	<i>SDU 1 Roof</i>	<i>Saltstone</i>	<i>Units</i>
$\theta_\ell$ (s)	0.108	0.118	0.133	0.142	0.568	cm <sup>3</sup> liquid / cm <sup>3</sup> total
$A$ (t)	0.17	0.18	0.21	0.24	0.72	cm/ $\sqrt{\text{yr}}$
<i>Conservative estimate</i>	<i>CE</i>	<i>CE</i>	<i>CE</i>	<i>CE</i>	<i>CE</i>	
$S_g$ (u)	0.05	0.05	0.05	0.05	0.05	cm <sup>3</sup> gas / cm <sup>3</sup> void
$S_\ell$ (q)	0.95	0.95	0.95	0.95	0.95	cm <sup>3</sup> liquid / cm <sup>3</sup> void
$\theta_g$ (r)	0.0055	0.0060	0.0068	0.0073	0.0290	cm <sup>3</sup> gas / cm <sup>3</sup> total
$\theta_\ell$ (s)	0.105	0.114	0.129	0.138	0.551	cm <sup>3</sup> liquid / cm <sup>3</sup> total
$A$ (t)	0.27	0.28	0.33	0.37	1.14	cm/ $\sqrt{\text{yr}}$

**Table 3-2 notes:**

(a) Millings (2012)

(b)  $p_{CO_2}$  and ideal gas law at 20°C(c) Sum of  $H_2CO_3$ ,  $HCO_3^-$ , and  $CO_3^{2-}$  concentrations from Table 3-1

(d) SRR (2009), Table 4.2-16

(e) Marrero and Mason (1972), Table 20, N<sub>2</sub>-CO<sub>2</sub> system

(f) SIMCO (2012), Tables 9 and 13, 28 day cure

(g) SIMCO (2010), Tables 6 and 13, WS-2 grout

(h)  $D_{e,g} = \tau D_{m,g}$ 

(i) Langton (2010b) Table 1-1, based on SIMCO (2010), rounded to one significant figure

(j)  $M_{Ca(OH)_2} = 40 + 2(16+1)$  g/mol(k)  $c_{Ca(OH)_2} = [Ca(OH)_2]\rho_b/M_{Ca(OH)_2}$ (l) The stoichiometry of CSH in cement paste is variable. SIMCO assumes  $CSH \rightarrow 0.65Ca(OH)_2 + CaH_2SiO_4 = 1.65CaO \cdot SiO_2 \cdot 1.65H_2O$  in STADIUM modeling (Samson 2010, Table 7).  $M_{CSH} = 1.65(40) + 3.3(1) + 1(28) + 5.3(16)$  g/mol(m)  $c_{CSH} = [CSH]\rho_b/M_{CSH}$ (n)  $c_{Ca} = c_{Ca(OH)_2} + 1.65 \cdot c_{CSH}$ ; see note (l)

(o) scaled from “SDU 1/4” concrete using CaO ratio from Table 3-3

(p) computed from van Genuchten (1980) water retention curve and 1500 cm suction

(q)  $S_g + S_\ell = 1$ (r)  $\theta_g = S_g n$ (s)  $\theta_\ell = S_\ell n$ 

(t) Equation (3.3)

(u) postulated condition.

**Table 3-3. Estimated calcium content in SDU 1 and 4 roof concrete relative to SDU 1/4 floor concrete.**

Binder	CaO (%)	SDU 1/4 Floor (lbs/yd <sup>3</sup> )	SDU 4 Roof (lbs/yd <sup>3</sup> )	SDU 1 Roof (lbs/yd <sup>3</sup> )
Type I/II cement Lafarge	64.8	419	466	400
Type IV cement Lehigh	63.8	0	0	0
GGBFS Holcim	37.8	278	0	0
Force 10000 SF Grace	0.6	0	0	0
Class F Fly Ash SEFA	1.32	0	62	70
CaO <sub>roof</sub> /CaO <sub>floor</sub>	-	-	0.80	0.69

The molar concentrations of  $CO_2$  in the gas and liquid phases are observed to be similar (within an order of magnitude), whereas the effective diffusion coefficient for gas phase transport is 4 to 5 orders of magnitude larger than its counterpart for the liquid phase. Therefore gas phase transport generally controls the carbonation process, and liquid phase transport is commonly neglected in the literature (e.g. Papadakis et al. 1989). The exception is saturated conditions, where liquid phase transport is the only mechanism delivering  $CO_2$  to the reaction front. The carbonation rate is minimal under these conditions. As a specific example, Rast and Rinker (2012) reported a carbonation depth of 1-2 mm for a concrete core taken from a 50 year old Hanford waste tank. The rate of carbonation is also minimal under dry conditions, because water is required to support the aqueous reaction  $Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O$ . The maximum rate of carbonation occurs at intermediate conditions, roughly 50% relative humidity (e.g. Papadakis et al. 1989, Walton et al. 1990). The carbonation rate is very sensitive to liquid saturation near full saturation.

Relative humidity and saturation are related through thermodynamic relationships and a material specific water retention curve. Total suction is related to water vapor pressure through the equilibrium thermodynamic relationship (Richards 1965, cited in Fredlund and Rahardjo 1993, Equations 4.1 and 4.3)

$$\psi = (P_g - P_\ell)/\rho g + \pi = \psi_c + \pi = -\frac{RT}{gM_w} \ln\left(\frac{P_v}{P_0}\right) = -\frac{RT}{gM_w} \ln(RH) \quad (3.5)$$

known as the Kelvin relationship where

$\psi$  = total suction [m]

$P_g$  = gas pressure [Pa]

$P_\ell$  = liquid pressure [Pa]

$\rho$  = liquid density [kg/m<sup>3</sup>]

$g$  = gravitational acceleration [m/s<sup>2</sup>]

$\pi$  = osmotic suction [m]

$\psi_c$  = capillary or matric suction [m]

$R$  = universal (molar) gas constant [J/mol-K = m<sup>3</sup>Pa/mol-K]

$T$  = temperature [K]

$M_w$  = molar mass of water [kg/mol]

$P_v$  = water vapor pressure [Pa]

$P_0$  = vapor pressure at saturation [Pa]

$RH$  = relative humidity,  $P_v/P_0$  [-]

In light of this expression, water vapor pressure can be viewed as a master variable defining the pressure state of both the gas and liquid phases (Hall and Hoff 2002). The osmotic suction can be estimated from the Morse equation ([http://en.wikipedia.org/wiki/Osmotic\\_pressure](http://en.wikipedia.org/wiki/Osmotic_pressure))

$$\rho g \pi = i M R T \quad (3.6)$$

where

$\rho$  = liquid density [kg/m<sup>3</sup>]

$g$  = gravitational acceleration [m/s<sup>2</sup>]

$\pi$  = osmotic suction [m]

$i$  = van't Hoff factor [-]

$M$  = molarity of the solution [mol/m<sup>3</sup>]

$R$  = universal (molar) gas constant [J/mol-K = m<sup>3</sup>Pa/mol-K]

$T$  = temperature [K].

Equation (3.6) assumes a dilute solution, but can be used with increasing approximation for more concentrated solutions. The dimensionless van't Hoff factor is approximately one ([http://en.wikipedia.org/wiki/Van %27t Hoff factor](http://en.wikipedia.org/wiki/Van_%27t_Hoff_factor)). Capillary suction is related to saturation through a water retention curve commonly expressed in the form (van Genuchten 1980)

$$S_e = \frac{S - S_r}{1 - S_r} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (\alpha \psi_c)^n} \right]^m \quad (3.7)$$

where

$S$  = saturation [m<sup>3</sup> liquid / m<sup>3</sup> void]

$S_r$  = material specific fitting parameter [m<sup>3</sup> liquid / m<sup>3</sup> void]

$\theta$  = water content [ $\text{m}^3$  liquid /  $\text{m}^3$  total]

$\theta_r$  = material specific fitting parameters [ $\text{m}^3$  liquid /  $\text{m}^3$  total]

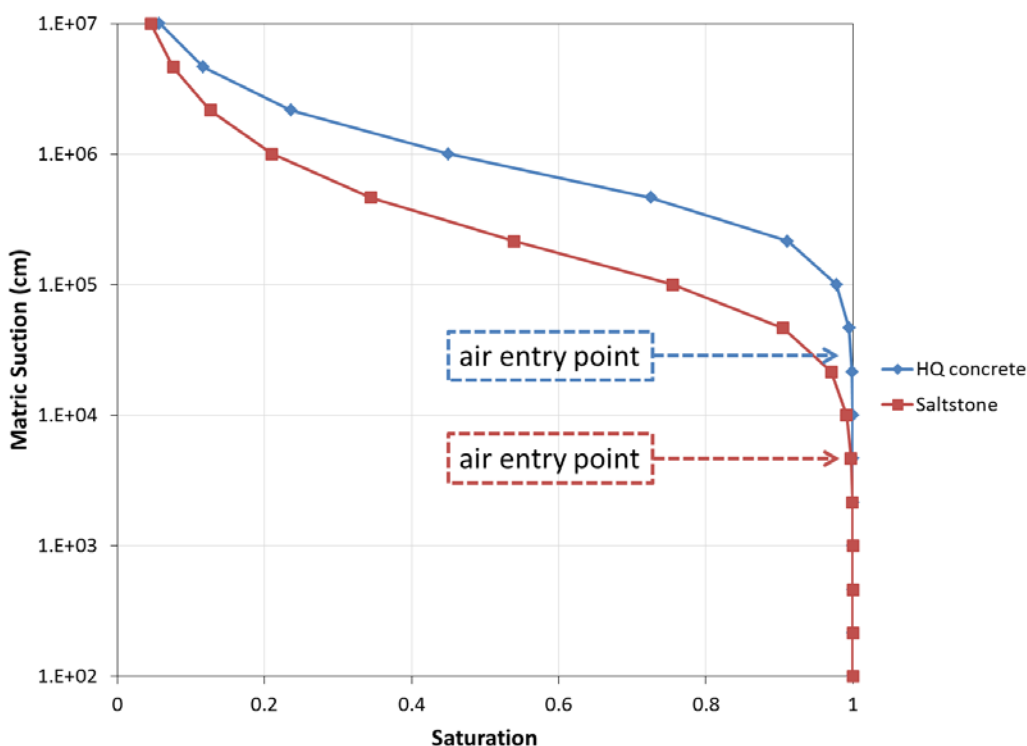
$\theta_s$  = saturated water content = porosity [ $\text{m}^3$  liquid /  $\text{m}^3$  total]

$\alpha$  = material specific fitting parameter [ $1/\text{m}$ ]

$\psi_c$  = capillary or matric suction [ $\text{m}$ ]

$n, m$  = material specific fitting parameters [-]

and the subscripts  $e$  and  $r$  denote “effective” and “residual”. Note that  $S_r$  and  $\theta_r$  are correlated (not independent) parameters. It is commonly assumed that  $m = 1 - 1/n$ . Figure 3-1 illustrates water retention curves characteristic of SDU concrete (Phifer et al. 2006) and 20°C cure temperature ARP/MCU saltstone (Dixon 2011).



**Figure 3-1. Water retention curves for SDF concrete and saltstone.**

As mentioned previously, the saturation state of a cementitious material strongly affects the rate of carbonation, particularly in the vicinity of full saturation. The anticipated saturation states for SDF cementitious materials can be assessed using Equations (3.5) through (3.7) and estimated soil suction and relative humidity values.

Once buried under a low-permeability cover system, the SDF will initially be exposed to soil conditions approaching gravity equilibrium (no infiltration), where the matric suction head is

equal to height above the water table. Soil moisture contains dissolved solids, but the concentrations are dilute such that osmotic suction is negligible compared to that within cementitious materials. Any infiltration above zero produces lower capillary suction levels than gravity equilibrium. Thus as the cover system degrades over time, soil suction levels will decrease. With this consideration, the maximum suction head anticipated for SDUs is roughly 1500 cm, the approximate height of the SDUs above the water table (15 meters). From Figure 3-1 the air entry head is observed to exceed 1500 cm for SDF grout and 10,000 cm for SDF concrete. Thus SDF concrete is expected to be saturated for all time. Ignoring osmotic effects, saltstone could potentially be slightly unsaturated immediately after cap placement, but if so, would then become saturated by the time the soil suction levels fall below approximately 1500 cm. Table 3-4 shows saturation calculated from the water retention curves depicted in Figure 3-1 for the expected maximum capillary suction of approximately 1500 cm, and 10x higher and lower levels as points of reference.

**Table 3-4. Saltstone and concrete saturation for selected capillary suctions.**

Parameter	Saltstone			Concrete			Units
saturated water content, $\theta_s$	0.58	0.58	0.58	0.1	0.1	0.1	
residual water content, $\theta_r$	0	0	0	0	0	0	
van Genuchten (1980) $\alpha$	1.008E-05	1.008E-05	1.008E-05	2.086E-06	2.086E-06	2.086E-06	1/cm
van Genuchten (1980) $n$	1.67131	1.67131	1.67131	1.9433	1.9433	1.9433	
$m=1-1/n$	0.402	0.402	0.402	0.485	0.485	0.485	
capillary suction, $\Psi_c$	15000	1500	150	15000	1500	150	cm
<b>saturation</b>	<b>0.983</b>	<b>1.000</b>	<b>1.000</b>	<b>0.999</b>	<b>1.000</b>	<b>1.000</b>	

The chemical compositions of pore water in SDU concrete and saltstone have been characterized by SIMCO (2010, 2012) and are reproduced in Table 3-5 through Table 3-7. The osmotic suctions associated with these molar concentrations are shown in Table 3-8 based on Equation (3.6). Over time dissolved species will advect and/or diffuse out of cementitious materials, thus lowering the initial molar concentrations, to levels approaching zero with sufficient time. Table 3-8 includes calculations for two additional concentrations: half the initial values and zero. The total suction is assumed to be 1500 cm in all cases based on the exposure to soil conditions. The relative humidity corresponding to 1500 cm is 99.89% from Equation (3.5). In comparison, carbonation rates reported in the literature are typically focused on 50-70% relative humidity, which is reflective of atmospheric exposure conditions and maximum penetration. For the initial and intermediate molar concentrations, the osmotic suctions exceed the total suction and the capillary suctions are negative-valued (Equation (3.5), total suction is composed of capillary and osmotic suction). The latter implies the pore water pressure is positive, in contrast to pure water that is under tension (negative pressure). Therefore, saturation is 100% when dissolved species are present at these concentrations.

**Table 3-5. Pore fluid composition for SDU 2 concrete (SIMCO 2012, Table 11).**

	28d V2	MW	28d V2	28d V2	water
ion	mmol/L	g/mol	mol/L	g/L	g/L
OH <sup>-</sup>	113.9	17	0.114	1.94	
Na <sup>+</sup>	26.5	23	0.027	0.61	
K <sup>+</sup>	35.8	39	0.036	1.40	
SO <sub>4</sub> <sup>2-</sup>	0	96	0.000	0.00	
Ca <sup>2+</sup>	2	40	0.002	0.08	
Cl <sup>-</sup>	4.2	35	0.004	0.15	
N†			0.000	0.00	
CO <sub>3</sub> <sup>2-</sup>			0.000	0.00	
			<b>0.182</b>	4.2	998
				<b>0.4%</b>	

† includes  $NO_2^-$  and  $NO_3^-$ **Table 3-6. Pore fluid composition for SDU 1/4 concrete (SIMCO 2012, Table 11).**

	28d V4	MW	28d V4	28d V4	water
ion	mmol/L	g/mol	mol/L	g/L	g/L
OH <sup>-</sup>	244.4	17	0.244	4.15	
Na <sup>+</sup>	73.9	23	0.074	1.70	
K <sup>+</sup>	140.7	39	0.141	5.49	
SO <sub>4</sub> <sup>2-</sup>	0.1	96	0.000	0.01	
Ca <sup>2+</sup>	1.8	40	0.002	0.07	
Cl <sup>-</sup>	4.8	35	0.005	0.17	
N†			0.000	0.00	
CO <sub>3</sub> <sup>2-</sup>			0.000	0.00	
			<b>0.466</b>	11.6	998
				<b>1.1%</b>	

† includes  $NO_2^-$  and  $NO_3^-$ **Table 3-7. Pore fluid composition for saltstone (SIMCO 2010, Table 8).**

	28d saltstone	28d saltstone	28d saltstone	28d saltstone	water
ion	mmol/L	mg/L	mol/L	g/L	g/L
OH <sup>-</sup>	383.9	6528	0.384	6.53	
Na <sup>+</sup>	4144.2	95274	4.144	95.27	
K <sup>+</sup>	120.5	4712	0.121	4.71	
SO <sub>4</sub> <sup>2-</sup>	111.7	10731	0.112	10.73	
Ca <sup>2+</sup>	0.1	2	0.000	0.00	
Cl <sup>-</sup>	11.9	421	0.012	0.42	
N†	3552.1	214540	3.552	214.54	
CO <sub>3</sub> <sup>2-</sup>	46.8	4683	0.047	4.68	
			<b>8.371</b>	336.9	998
				<b>25%</b>	

† includes  $NO_2^-$  and  $NO_3^-$

**Table 3-8. Relative humidity and capillary suction corresponding to a total suction of 1500 cm.**

Parameter	Saltstone			Concrete-V2			Concrete-V4			Units
	20	20	20	20	20	20	20	20	20	
temperature, T	293.15	293.15	293.15	293.15	293.15	293.15	293.15	293.15	293.15	C
<b>relative humidity, RH</b>	99.89%	99.89%	99.89%	99.89%	99.89%	99.89%	99.89%	99.89%	99.89%	K
saturation pressure, $P_0$	23.46	23.46	23.46	23.46	23.46	23.46	23.46	23.46	23.46	millibar
water vapor pressure, $P_v$	2346	2346	2346	2346	2346	2346	2346	2346	2346	Pa
gas constant, R	2344	2344	2344	2344	2344	2344	2344	2344	2344	Pa
molecular mass of water, $M_w$	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	J/K-mol
gravitational acceleration, g	18	18	18	18	18	18	18	18	18	g/mol
density of water, $\rho$	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	m/s <sup>2</sup>
pg	998	998	998	998	998	998	998	998	998	kg/m <sup>3</sup>
<b>total suction, <math>\psi</math></b>	9790.38	9790.38	9790.38	9790.38	9790.38	9790.38	9790.38	9790.38	9790.38	Pa/m
	15	15	15	15	15	15	15	15	15	m
	1500	1500	1500	1500	1500	1500	1500	1500	1500	cm
	146856	146856	146856	146856	146856	146856	146856	146856	146856	Pa
	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	bar
van't Hoff factor, i	1	1	1	1	1	1	1	1	1	1
molarity, M	8.37	4.185	0	0.18	0.09	0	0.47	0.235	0	mol/L
<b>osmotic suction, <math>\Pi</math></b>	20399775	10199887	0	438705	219352	0	1145507	572754	0	Pa
	2083.66	1041.83	0.00	44.81	22.40	0.00	117.00	58.50	0.00	m
	208366	104183	0	4481	2240	0	11700	5850	0	cm
	204.0	102.0	0.0	4.4	2.2	0.0	11.5	5.7	0.0	bar
<b>capillary (matric) suction, <math>\psi_c</math></b>	-2069	-1027	15	-30	-7	15	-102	-44	15	m
	-206866	-102683	1500	-2981	-740	1500	-10200	-4350	1500	cm
	-20252919	-10053032	146856	-291849	-72497	146856	-998651	-425898	146856	Pa
	-202.5	-100.5	1.5	-2.9	-0.7	1.5	-10.0	-4.3	1.5	bar
saturated water content, $\theta_s$	0.58	0.58	0.58	0.1	0.1	0.1	0.1	0.1	0.1	
residual water content, $\theta_r$	0	0	0	0	0	0	0	0	0	
van Genuchten (1980) $\alpha$	1.008E-05	1.008E-05	1.008E-05	2.086E-06	2.086E-06	2.086E-06	2.086E-06	2.086E-06	2.086E-06	1/cm
van Genuchten (1980) n	1.67131	1.67131	1.67131	1.9433	1.9433	1.9433	1.9433	1.9433	1.9433	
m=1-1/n	0.402	0.402	0.402	0.485	0.485	0.485	0.485	0.485	0.485	
capillary suction, $\psi_c$	-206866	-102683	1500	-2981	-740	1500	-10200	-4350	1500	cm
<b>saturation</b>	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	



The practical implication is that saltstone is expected to be fully saturated at early times, when soil suction levels are the highest, because of osmotic suction. At later times when the molar concentration of the pore fluid drops, soil (total) suction levels will also be lower such that saltstone will remain saturated, even with pure water in its pore space. Thus the pore spaces of both concrete and grout are expected to be fully saturated for all time once these materials are in the subsurface.

While saturated pores preclude gas-phase  $CO_2$  transport and relatively fast carbonation, these processes may occur should either cementitious material be fractured, depending on matric suction levels and crack aperture. For a perfectly wetting fluid, the capillary rise between two vertical parallel surfaces is

$$h = \frac{2\sigma}{\rho g b} \quad (3.8)$$

where

$h$  = capillary rise [m]

$\sigma$  = surface tension [N/m]

$\rho$  = density [ $kg/m^3$ ]

$g$  = gravitation acceleration [ $m/s^2$ ]

$b$  = aperture [m]

In the context of a vertical fracture subjected to a given pressure head,  $P/\rho g$  [m], in the surrounding matrix, the aperture will be liquid-filled under the condition (Wang and Narasimhan 1985)

$$\frac{P}{\rho g} > -\frac{2\sigma}{\rho g b} \quad (3.9)$$

In other words, the fracture will be liquid-filled for positive pressure head and suction (negative pressure) head less than  $2\sigma/\rho g b$ . Alternatively, the maximum aperture that can be liquid-filled for a given capillary suction head,  $\psi_c$  [m], is

$$b = \frac{2\sigma}{\rho g \psi_c} \quad (3.10)$$

For  $\psi_c = 1500 \text{ cm} = 15\text{m}$ , the result is  $b = 1 \text{ } \mu\text{m} = 0.04 \text{ mil}$ . Hence fractures, if present, are expected to be unsaturated unless very narrow. If these postulated fractures are connected, then they would provide a means for gas-phase transport of  $CO_2$  through the porous medium.

Returning to Equations (3.2) and (3.3), three conditions are considered for predicting carbonation rates in SDU concrete and saltstone, as shown in Table 3-2. The best-estimate (BE) rate is calculated assuming a capillary suction of 1500 cm and pure water occupying pore space, i.e., neglecting osmotic effects. Under these conditions SDF concrete is fully liquid saturated and

SDF grout is liquid saturated at 99.96% (practically saturated). The “best-estimate (BE)” label is somewhat of a misnomer because suction levels will be less than 1500 cm for much of the performance period, osmotic effects are present, and saltstone is expected to be liquid saturated. Rather, the label is used in a relative sense compared to the other two scenarios. The conservative-estimate (CE) rate implicitly assumes that connected fractures or similar unsaturated macro-porous features are present such that an equivalent of 5% of the pore space is open for gas-phase transport, i.e., 5% gas saturation. An intermediate setting of 2% gas saturation is chosen for the nominal value (NV) calculation. Table 3-2 indicates the carbonation rate coefficient  $A$  [cm/ $\sqrt{\text{yr}}$ ] from Equation (3.3) for the BE, NV, and CE conditions. The carbonation rate coefficient can be used in Equation (1.8) to predict degradation time  $t_0$  for a specified material thickness  $x_0$ .

As a point of reference, Brown et al. (2012) performed detailed simulations of carbonation in “VCT” concrete, which is essentially Saltstone SDU 2 concrete, using LeachXS<sup>TM</sup>/ORCHESTRA in a developmental CBP Software Toolbox carbonation module (Brown et al. 2013a, b). The carbonation depth was defined as the location where  $\text{pH} < 9$ . Figure 3-2 is a reproduction of simulation results for various  $\text{CO}_2$  concentrations based on 30% porosity, 90% liquid saturation, and a diffusion coefficient of  $1.E-6 \text{ m}^2/\text{s}$ . These settings are more conservative than any of the cases considered in Table 3-2. Focusing on the 1%  $\text{CO}_2$  curve (0.01 atm), the numerical simulations are observed to exhibit an initial time lag before the carbonation front advances from the exposure surface. After  $\sqrt{t} = 15 \sqrt{\text{yr}}$  ( $t = 225 \text{ yr}$ ), the carbonation front stalls at about 1.25 cm. Using  $t_0 = 225 \text{ yr}$  and  $x_0 = 1.25 \text{ cm}$  in Equation (1.7), the equivalent carbonation rate constant is  $A = 0.083 \text{ cm}/\sqrt{\text{yr}}$ . The latter is significantly lower than the conservative-estimate value in Table 3-2, which suggests that the analytic solution given by Equation (3.2) and other input assumptions are biased in the conservative direction.

Implicit in Equations (1.2) and (3.2) is the assumption of a constant diffusion coefficient. If physical damage is occurring as a result of carbonation, then the diffusion coefficient may increase and the front penetrate deeper than indicated by a  $\sqrt{t}$  dependence. The  $\sqrt{t}$  dependence is a result of increasing distance between the exposure boundary and reaction front. If damage occurs around the reaction front, then the diffusion distance may effectively not increase beyond some maximum distance,  $\delta$  [cm], and penetration will be proportional to time instead of  $\sqrt{t}$ . Assuming penetration initially follows Equation (1.5), this alternative relationship is described by

$$x = \frac{\delta}{t_\delta} t = \frac{\delta}{\delta^2/A^2} t = \frac{A^2}{\delta} t \quad (3.11)$$

where

$\delta$  = penetration through time  $t_\delta$  [cm]

$t_\delta$  = time at which penetration reaches  $\delta$  [yr]

Equations (1.5) and (3.11) are schematically depicted in Figure 3-3. Solving Equation (3.11) for time yields

$$t = \frac{\delta x}{A^2} \quad (3.12)$$

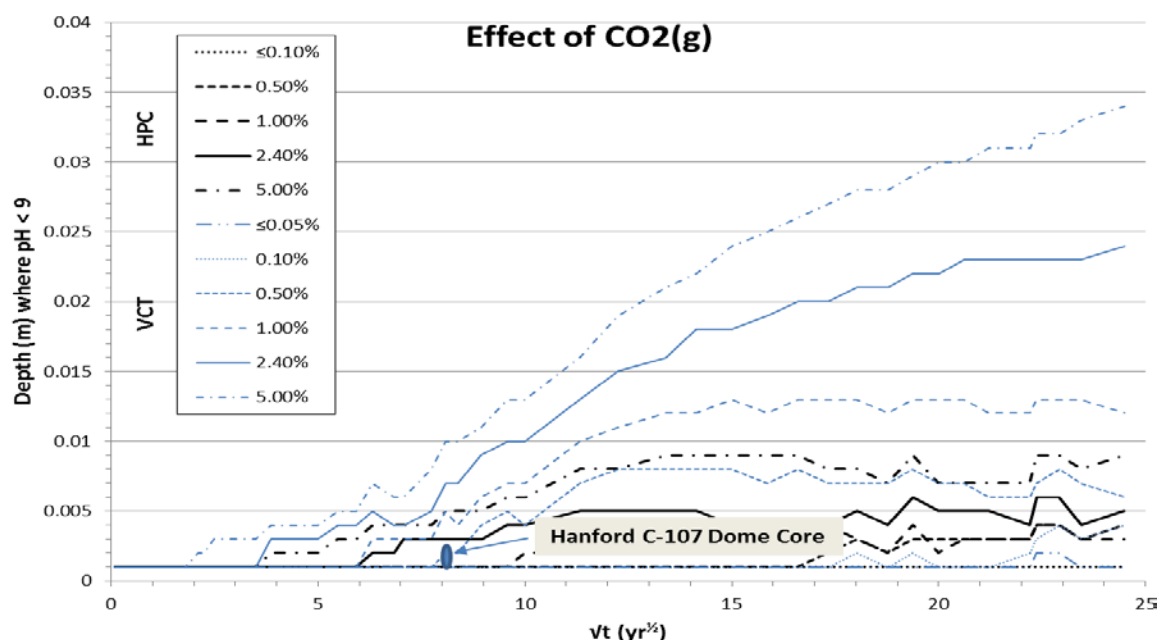
compared to

$$t = \frac{x^2}{A^2} \quad (3.13)$$

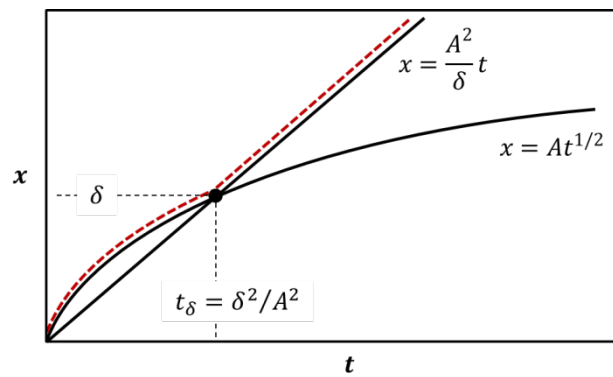
for a fixed diffusion coefficient from Equation (1.5). To account for the feedback effects of physical damage on diffusion rates, the minimum of Equations (3.12) and (3.13) is taken as the estimated degradation time  $t_0$  for a specified material thickness  $x_0$ :

$$t_0 = \min \left[ \frac{x_0^2}{A^2}, \frac{\delta x_0}{A^2} \right]. \quad (3.14)$$

The minimum time curve is shown in Figure 3-3 as a dashed red line. A reasonable assumption for the maximum diffusion distance,  $\delta$  [yr], is the depth of concrete cover over reinforcing steel, approximately 5 cm in typical construction based on American Concrete Institute (ACI) code 318 ([http://en.wikipedia.org/wiki/Concrete\\_cover](http://en.wikipedia.org/wiki/Concrete_cover)). Calculation of specific degradation times is postponed until Section 5.0.



**Figure 3-2. Carbonation simulation results as a function of soil-gas CO<sub>2</sub> concentration for 90% concrete saturation from Brown et al (2012) (VCT = SDU 2 concrete, HPC = high performance concrete).**



**Figure 3-3. Square-root and linear penetration with respect to time.**

## 4.0 DECALCIFICATION

Decalcification in this application refers to leaching of  $Ca^{2+}$  in pore water to exterior soil, where the concentration is assumed to be zero (Walton et al. 1990, Langton 2007, 2010a). Leaching may occur through diffusion and/or advection. For diffusion-controlled release between a sharp dissolution front and the soil interface, the penetration depth follows the general Equation (1.2) as

$$x = \left[ \frac{2\theta D_e c_{Ca^{2+}} t}{c_{Ca}} \right]^{1/2} = A t^{1/2} \quad (4.1)$$

where

$x$  = penetration depth [cm]

$\theta$  = liquid content,  $Sn$  [ $cm^3$  liquid /  $cm^3$  total]

$D_e$  = effective diffusion coefficient for liquid phase,  $\tau D_m$  [ $cm^2$ /yr]

$t$  = elapsed time [yr]

$c_{Ca^{2+}}$  = dissolved  $Ca^{2+}$  concentration [mol /  $cm^3$  liquid]

$c_{Ca}$  = calcium concentration in solid phase [mol /  $cm^3$  total]

and

$$A \equiv \left[ \frac{2\theta D_e c_{Ca^{2+}}}{c_{Ca}} \right]^{1/2} \quad (4.2)$$

Table 4-1 summarizes best-estimate input parameters for use in Equations (4.1) and (4.2). Most parameters come from Table 3-2. The concentration of  $Ca^{2+}$  varies through the leaching process; alkali metals leach first, followed by  $(OH)_2$ , and then  $CSH$  (Walton et al. 1990). In this analysis dissolution of  $CSH$  is assumed to control the concentration of  $Ca^{2+}$  over most of the leaching process, considering that little or no Portlandite is expected in SDF cementitious materials (Table 4-1).  $CSH$  dissolves incongruently in that calcites leach preferentially in comparison to silicates. SIMCO (2012, Table 11) measured  $c_{Ca^{2+}} = 1.8 - 2.0$  mmol/L in SDU concrete, which is consistent with Clodic and Meike (1997, Table 15, Ca/Si = 0.9). A value of  $2.e-6$  mol/ $cm^3$  is assumed in Table 4-1. The rate constants for decalcification controlled by diffusion are low indicating a slow process.

While diffusion may control the decalcification of thinner features at earlier times, specifically in concrete barriers, advection is more likely to control decalcification of saltstone considering its greater dimensions and high hydraulic conductivity. Considering downward flow, a quasi-steady state advective mass balance for decalcification is

$$U \cdot c_{Ca^{2+}} \cdot t = c_{Ca} \cdot h \quad (4.3)$$

where

$U$  = Darcy velocity (volumetric water flux) [cm/yr]

$t$  = elapsed time [yr]

$h$  = monolith height [cm]

and the concentrations are as defined for Equation (4.1). Equation (4.3) assumes that advection occurs uniformly through the entire thickness, the dissolution front advances uniformly, and the exit concentration coincides with  $Ca^{2+}$  solubility. Solving for time yields

$$t = \frac{c_{Ca}}{c_{Ca^{2+}}} \cdot \frac{h}{U} \equiv \left( \frac{1}{A_U} \right) \cdot h \quad (4.4)$$

where  $A_U$  [cm/yr] is the rate coefficient for this advection-based degradation. Equation (4.4) is more limiting than Equation (4.1) for saltstone.

The hydraulic head gradient in vadose zone soil tends to be one or less, such that the flowrate is equal to or less than the saturated hydraulic conductivity, per Darcy's law. For a cementitious monolith placed in the vadose zone, the head gradient can be higher as infiltration flows around the lower permeability obstacle. The assumptions for the BE, NV, and CE scenarios are  $U = 1$ , 10, and 100 times the saturated conductivity respectively.

The hydraulic conductivity of saltstone may vary with water to premix ratios and curing temperature profiles. An analysis of recent production runs (Isom 2012) indicates the water to premix ratio is bounded by a low value of 0.59 and a high value of 0.64. Reigel et al. (2012) characterized the saturated conductivity of saltstone for various water to premix ratios and two different curing temperature profiles. The average hydraulic conductivity for this operating band is 6.4E-09 cm/s (Table 4-2). Calculation of specific degradation times is postponed until Section 5.0.

**Table 4-1. Input data and rate constants for diffusion-limited decalcification.**

<i>Parameter</i>	<i>SDU 2</i>	<i>SDU 1/4</i>	<i>SDU 4 Roof</i>	<i>SDU 1 Roof</i>	<i>Saltstone</i>	<i>Units</i>
$c_{Ca^{2+}}$ (a)	2.0e-6	2.0e-6	2.0e-6	2.0e-6	2.0e-6	mol/cm <sup>3</sup> liquid
$n$ (b)	0.11	0.12	0.136	0.145	0.58	cm <sup>3</sup> void / cm <sup>3</sup> total
$\rho_b$ (b)	2.22	2.24	2.21	2.20	1.01	g/cm <sup>3</sup> total
$D_e$ (b,c)	5.0e-8 (b)	5.0e-8 (b)	1.0e-7 (b)	1.0e-7 (b)	1.0e-8 (c)	cm <sup>2</sup> /s
$[Ca(OH)_2]$ (d,e)	0 (d)	7.2 (d)	-	-	0 (e)	g/kg
$M_{Ca(OH)_2}$ (f)	74	74	-	-	74	g/mol
$c_{Ca(OH)_2}$ (g)	0	2.18e-4	-	-	0	mol/cm <sup>3</sup> total
$[CSH]$ (d,e)	81.2 (d)	118.8 (d)	-	-	147.4 (e)	g/kg
$M_{CSH}$ (h)	182.1	182.1	-	-	182.1	g/mol
$c_{CSH}$ (i)	9.90e-4	1.46e-3	-	-	8.18e-4	mol/cm <sup>3</sup> total
$c_{Ca}$ (j,k)	1.63e-3 (j)	2.63e-3 (j)	2.11e-3 (k)	1.82e-3 (k)	1.35e-3 (j)	mol/cm <sup>3</sup> total
$S_\ell$ (l)	1	1	1	1	0.9983	cm <sup>3</sup> liquid / cm <sup>3</sup> void
$\theta_\ell$ (m)	0.110	0.120	0.136	0.145	0.579	cm <sup>3</sup> liquid / cm <sup>3</sup> total
$A$ (n)	0.021	0.017	0.028	0.032	0.023	cm/ $\sqrt{\text{yr}}$

**Table 4-1 notes:**

(a) approximate solubility of CSH

(b) SRR (2009), Table 4.2-16

(c) Langton (2010b) Table 1-1, based on SIMCO (2010), rounded to one significant figure

(d) SIMCO (2012), Tables 9 and 13, 28 day cure

(e) SIMCO (2010), Tables 6 and 13, WS-2 grout

(f)  $M_{Ca(OH)_2} = 40 + 2(16+1)$  g/mol(g)  $c_{Ca(OH)_2} = [Ca(OH)_2]\rho_b/M_{Ca(OH)_2}$ (h) The stoichiometry of CSH in cement paste is variable. SIMCO assumes  $CSH \rightarrow 0.65Ca(OH)_2 + CaH_2SiO_4 = 1.65CaO \cdot SiO_2 \cdot 1.65H_2O$  in STADIUM modeling (Samson 2010, Table 7).  $M_{CSH} = 1.65(40) + 3.3(1) + 1(28) + 5.3(16)$  g/mol(i)  $c_{CSH} = [CSH]\rho_b/M_{CSH}$ (j)  $c_{Ca} = c_{Ca(OH)_2} + 1.65 \cdot c_{CSH}$ ; see note (h)

(k) scaled from “SDU 1/4” concrete using CaO ratio from Table 3-3

(l) computed from van Genuchten (1980) water retention curve and 1500 cm suction

(m)  $\theta_\ell = S_\ell n$ 

(n) Equation (4.2).

**Table 4-2. Measured hydraulic conductivity from SRNL-STI-2012-00558 (Reigel et al. 2012).**

Final w/p ratio	Hydraulic Conductivity (cm/s)			
	Cell K Temperature Profile		Cell F Temperature Profile	
	Saturated	Exposed Surface	Saturated	Exposed Surface
0.59	1.7E-09	4.5E-09	1.4E-09	4.3E-09
0.59	1.9E-09	3.9E-10	3.6E-09	1.6E-09
0.6	1.7E-09	1.7E-09	4.1E-09	2.1E-09
0.6	2.1E-09	2.2E-09	3.7E-09	1.3E-09
0.64	3.2E-08	4.5E-08	7.0E-09	1.3E-09
0.64	9.6E-09	1.3E-08	5.0E-09	3.1E-09
Maximum	3.2E-08	4.5E-08	7.0E-09	4.3E-09
Average	8.2E-09	1.1E-08	4.1E-09	2.3E-09
Maximum	4.5E-08		7.0E-09	
Average	9.7E-09		3.2E-09	
Maximum	4.5E-08			
Average	6.4E-09			



## 5.0 SDF CEMENTITIOUS MATERIAL DEGRADATION TIMES

Degradation rates are defined for sulfate attack, carbonation-induced steel corrosion, and decalcification in Table 5-1 through Table 5-3 for SDU 2, 4, and 1 respectively at three levels: conservative estimate (CE), nominal value (NV), and best estimate (BE). As noted in the Introduction, the nominal value is defined to be an intermediate result that is more probable than the conservative estimate and more defensible than the best estimate. Table 5-1 through Table 5-3 present the thicknesses of the key SDU cementitious components. Degradation times can be computed from degradation rates and material thicknesses using Equation (2.3) for sulfate attack, Equation (3.14) for carbonation, and Equation (4.4) for decalcification.

As noted earlier, steel corrosion products (rust) are expansive and when present inside concrete (e.g. corroded rebar) can exert stresses that cause cracking. Under high pH conditions, such as found in uncarbonated concrete, a passivating layer forms on steel surfaces leading to relatively slow corrosion rates. Specifically, the passive corrosion rate is typically  $0.1 \mu\text{m/yr}$  (ACI 222R-01) and might range between  $0.01$  and  $1 \mu\text{m/yr}$  (see Ahmad 2003, Equation (14) and surrounding discussion). Much higher corrosion rates, roughly  $1000\times$  (ACI 222R-01, Ahmad 2003), occur at lower pH, found in concrete following the arrival of a carbonation front. Degradation of concrete barriers via corrosion of embedded steel is analyzed here in the manner typical of civil engineering applications focused on structural service life. That is, corrosion is assumed to be negligible prior to carbonation and extensive damage is assumed to coincide with carbonation. Neglecting passive steel corrosion prior to carbonation is deemed an acceptable simplifying assumption considering the time scale of combined carbonation and external sulfate attack on concrete. In the degradation analysis that follows, concrete barriers become fully degraded after roughly a thousand years from a combination of sulfate attack and carbonation. The corrosion depth for passivated steel over this time frame would be nominally  $0.1 \text{ mm}$  and conservatively  $1 \text{ mm}$ , which is not expected to cause significant damage. That is, passive steel corrosion is expected to be a non-limiting degradation phenomenon and is thus not explicitly considered in the degradation calculations that follow. Regarding other degradation mechanisms, Turick and Berry (2012) concluded that biodegradation of SDU concrete is likely, but would be concentrated near outer surfaces with penetration limited by the high pH and osmotic pressure of saltstone grout pore fluid, at least for early times. Biodegradation is also assumed to be a non-limiting phenomenon and neglected in degradation calculations. Carbonation advances from the outside in, while sulfate attack, arising from sulfate in saltstone pore water, occurs from the inside moving outward. Complete degradation is assumed to occur when the two reaction fronts meet. In some cases, one or the other degradation mechanism is delayed. Sulfate attack on the underside of each SDU roof is delayed until sulfate migrates through the clean grout overlying saltstone. SDU 2 has a High Density Polyethylene (HDPE) liner along the exterior of the walls and a composite layer of HDPE and a Geosynthetic Clay Liner (GCL) that covers the roof and separates the upper and lower mudmats. Carbonation in SDU 2 concrete is assumed to be delayed until HDPE/GCL liners are significantly degraded. If the delay is long enough for one process, the other may fully penetrate the thickness in question.

Sulfate attack and carbonation are assumed to begin at facility closure, time zero with respect to the Performance Assessment, on the general basis that the operational period is short compared to PA timeframes and can be neglected compared to analysis uncertainties. However, in some

cases concrete will be fully protected from degradation for at least the operational phase, thus avoiding any non-conservative approximation. For example, the SDU 2 interior waterproof coating and exterior shotcrete layer will protect wall concrete for at least several decades from sulfate attack and carbonation respectively. Also, the SDU 1 and 4 wall concrete is assumed to be already fully degraded at  $t=0$ .

The lag time for sulfate to reach the roof is estimated using the analytic solution for diffusion into a semi-infinite medium (Myer 1971, Equation (6.4.29); Flach et al. 2009, Equation 19b)

$$c = c_0 \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} \right) \quad (5.1)$$

where

$c$  = interior concentration [mol/L]

$c_0$  = boundary concentration [mol/L]

$x$  = penetration depth [cm]

$D_e$  = effective diffusion coefficient for liquid phase,  $\tau D_m$  [cm<sup>2</sup>/yr]

$t$  = elapsed time [yr]

The penetration depth is the thickness of the clean grout. Effective diffusion coefficients are defined in Table 3-2 and Table 4-1 (same values). The ratio  $c/c_0$  is assumed to be 10%, 20%, and 50% for the CE, NV, and BE cases. When these trigger values are reached, carbonation is conservatively assumed to occur as though the underside of the roof were exposed to the full sulfate concentration,  $c_0$ . The resulting delay times are indicated in Table 5-1 through Table 5-3.

Significant degradation of the HDPE and GCL barriers is assumed to be necessary for  $CO_2$  diffusion into the concrete. The degradation of these barriers is evaluated in Flach et al. (2009) and data extracted from Appendix E of SRNL-STI-2009-00115 is provided in Table 5-4. “Significant” degradation is defined as a 100x increase in hydraulic conductivity (due to holes, tears), and occurs at approximately 900 and 1400 years for HDPE and HDPE-GCL respectively. These delay times appear in Table 5-1.

The maximum diffusion distance,  $\delta$  [cm], in Equation (3.14) is generally assumed to be 5 cm, the typical thickness of concrete cover over reinforcing steel based on ACI code 318, as previously discussed. The exception is the floor and upper mudmat system. Because the 10 cm thick upper mudmat does not contain rebar, carbonation is assumed to cause no damage to this material. Therefore the minimum diffusion distance is 10 cm. Although presented in the context of carbonation, Equation (3.14) is also applied to diffusion-controlled decalcification.

For SDU 4, the top portion of saltstone and the clean grout contains roof support trusses. The joist girder system employed for the construction of the permanent roof in SDU 4 has a depth of 28 inches (Drawing C-CC-Z-0011). The top elevation of the girder is at least 296 feet, 0 inches (Drawing C-CS-Z-0002). Thus, the bottom elevation of the girder would be no less than 294 feet,

4 inches. With a top of concrete floor elevation of 271 feet (Drawing W828992) and a maximum saltstone fill height of 24 feet, 9 inches (Phifer et al. 2006, Section 4.6.2), the maximum elevation of saltstone would be 295 feet, 9 inches. Thus, the joist girders would not extend more than 1 foot, 5 inches into the saltstone. However, Performance Assessment analysts anticipate modeling the upper 3.45 feet of grout and saltstone (“Top saltstone”) as influenced by carbonation-induced steel corrosion to be conservative. The remaining saltstone thickness, with the exception of the roof support columns, degrades by decalcification.

The 12 inch “FloorUMM” thickness for SDU 2 denotes the combination of an 8 inch floor with rebar and a 4 inch upper mudmat without rebar. “Grout” thicknesses include saltstone and clean grout that covers the saltstone. Decalcification of concrete by diffusion is much slower than sulfate attack and carbonation and not limiting; only best-estimate values are provided to indicate the slowness of this process. Sulfate attack and carbonation occur simultaneously, generally meeting at a point in the interior of the concrete. Thus the indicated degradation times are usually the same for both phenomena. Exceptions occur when one phenomenon is significantly delayed, such that the other mechanism is capable of degrading the entire thickness before the lag time of the former expires. Carbonation does not damage saltstone in general, an exception being in the vicinity of vertical steel columns supporting the roof. These column regions degrade differently than the surrounding grout and saltstone.

Column degradation for SDU 1/4 is driven by carbonation fronts advancing inside the pipe column through concrete and outside the column through grout; both processes lead to accelerated steel corrosion. Carbonation occurs faster through the grout, so only the outer carbonation front is calculated. Carbonation through the column region is assumed to start after the earlier of the roof and floor degradation times, such that columns degrade symmetrically from the top and bottom. Performance Assessment analysts anticipate discretizing the columns in 2 ft segments for flow and transport simulations; therefore, degradation times are computed for 24 inch increments. The main calculation table indicates the degradation times for the first pair of column segments. Degradation times for all column segments (denoted “grout1”, “grout2”, etc.) are indicated by a summary list adjoining the main table. Because the carbonation front advances at a constant rate (past 5 cm), the elapsed time for the carbonation front to pass through a segment is the same for all segments.

In Revisions 0 and 1 of this report, SDU 2/6 columns were assumed to degrade in the same manner as SDU 1/4, that is, by carbonation progressing longitudinally. For continuity with these earlier report versions and associated flow and transport simulations (e.g. Flach and Taylor 2014), degradation estimates are first presented assuming carbonation-induced steel corrosion as the controlling mechanism for SDU 2/6 columns (Table 5-1, Table 5-5 through Table 5-7, and Table 5-11). However, unlike the concrete-filled steel pipes of the SDU 1/4 design (SRR 2013), SDU 2/6 columns are actually reinforced concrete (SRR 2013, 2014), which enables sulfate attack to advance radially inward. With this realization, further results are presented for each prior SDU 2/6 case assuming sulfate attack as the controlling degradation mechanism. Under this scenario, SDU 2/6 columns degrade uniformly from top to bottom, precluding the need to define vertical segments as with SDU 1/4. The maximum sulfate attack depth for these circular cross-sections is approximated by half the side length of the equivalent area square.

Degradation times are defined for sulfate attack, carbonation-induced steel corrosion, and decalcification in Table 5-1 through Table 5-3 for SDU 2 (assuming column degradation by carbonation), 4, and 1, respectively. The differences among the CE, NV, and BE values is an indication of the level of uncertainty inherent in the underlying degradation analyses. The nominal values, which are intended to reflect moderate conservatism, are recommended for baseline Performance Assessment simulations.

Compared to Revision 0, the BE degradation rates for column segments are much slower in this report. The reason is a 4x decrease in the gas phase saturation for grout from 0.0017 to 0.0004, due to a revised saltstone moisture characteristic curve, and the fact that gas phase diffusion dominates liquid phase diffusion. The carbonation analysis invokes a simplified concept for steel corrosion, specifically, that no corrosion occurs prior to the arrival of the carbonation front due to high pH and passivated steel, and instantaneous corrosion at the time of arrival. The assumption of zero corrosion prior to carbonation becomes increasingly inaccurate for longer carbonation times, and the BE column corrosion degradation times are biased high from this perspective.

Compared to Revision 0, additional degradation times are defined for SDU 2 and future SDU 6 designs in Table 5-5 through Table 5-7 assuming saltstone fills the upper portion of the interior volume (no clean cap fill), to bound expected future operations which may reduce the thickness of the clean cap. The direct effect is immediate, rather than delayed, sulfate attack on the underside of the concrete roof for each SDU type. The earlier roof degradation time leads to earlier degradation of saltstone and the roof support columns. The cementitious materials associated with SDU 2 will also be used in SDU 6 construction and operation. Thus the basic degradation rates calculated for SDU 2 apply to SDU 6 as well. However, geometric differences in the two designs lead to different degradation times. Also, the SDU 6 design lacks an interior waterproof coating which protects the interior wall from sulfate attack during operations. Flach (2013, Tables 4 and 7) estimated an initial degradation thickness for SDU 6 wall segments (segmented because the wall is tapered) and these values were used in Revision 0 and 1 of this report. Since then an error in the molecular weight of the AFm phase used in the analysis was discovered and Table 5-8 through Table 5-10 reflect the corrected analysis. The changes to the remaining intact thickness at the time of facility closure are practically insignificant. Two sets of SDU 6 estimates for overall degradation are provided in Table 5-6 and Table 5-7. The “Design” case constitutes the expected nominal dimensions of the final SDU 6 design. The “Design w/Margin” case is based on more conservative (thinner) dimensions. Table 5-11 presents SDU 2 degradation times for the intermediate case of a six inch clean cap. Because Equation (5.1) is non-linear in time the benefit of a six inch clean cap is minimal compared to the traditional 24 inch thickness.

As discussed previously, the SDU 2/6 degradation calculations summarized in Table 5-1, Table 5-5 through Table 5-7, and Table 5-11 assume carbonation as the controlling degradation mechanism for roof support columns. These five scenarios were reanalyzed under the assumption of column degradation by sulfate attack and summary results are presented in Table 5-12 through Table 5-16.

**Table 5-1. Degradation analysis for SDU 2 concrete and saltstone with 24 inch clean cap and column degradation by carbonation.**

Degradation mechanism: SA Carb SA Carb SA Carb SA Carb SA Carb									
Sulfate attack									
Carbonation									
Component	Thickness: (in)	SA CE (cm)	Carb CE (cm)	SA NV (cm)	Carb NV (cm)	SA BE (cm)	Carb BE (cm)	A <sub>L</sub> (cm/yr) CE NV BE	Time (yr) CE NV BE
Roof delay									
Roof degradation	8	20.32	5.73	14.6	5.66	14.7	17.2	3.1	0.027
Roof delay+degradation			0		0		0		
FloorUMM delay									
FloorUMM degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027
FloorUMM delay+degradation			-265		0		0		
Wall delay									
Wall degradation	8	20.32	20.3	0	19.5	0.82	19.5	0.81	0.027
Wall delay+degradation			-143		0		0		
Grout delay									
Grout degradation	264	670.6							
Grout delay+degradation									
Column delay									
Column degradation*	24	60.96							
Column delay+degradation									
Decalcification									
Component	Thickness: (in)	SA CE (cm)	Carb CE (cm)	SA NV (cm)	Carb NV (cm)	SA BE (cm)	Carb BE (cm)	A <sub>U</sub> (cm/yr) CE NV BE	Time (yr) CE NV BE
Roof delay									
Roof degradation	8	20.32							
Roof delay+degradation									
FloorUMM delay									
FloorUMM degradation	12	30.48							
FloorUMM delay+degradation									
Wall delay									
Wall degradation	8	20.32							
Wall delay+degradation									
Grout delay									
Grout degradation	264	670.6							
Grout delay+degradation									
Column delay									
Column degradation*	24	60.96							
Column delay+degradation									

\* Use degradation time for successive column segments

**Table 5-2. Degradation analysis for SDU 4 concrete and saltstone.**

Degradation mechanism:										Carbonation																			
Component	Thickness:		SA		Carb		SA		Carb		SA		Carb		Sulfate attack		Time (yr)			A (cm/vyr)			Time (yr)			max δ			
	(in)	(cm)	CE	(cm)	CE	(cm)	NV	(cm)	NV	(cm)	BE	(cm)	BE	(cm)	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	(cm)		
Roof delay																													
Roof degradation	4	10.16	0	10.2	0	10.2	0	10.2	0	10.2	6.98	3.18	0.046	0.037	0.015	clean grout:			1141	1879	6784				0	0	0		
Roof delay+degradation			690				773				0														451	1106	7237	5	
Floor delay																													
Floor degradation	24	60.96	45.3	15.7	51.9	9.01	59.6	1.39	0.046	0.037	0.015														0	0	0		
Floor delay+degradation			0				0				0															985	1404	3868	5
Grout - 3.45' delay																													
Grout - 3.45' degradation	273.0	693.4																											
Grout - 3.45' delay+degradation																													
Top saltstone delay																													
Top saltstone degradation	41.37	105.1																											
Top saltstone delay+degradation																													
Column delay																													
Column degradation*	24	60.96																											
Column delay+degradation																													

Degradation mechanism:										Decalcification										Limiting									
Component	Thickness:		A (cm/vyr)		Time (yr)		max δ		NV																				
	(in)	(cm)	CE	NV	BE	CE	NV	BE		(cm)	(yr)																		
Roof delay																													
Roof degradation	4	10.16				0.028																							
Roof delay+degradation																													
Floor delay																													
Floor degradation	24	60.96				0.017																							
Floor delay+degradation																													
Grout - 3.45' delay																													
Grout - 3.45' degradation	273.0	693.4	3.0E-02	3.0E-03	3.0E-04																								
Grout - 3.45' delay+degradation																													
Top saltstone delay																													
Top saltstone degradation	41.37	105.1																											
Top saltstone delay+degradation																													
Column delay																													
Column degradation*	24	60.96																											
Column delay+degradation																													

\* Use degradation time for successive column segments

**Table 5-3. Degradation analysis for SDU 1 concrete and saltstone.**

Degradation mechanism: Carbonation																				
Component	Thickness: (in)	SA CE (cm)	Carb CE (cm)	SA NV (cm)	Carb NV (cm)	SA BE (cm)	Carb BE (cm)	Sulfate attack			Time (yr)			A (cm/vyr)			Time (yr)			max δ (cm)
								CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	
Roof delay																				
Roof degradation	6	15.24	7.11	8.13	9.7	5.54	13.5	1.71	0.046	0.037	0.015	clean grout:	136	224	809				0	0
Roof delay+degradation			0		0		0						155	262	878	0.37	0.24	0.0417	291	486
Floor delay													291	486	1687				291	486
Floor degradation	24	60.96	45.3	15.7	51.9	9.01	59.6	1.39	0.046	0.037	0.015		0	0	0	0.28	0.18	0.0224	985	1404
Floor delay+degradation			0		0		0						985	1404	3868				985	1404
GROUT delay																				
GROUT degradation	294	746.8																		
GROUT delay+degradation																				

Degradation mechanism: Decalcification												
Component	Thickness: (in)	SA CE (cm)	Carb CE (cm)	SA NV (cm)	Carb NV (cm)	SA BE (cm)	Carb BE (cm)	Time (yr)			max δ (cm)	Limiting NV (yr)
								CE	NV	BE		
Roof delay												0
Roof degradation	6	15.24			0.032			75657	5	Roof		
Roof delay+degradation								75657		486		
Floor delay										0		
Floor degradation	24	60.96			0.017			1058813	5	Floor		
Floor delay+degradation								1058813		1404		
GROUT delay										486		
GROUT degradation	294	746.8	3.0E-02	3.0E-03	3.0E-04			249550	24955499	GROUT		
GROUT delay+degradation								25246	250036	2497186		

**Table 5-4. Degradation of HDPE and HDPE-GCL materials.**

<b>Time Period (years)</b>	<b>HDPE Hydraulic Conductivity</b>		<b>HDPE-GCL Hydraulic Conductivity</b>	
	<b>Value (cm/sec)</b>	<b>Ratio to Initial Value</b>	<b>Value (cm/sec)</b>	<b>Ratio to Initial Value</b>
0 - 50	5.87E-10	1	2.19E-11	1
900 – 1,000	6.04E-08	103	1.50E-09	68.5
1,400 – 1,600	9.69E-08	165	2.31E-09	105
9,500 – 10,000	6.44E-07	1,097	1.09E-08	498



**Table 5-5. Degradation analysis for SDU 2 concrete and saltstone assuming no clean cap fill and column degradation by carbonation.**

[illegible]

\* Use degradation time for successive column segments

**Table 5-6. Degradation analysis for SDU 6 “Design” case assuming no clean cap fill and column degradation by carbonation.**

[illegible]

\* Use degradation time for successive column segments

**Table 5-6      Degradation analysis for SDU 6 “Design” case assuming no clean cap fill and column degradation by carbonation (continued).**

Degradation mechanism:		Decalcification						Limiting	
		Thickness: (in)	(cm)	CE	NV	BE	max δ (cm)		
Component									
Roof delay						1400			
Roof degradation		12	30.48			358791	5	Roof	0
Roof delay+degradation						360191			1413
FloorUMM delay						1400			0
FloorUMM degradation		12	30.48			358791	5	FloorUMM	
FloorUMM delay+degradation						360191			1413
Wall delay						900			0
Wall degradation		8.73	22.17			261020	5	Wall	
Wall delay+degradation						261920			815
Wall delay						900			0
Wall degradation		10.45	26.54			312447	5	Wall	
Wall delay+degradation						313347			979
Wall delay						900			0
Wall degradation		13.46	34.19			402444	5	Wall	
Wall delay+degradation						403344			1261
Wall delay						900			0
Wall degradation		16.5	41.91			493338	5	Wall	
Wall delay+degradation						494238			1546
Wall delay						900			0
Wall degradation		19.45	49.4			581540	5	Wall	
Wall delay+degradation						582440			1822
Grout delay						1135	1413		1413
Grout degradation		516	1311			437985	437985	Grout	
Grout delay+degradation						44933	439398		439398
Column delay									1413
Column degradation*		24	60.96					Column	
Column delay+degradation									1996

\* Use degradation time for successive column segments

**Table 5-7. Degradation analysis for SDU 6 “Design w/Margin” case assuming no clean cap fill and column degradation by carbonation.**

Degradation mechanism:				SA Carb						SA Carb						SA Carb						Sulfate attack						Carbonation						max δ (cm)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
Thick- (in)		(cm)		CE (cm)	CE (cm)	NV (cm)	NV (cm)	BE (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE (cm)	NV (cm)	BE (cm)	CE

\* Use degradation time for successive column segments

**Table 5-7      Degradation analysis for SDU 6 “Design w/Margin” case assuming no clean cap fill and column degradation by carbonation (continued).**

Degradation mechanism:		Decalcification					Limiting	
		Thickness: (in)	CE	NV	BE	Time (yr)		
Component		(cm)					max $\delta$ (cm)	NV
Roof delay							1400	0
Roof degradation	9	22.86					269093	5
Roof delay+degradation							270493	1081
FloorUMM delay							1400	0
FloorUMM degradation	9	22.86					269093	5
FloorUMM delay+degradation							270493	1081
Wall delay							900	0
Wall degradation	6.04	15.34					180591	5
Wall delay+degradation							181491	536
Wall delay							900	0
Wall degradation	7.63	19.38					228131	5
Wall delay+degradation							229031	700
Wall delay							900	0
Wall degradation	10.43	26.49					311849	5
Wall delay+degradation							312749	977
Wall delay							900	0
Wall degradation	13.26	33.58					396464	5
Wall delay+degradation							397364	1242
Wall delay							900	0
Wall degradation	15.99	40.61					478089	5
Wall delay+degradation							478989	1498
Grout delay							851	1081
Grout degradation	516	1311					43799	437985
Grout delay+degradation							44650	439067
Column delay								1081
Column delay+degradation*	24	60.96						1665

\* Use degradation time for successive column segments

**Table 5-8. Estimated reaction capacity for concrete reaction with sulfate.**

<b>SIMCO March 2012 report</b>						
Bulk density	2309	kg/m <sup>3</sup>				
	2.309	g/mL				
	<i>Mass fraction</i>	<i>Molecular mass</i>	<i>Molar density</i>	<i>Ca</i>	<i>Al</i>	
	<i>g/kg</i>	<i>g/mol</i>	<i>mol/mL</i>	<i>mol/mL</i>	<i>mol/mL</i>	
CSH	81.2	182.1	1.03E-03	1.70E-03	0.00E+00	
Portlandite	0	74	0	0	0	
AFm	10.0	622	3.71E-05	1.48E-04	7.42E-05	
C4FH13	0					
SDU-2 Concrete				1.85E-03	7.42E-05	
				<i>Ca/Al</i>	<i>Al/Ca</i>	
				24.9	0.040	
Ettringite				3	0.3333333	
				<i>Al is limiting</i>		
				Maximum ettringite	3.71E-05	mol/mL
				Sulfate per ettringite	3	
				Sulfate required for reaction	1.11E-04	mol/mL
					<b>4.82E-05</b>	mol/g

<b>Minerals</b>		<i>Ca</i>	<i>Si</i>	<i>H</i>	<i>O</i>	<i>Al</i>	<i>S</i>	<i>MW</i>	<i>Note</i>
	MW (g/mol)	40	28	1	16	27	32	g/mol	
1.65CaO . SiO <sub>2</sub> . 1.65H <sub>2</sub> O	CSH	1.65	1	3.3	5.3	0	0	182.1	a)
Ca(OH) <sub>2</sub>	Portlandite	1	0	2	2	0	0	74	
3CaO . Al <sub>2</sub> O <sub>3</sub> . CaSO <sub>4</sub> . 12H <sub>2</sub> O	AFm	4	0	24	22	2	1	622	b)
?	C4FH13							0	
3CaO . Al <sub>2</sub> O <sub>3</sub> . 3CaSO <sub>4</sub> . 32H <sub>2</sub> O	Ettringite	6	0	64	50	2	3	1254	c)
<i>Notes</i>									
a) see Note (l) to Table 3-1, SRNL-STI-2013-00118, Rev. 0 for CSH formula									
b) <a href="http://www.understanding-cement.com/hydration.html">http://www.understanding-cement.com/hydration.html</a> , <a href="http://en.wikipedia.org/wiki/Cement_chemist_notation">http://en.wikipedia.org/wiki/Cement_chemist_notation</a>									
c) <a href="http://en.wikipedia.org/wiki/Ettringite">http://en.wikipedia.org/wiki/Ettringite</a> , <a href="http://webmineral.com/data/Ettringite.shtml">http://webmineral.com/data/Ettringite.shtml</a>									

**Table 5-9. Initial SDU-6 wall degradation from bleedwater exposure, “Design” case.**

<b>SDU-6</b>	<i>Wall 1</i>	<i>Wall 2</i>	<i>Wall 3</i>	<i>Wall 4</i>	<i>Wall 5</i>		<i>Note</i>
thickness, L	22.37	19.07	15.66	12.28	10.35	in	
	56.82	48.44	39.78	31.19	26.29	cm	
initial saturation, $S_i$	0.73	0.73	0.73	0.73	0.73	mL liquid / mL void	a)
final saturation, $S_f$	1	1	1	1	1	mL liquid / mL void	
change in saturation, $\Delta S$	0.27	0.27	0.27	0.27	0.27	mL liquid / mL void	
porosity, $n$	0.11	0.11	0.11	0.11	0.11	mL void / mL total	b)
surface crack depth	1	1	1	1	1	cm	c)
	0.39	0.39	0.39	0.39	0.39	in	
<b>Slow reaction</b>							
penetration fraction	0.27	0.27	0.27	0.27	0.27		
penetration distance, x	15.34	13.08	10.74	8.42	7.10	cm	
total degraded thickness	16.34	14.08	11.74	9.42	8.10	cm	
	6.43	5.54	4.62	3.71	3.19	in	
<b>Fast reaction</b>							
bulk density, $\rho_b$	2.22	2.22	2.22	2.22	2.22	g/mL	b)
bleedwater concentration, c	150	150	150	150	150	mmol/L	d)
	0.15	0.15	0.15	0.15	0.15	mol/L	
	1.50E-04	1.50E-04	1.50E-04	1.50E-04	1.50E-04	mol/mL	
reaction capacity, R	4.8E-05	4.8E-05	4.8E-05	4.8E-05	4.8E-05	mol/g	e)
	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04	mol/mL	
	0.11	0.11	0.11	0.11	0.11	mol/L	
penetration fraction	0.04	0.04	0.04	0.04	0.04		
penetration distance, x	2.36	2.02	1.65	1.30	1.09	cm	
total degraded thickness	3.36	3.02	2.65	2.30	2.09	cm	
	1.32	1.19	1.05	0.90	0.82	in	
<b>Initial damage</b>							
Geometric mean value	7.41	6.52	5.58	4.65	4.12	cm	
	2.92	2.57	2.20	1.83	1.62	in	
Intact wall thickness	49.41	41.92	34.19	26.54	22.17	cm	
	19.45	16.50	13.46	10.45	8.73	in	
<i>Notes:</i>							
a) based on 73% average observed in Sappington and Phifer (2005)							
b) SRNL-STI-2013-00118, Rev. 0, Table 3-1							
c) Page 5 in Levitt, M. Concrete Materials: Problems and Solutions. Taylor & Francis e-Library. 2003.							
d) bleedwater taken as the midpoint between feedwater (0.1 mol/L) and porewater (~2x) values;							
2x based on SIMCO June 2010 report							
e) based on SIMCO March 12 characterization							

**Table 5-10. Initial SDU-6 wall degradation from bleedwater exposure, “Design w/Margin” case.**

<b>SDU-6</b>	<i>Wall 1</i>	<i>Wall 2</i>	<i>Wall 3</i>	<i>Wall 4</i>	<i>Wall 5</i>		<i>Note</i>
thickness, L	18.49	15.43	12.26	9.12	7.33	in	
	46.96	39.19	31.14	23.16	18.62	cm	
initial saturation, $S_i$	0.73	0.73	0.73	0.73	0.73	mL liquid / mL void	a)
final saturation, $S_f$	1	1	1	1	1	mL liquid / mL void	
change in saturation, $\Delta S$	0.27	0.27	0.27	0.27	0.27	mL liquid / mL void	
porosity, n	0.11	0.11	0.11	0.11	0.11	mL void / mL total	b)
surface crack depth	1	1	1	1	1	cm	c)
	0.39	0.39	0.39	0.39	0.39	in	
<b>Slow reaction</b>							
penetration fraction	0.27	0.27	0.27	0.27	0.27		
penetration distance, x	12.68	10.58	8.41	6.25	5.03	cm	
total degraded thickness	13.68	11.58	9.41	7.25	6.03	cm	
	5.39	4.56	3.70	2.86	2.37	in	
<b>Fast reaction</b>							
bulk density, $\rho_b$	2.22	2.22	2.22	2.22	2.22	g/mL	b)
bleedwater concentration, c	150	150	150	150	150	mmol/L	d)
	0.15	0.15	0.15	0.15	0.15	mol/L	
	1.50E-04	1.50E-04	1.50E-04	1.50E-04	1.50E-04	mol/mL	
reaction capacity, R	4.8E-05	4.8E-05	4.8E-05	4.8E-05	4.8E-05	mol/g	e)
	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04	mol/mL	
	0.11	0.11	0.11	0.11	0.11	mol/L	
penetration fraction	0.04	0.04	0.04	0.04	0.04		
penetration distance, x	1.95	1.63	1.30	0.96	0.77	cm	
total degraded thickness	2.95	2.63	2.30	1.96	1.77	cm	
	1.16	1.04	0.90	0.77	0.70	in	
<b>Initial damage</b>							
Geometric mean value	6.36	5.52	4.65	3.77	3.27	cm	
	2.50	2.17	1.83	1.49	1.29	in	
Intact wall thickness	40.61	33.67	26.49	19.39	15.35	cm	
	15.99	13.26	10.43	7.63	6.04	in	
<i>Notes:</i>							
a) based on 73% average observed in Sappington and Phifer (2005)							
b) SRNL-STI-2013-00118, Rev. 0, Table 3-1							
c) Page 5 in Levitt, M. Concrete Materials: Problems and Solutions. Taylor & Francis e-Library. 2003.							
d) bleedwater taken as the midpoint between feedwater (0.1 mol/L) and porewater (~2x) values;							
2x based on SIMCO June 2010 report							
e) based on SIMCO March 12 characterization							



**Table 5-11. Degradation analysis for SDU 2 concrete and saltstone assuming a six inch clean cap fill and column degradation by carbonation.**

Degradation mechanism:				Sulfate attack										Carbonation										
Thickness:		SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	Time (yr)			A (cm/vyr)			Time (yr)			max δ (cm)			
Component	(in)	(cm)	CE	CE	NV	NV	BE	BE	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE
Roof delay																								
Roof degradation	8	20.32	20.3	0	20.3	0	19.4	0.94	0.027	0.021	0.011	0.011	136	224	809	136	224	809	136	224	809	136	224	809
Roof delay+degradation			-507	0	-215	0	0	0	0	0	0	0	893	1185	2595	893	1185	2595	893	1185	2595	893	1185	2595
FloorUMM delay																								
FloorUMM degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027	0.021	0.011	0.011	1135	1413	2717	1135	1413	2717	1135	1413	2717	1135	1413	2717
FloorUMM delay+degradation			-265	0	0	0	0	0	0	0	0	0	1135	1413	2717	1135	1413	2717	1135	1413	2717	1135	1413	2717
Wall delay																								
Wall degradation	8	20.32	20.3	0	19.5	0.82	19.5	0.81	0.027	0.021	0.011	0.011	757	922	1797	757	922	1797	757	922	1797	757	922	1797
Wall delay+degradation			-143	0	0	0	0	0	0	0	0	0	757	922	1797	757	922	1797	757	922	1797	757	922	1797
GROUT delay																								
GROUT degradation	264	670.6																						
GROUT delay+degradation																								
Column delay																								
Column degradation*	24	60.96																						
Column delay+degradation																								

Degradation mechanism:				Decalcification				Limiting																	
Thickness:		SA	Carb	SA	Carb	SA	Carb	Time (yr)			max δ (cm)														
Component	(in)	(cm)	CE	CE	NV	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE
Roof delay																									
Roof degradation	8	20.32																							
Roof delay+degradation																									
FloorUMM delay																									
FloorUMM degradation	12	30.48																							
FloorUMM delay+degradation																									
Wall delay																									
Wall degradation	8	20.32																							
Wall delay+degradation																									
GROUT delay																									
GROUT degradation	264	670.6																							
GROUT delay+degradation																									
Column delay																									
Column degradation*	24	60.96																							
Column delay+degradation																									

segment	start (yr)	end (yr)	segment
grout1	1185	1769	grout11
grout2	1769	2353	grout10
grout3	2353	2937	grout9
grout4	2937	3521	grout8
grout5	3521	4105	grout7
grout6	4105	4689	grout6

\* Use degradation time for successive column segments

**Table 5-12. Degradation analysis for SDU 2 concrete and saltstone with 24 inch clean cap and column degradation by sulfate attack.**

Degradation mechanism:				Sulfate attack										Carbonation						max δ																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
Component		Thickness:	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA	Carb	SA

**Table 5-13. Degradation analysis for SDU 2 concrete and saltstone assuming no clean cap fill and column degradation by sulfate attack.**

Degradation mechanism:										Sulfate attack										Carbonation						max δ						
Thickenss:		(in)		(cm)		CE	Carb	SA	Carb	SA	Carb	BE	SA	Carb	BE	CE	A <sub>i</sub> (cm/yr)		Time (yr)			A (cm/vyr)			Time (yr)			BE		max δ		
Component																	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	max δ		
Roof delay																																
Roof degradation	8	20.32	20.3	0	20.3	0	20.3	0	20.3	0	20.3	0	19.8	0.56	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	
Roof delay+degradation																																
FloorUUMM delay																																
FloorUUMM degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	
FloorUUMM delay+degradation																																
Wall delay																																
Wall degradation	8	20.32	20.3	0	19.5	0.82	19.5	0.81	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	0.011	0.027	0.021	
Wall delay+degradation																																
Grout delay																																
Grout degradation	264	670.6																														
Grout delay+degradation																																
Column delay																																
Column degradation	6.20	15.7	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0
Column delay+degradation																																

Degradation mechanism:										Decalcification										Limiting				Limiting			
Thickenss:		(in)		(cm)		CE	Carb	SA	Carb	SA	Carb	BE	SA	Carb	BE	CE	Time (yr)		max δ		NV		BE				
Component																	CE	NV	BE	CE	NV	BE	CE	NV	BE		
Roof delay																											
Roof degradation	8	20.32																									
Roof delay+degradation																											
FloorUUMM delay																											
FloorUUMM degradation	12	30.48																									
FloorUUMM delay+degradation																											
Wall delay																											
Wall degradation	8	20.32																									
Wall delay+degradation																											
Grout delay																											
Grout degradation	264	670.6																									
Grout delay+degradation																											
Column delay																											
Column degradation	6.20	15.7	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0	15.7		
Column delay+degradation																											

**Table 5-14. Degradation analysis for SDU 6 “Design” case assuming no clean cap fill and column degradation by sulfate attack.**

Degradation mechanism:				Sulfate attack												Carbonation						max δ		
Thickmess:		SA	Carb	SA	Carb	SA	Carb	SA	Carb	A <sub>s</sub> (cm/yr)			Time (yr)			A (cm/Vyr)			Time (yr)			max δ		
Component	(in)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE	CE	NV	BE
Roof delay																								
Roof degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027	0.021	0.011	clean grout:	0	0	0	1135	1413	2717	0.27	0.17	0.0271	1400	1400	1400
Roof delay+degradation			-265				0						1135	1413	2717	1135	1413	2717	0.27	0.17	0.0271	1400	1413	2717
FloorUIMM delay																0	0	0				1400	1400	1400
FloorUIMM degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027	0.021	0.011		1135	1413	2717	1135	1413	2717	0.27	0.17	0.0271	1400	1413	2717
FloorUIMM delay+degradation			-265				0						1135	1413	2717	1135	1413	2717	0.27	0.17	0.0271	1400	1413	2717
Wall delay																0	0	0				0	0	0
Wall degradation	8.73	22.17	14.3	7.85	17.2	4.93	21.0	1.19	0.027	0.021	0.011		533	815	1933	533	815	1933	0.27	0.17	0.0271	533	815	1933
Wall delay+degradation			0				0						533	815	1933	533	815	1933	0.27	0.17	0.0271	533	815	1933
Wall delay																0	0	0				0	0	0
Wall degradation	10.45	26.54	17.1	9.39	20.7	5.85	25.2	1.31	0.027	0.021	0.011		639	979	2324	639	979	2324	0.27	0.17	0.0271	639	979	2324
Wall delay+degradation			0				0						639	979	2324	639	979	2324	0.27	0.17	0.0271	639	979	2324
Wall delay																0	0	0				0	0	0
Wall degradation	13.46	34.19	22.1	12.1	26.7	7.53	32.7	1.49	0.027	0.021	0.011		822	1261	3012	822	1261	3012	0.27	0.17	0.0271	822	1261	3012
Wall delay+degradation			0				0						822	1261	3012	822	1261	3012				822	1261	3012
Wall delay																						0	0	0
Wall degradation	16.50	41.91	27.1	14.8	32.7	9.23	40.3	1.65	0.027	0.021	0.011		1008	1546	3708	1008	1546	3708	0.27	0.17	0.0271	1008	1546	3708
Wall delay+degradation			0				0						1008	1546	3708	1008	1546	3708				1008	1546	3708
Wall delay																0	0	0				0	0	0
Wall degradation	19.45	49.4	31.9	17.5	38.5	10.9	47.6	1.79	0.027	0.021	0.011		1188	1822	4385	1188	1822	4385	0.27	0.17	0.0271	1188	1822	4385
Wall delay+degradation			0				0						1188	1822	4385	1188	1822	4385				1188	1822	4385
Grout delay																								
Grout degradation	516	1311																						
Grout delay+degradation																								
Column delay																0	0	0						
Column degradation	10.63	27.0	27.0	0	27.0	0	27.0	0	0.027	0.021	0.011		1005	1277	2487	1005	1277	2487						
Column delay+degradation													1005	1277	2487	1005	1277	2487						

**Table 5-14 Degradation analysis for SDU 6 “Design” case assuming no clean cap fill and column degradation by sulfate attack (continued).**

Degradation mechanism:		Decalcification					Limiting	
Component	Thickness:	A (cm/vyr)			Time (yr)		max $\delta$	NV
	(in)	CE	NV	BE	CE	NV	(cm)	(yr)
Roof delay							1400	0
Roof degradation	12			HDPE-GCL:			358791	Roof
Roof delay+degradation				0.021			360191	1413
FloorUMM delay							1400	0
FloorUMM degradation	12			HDPE-GCL:			358791	FloorUMM
FloorUMM delay+degradation				0.021			360191	1413
Wall delay							900	0
Wall degradation	8.73			HDPE:			261020	Wall
Wall delay+degradation				0.021			261920	815
Wall delay							900	0
Wall degradation	10.45			HDPE:			312447	Wall
Wall delay+degradation				0.021			313347	979
Wall delay							900	0
Wall degradation	13.46			HDPE:			402444	Wall
Wall delay+degradation				0.021			403344	1261
Wall delay							900	0
Wall degradation	16.5			HDPE:			493338	Wall
Wall delay+degradation				0.021			494238	1546
Wall delay							900	0
Wall degradation	19.45			HDPE:			581540	Wall
Wall delay+degradation				0.021			582440	1822
Grout delay							1135	1413
Grout degradation	516			$A_u$ (cm/vr)			43799	Grout
Grout delay+degradation				3.0E-02 3.0E-03 3.0E-04			44933	439398
Column delay								0
Column degradation	10.63							Column
Column delay+degradation								1277

Initial thickness (in)	t=0 thickness (in)	Times: (yr)
⑤	10.35	26.3
④	12.28	31.2
③	15.66	39.8
②	19.07	48.4
①	22.37	56.8

**Table 5-15. Degradation analysis for SDU 6 “Design w/Margin” case assuming no clean cap fill and column degradation by sulfate attack.**

Degradation mechanism:		SA						Carb						Sulfate attack						Carbonation						max δ (cm)
		Thick:		CE	CE	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	CE	NV	BE	CE	NV	BE	
Component	Thickness: (in)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)
Roof delay																										
Roof degradation	9	22.86	22.9	0	22.9	0	22.9	0	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69
Roof delay+degradation			-549		-319																					
FloorUIMM delay																										
FloorUIMM degradation	9	22.86	22.9	0	22.9	0	22.9	0	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69	22.2	0.69
FloorUIMM delay+degradation			-549		-319																					
Wall delay																										
Wall degradation	6.04	15.34	9.91	5.43	11.3	4.00	11.3	4.00	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99	14.4	0.99
Wall delay+degradation			0		0		0		0		0		0		0		0		0		0		0		0	
Wall delay																										
Wall degradation	7.63	19.38	12.5	6.86	14.8	4.57	14.8	4.57	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11	18.3	1.11
Wall delay+degradation			0		0		0		0		0		0		0		0		0		0		0		0	
Wall delay																										
Wall degradation	10.43	26.49	17.1	9.38	20.7	5.84	20.7	5.84	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30	25.2	1.30
Wall delay+degradation			0		0		0		0		0		0		0		0		0		0		0		0	
Wall delay																										
Wall degradation	13.26	33.68	21.8	11.9	26.3	7.42	26.3	7.42	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48	32.2	1.48
Wall delay+degradation			0		0		0		0		0		0		0		0		0		0		0		0	
Wall delay																										
Wall degradation	15.99	40.61	26.2	14.4	31.7	8.95	31.7	8.95	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62	39.0	1.62
Wall delay+degradation			0		0		0		0		0		0		0		0		0		0		0		0	
Grout delay																										
Grout degradation	516	1311																								
Grout delay+degradation																										
Column delay																										
Column degradation	10.63	27.0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0	27.0	0
Column delay+degradation																										

**Table 5-15 Degradation analysis for SDU 6 “Design w/Margin” case assuming no clean cap fill and column degradation by sulfate attack (continued).**

Degradation mechanism:			Decalcification					Limiting	
Component	Thickness: (in)	(cm)	A (cm/yr)			Time (yr)	max $\delta$ (cm)	NV (yr)	NV (yr)
			CE	NV	BE	CE	BE		
Roof delay							1400		0
Roof degradation	9	22.86			HDPE-GCL: 0.021		269093		Roof
Roof delay+degradation							270493		1081
FloorUMM delay							1400		0
FloorUMM degradation	9	22.86			HDPE-GCL: 0.021		269093		FloorUMM
FloorUMM delay+degradation							270493		1081
Wall delay					HDPE:		900		0
Wall degradation	6.04	15.34			0.021		180591		Wall
Wall delay+degradation							181491		536
Wall delay					HDPE:		900		0
Wall degradation	7.63	19.38			0.021		228131		Wall
Wall delay+degradation							229031		700
Wall delay					HDPE:		900		0
Wall degradation	10.43	26.49			0.021		311849		Wall
Wall delay+degradation							312749		977
Wall delay					HDPE:		900		0
Wall degradation	13.26	33.68			0.021		396464		Wall
Wall delay+degradation							397364		1242
Wall delay					HDPE:		900		0
Wall degradation	15.99	40.61			0.021		478089		Wall
Wall delay+degradation							478989		1498
Grout delay							851	1081	1081
Grout degradation	516	1311	3.0E-02	3.0E-03	3.0E-04	43799	437985	437985	Grout
Grout delay+degradation						44650	439067	4381897	439067
Column delay									0
Column degradation	10.63	27.0							Column
Column delay+degradation									1277

Initial thickness (in)	Initial thickness (cm)	t=0 thickness (in)	t=0 thickness (cm)	Times: (yr)
⑤	7.33	18.6	6.04	15.3
				Wall
				536
④	9.12	23.2	7.63	19.4
				Wall
				700
③	12.26	31.1	10.43	26.5
				Wall
				977
②	15.43	39.2	13.26	33.7
				Wall
				1242
①	18.49	47.0	15.99	40.6
				Wall
				1498

**Table 5-16. Degradation analysis for SDU 2 concrete and saltstone assuming a six inch clean cap fill and column degradation by sulfate attack.**

Degradation mechanism:		Sulfate attack										Carbonation				
		Thickness: (in)	SA (cm)	CE (cm)	SA (cm)	Carb (cm)	SA (cm)	CE (cm)	SA (cm)	Carb (cm)	BE (cm)	A <sub>s</sub> (cm/yr)		Time (yr)		max δ (cm)
Component												CE	NV	BE	CE	BE
Roof delay																
Roof degradation	8	20.32	20.3	0	20.3	0	19.4	0.94	0.027	0.021	clean grout:	136	224	809	1400	1400
Roof delay+degradation			-507		-215							757	961	1785	0	1195
FloorUUMM delay												893	1185	2595	1400	2595
FloorUUMM degradation	12	30.48	30.5	0	29.9	0.61	29.5	0.98	0.027	0.021		0	0	0	1400	1400
FloorUUMM delay+degradation			-265		0							1135	1413	2717	0	1317
Wall delay												0	0	0	1400	1413
Wall degradation	8	20.32	20.3	0	19.5	0.82	19.5	0.81	0.027	0.021		757	922	1797	900	900
Wall delay+degradation			-143		0							757	922	1797	0	897
Grout delay															900	922
Grout degradation	264	670.6														
Grout delay+degradation																
Column delay																
Column degradation	6.20	15.7	15.7	0	15.7	0	15.7	0	0.027	0.021		586	745	1450		5
Column delay+degradation												586	745	1450		

Degradation mechanism:		Decalcification										Limiting	
		Thickness: (in)	SA (cm)	CE (cm)	SA (cm)	CE (cm)	SA (cm)	CE (cm)	SA (cm)	CE (cm)	BE (cm)	max δ (cm)	NV (yr)
Component													
Roof delay													
Roof degradation	8	20.32									1400		224
Roof delay+degradation											239194	5	Roof
FloorUUMM delay											240594		1185
FloorUUMM degradation	12	30.48									1400		0
FloorUUMM delay+degradation											358791	5	FloorUUMM
Wall delay											360191		1413
Wall degradation	8	20.32									900		0
Wall delay+degradation											239194	5	Wall
Grout delay											240094		922
Grout degradation	264	670.6									1185		1185
Grout delay+degradation											224086	2240856	GROUT
Column delay											23301	2243451	225271
Column degradation	6.2	15.7											0
Column delay+degradation													Column
													745



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