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Leach Testing of Laboratory-Scale Melter Evaporator Condensate Cementitious Waste Forms

September 2019

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

Cementitious waste forms immobilizing evaporated AP-105 off-gas condensate were used to determine radionuclide and contaminant leachability in deionized water over a 63-day period. The off-gas condensate was collected during the actual tank AP-105 low activity waste continuous laboratory-scale melter (LSM) run performed in fiscal year 2018 and was then solidified as a cementitious waste form using the Cast Stone formulation (8 weight percent [wt%] ordinary Portland cement, 45 wt% class F fly ash, 47 wt% blast furnace slag). Here, using the U.S. Environmental Protection Agency Method 1315 leach testing procedure, the release rates of technetium-99 (Tc), iodine-129 (I), nitrate (NO_3^-), and sodium (Na^+) from two Cast Stone specimens were measured. From these measurements, observed diffusivity values for each constituent were calculated and can be used in future iterations and maintenance of the Integrated Disposal Facility performance assessments. Furthermore, by testing Cast Stone specimens immobilizing off-gas produced while vitrifying actual tank waste, the results of this effort improve the technical defensibility of waste form performance estimates for the Cast Stone formulation. Finally, ^{99}Tc distribution within a representative waste form at the end of the 63-day leach period as well as bulk mineralogy were determined using solid phase characterization methods.

Executive Summary

This report describes the results from leach tests and characterization performed on two cementitious waste forms prepared in fiscal year (FY) 2018 using the condensate collected during vitrification of a tank AP-105 sample on the lab scale melter. The collected condensate was evaporated prior to solidification to simulate an evaporator concentrate waste stream. This work supports the technical development for liquid secondary waste immobilization, including development of an alternative immobilization path for the effluent management facility (EMF) evaporator bottoms waste stream to be generated during direct-feed low-activity waste (DFLAW) operations at the Hanford Site.

High-priority activities included U.S. Environmental Protection Agency (EPA) Method 1315 leach testing and waste form characterization after leach test completion. The work described in this report relates to waste form development and testing. However, this work contains information that can be utilized in future iterations of the integrated disposal facility (IDF) performance assessment (PA), in maintenance of the 2017 IDF PA, and to guide future waste form development efforts.

Specific grout formulation and waste form testing efforts described in this report include:

- determination of observed diffusivity (D_{obs})[1] values for ^{99}Tc, ^{127}I, NO_3^-, and Na^+ in deionized water (DIW) using EPA Method 1315 to assess the retention potential of Cast Stone immobilized evaporated off-gas condensate, and
- solid phase characterization of a select specimen to determine radionuclide distribution and bulk mineralogy after leaching with DIW for 63 days.

The key findings from this work are listed below and are supported by the details that follow:

1. The range of average values reported for **^{99}Tc D_{obs} (~3 × 10^{-12} to ~5 × 10^{-12} cm^2/s) determined from 28- to 63-day leaching intervals** represents the effects of diffusion-controlled processes in addition to physical and/or chemical processes that immobilize ^{99}Tc. These ^{99}Tc D_{obs} values indicate an approximately one order of magnitude improvement in ^{99}Tc release compared to previously tested simulated waste forms using the Cast Stone formulation to immobilize EMF evaporator bottoms (Saslow et al, 2018)[2] and comparable to other previously measured Cast Stone waste forms from various simulant feeds.
2. Reported average ^{127}I D_{obs} values (~6 × 10^{-12} to ~1 × 10^{-11} cm^2/s) determined from 28- to 63-day leaching intervals are up to two orders of magnitude lower than previously reported D_{obs} values for simulated waste forms using the Cast Stone formulation. The source of improvement is unknown but may be correlated to the chemical composition of the evaporated concentrate.
3. Reported NO_3^- D_{obs} values were determined to range between ~7 × 10^{-11} and ~1 × 10^{-10} cm^2/s and Na^+ D_{obs} values ranging from ~1 × 10^{-8} to ~2 × 10^{-8} cm^2/s suggest Na^+ is readily released. This behavior is

[1] Observed diffusion coefficients (D_{obs}) are used in EPA test methodologies to describe values obtained from a leach test and are often represented as synonymous with intrinsic effective diffusion coefficients impacted only by physical properties.

[2] Saslow SA, W Um, RL Russell, BD Williams, RM Asmussen, T Varga, O Qafoku, BJ Riley, AR Lawter, MV Snyder, SR Baum, and II Leavy. 2018. *Effluent Management Facility Evaporator Bottoms: Waste Streams Formulation and Waste Form Qualification Testing*. PNNL-26570, Rev. 1. Pacific Northwest National Laboratory, Richland, WA.

different than previously reported for NO_3^- which commonly has D_{obs} equal to mobile Na^+. This cause of NO_3^- improvement is not known.

4. Throughout the 63-day leach period, some periods of ^{99}Tc and ^{127}I release did not follow a pure diffusion trend, suggesting additional chemical reactions may influence contaminant leaching from the waste form. As such, the calculated and reported observed diffusivity values when used should be reported with this information as EPA Method 1315 assumes diffusion-controlled contaminant release.
5. Of the two samples tested one was continued through leach testing and the second characterized with X-ray diffraction (XRD) and an ionizing-radiation Quantum Imaging Detector (iQID). The solid phase characterization suggests that after the 63-day leach period, ^{99}Tc does not generate localized "hot spots" with elevated ^{99}Tc concentrations and showed higher concentrations near the outer wall. From XRD analysis, the waste form consisted of 86.0 wt% amorphous material, 2.5 wt% ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}$•$26H_2O$], 0.1 wt% calcite [$CaCO_3$], and 2.3 wt% quartz [$SiO_2$] and the remainder minor phases and the internal standard used.

The results described herein help establish a baseline dataset from testing a cementitious waste form immobilizing an evaporated melter off-gas condensate produced from actual tank AP-105 sample. The dataset can be used to compare to laboratory data of waste form samples prepared using evaporator condensate simulants, adding to the technical defensibility of waste form performance estimates for the Cast Stone formulation. Based on this work, recommended future work includes:

1) Sample fabrication and leach testing efforts using off-gas condensate collected from the FY18 AP-107 LSM run and/or future LSM runs, to allow a comparison to the AP-105 sample in this report to assess the source of improvements to ^{127}I and NO_3^- retention. If similar behavior is observed from an immobilized AP-107 evaporated off-gas condensate sample then the source of the improvement is likely due to the chemical composition of the real waste,

2) Use of a hydrated lime-based formulation to prepare samples from evaporated off-gas condensate to compare to the Cast Stone samples. Previous testing of simulated EMF evaporator concentrate waste forms showed an order of magnitude improvement in Tc leachability using the hydrated lime formulation.

These analytical results can be used by: (i) cementitious waste form scientists to further the understanding of cementitious leach behavior of contaminants of concern; and (ii) the U.S. Department of Energy, their Hanford Site contractors, and stakeholders as they continue to assess the IDF PA program at the Hanford Site. The reported results provide a comparison between simulated samples and those from actual waste treatment, support alternative disposition of EMF evaporator bottoms waste, and improve the technical defensibility for waste form performance modeling using laboratory data.

Acknowledgments

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Acronyms and Abbreviations

ANS	American Nuclear Society
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	ASTM International (West Conshohocken, PA)
CSH	calcium silicate hydrate
DFLAW	direct feed low-activity waste
DIW	deionized water (ASTM D1193 - 06(2018) Type II)
EC	electrical conductivity
EMF	Effluent Management Facility
EPA	U.S. Environmental Protection Agency
EQL	estimated quantitation limit
FY	fiscal year
IC	ion chromatography
ICP-MS	inductively coupled plasma mass spectrometry
ICP-OES	inductively coupled plasma optical emission spectroscopy
IDF	Integrated Disposal Facility
iQID	ionizing-radiation Quantum Imaging Detector
IX	ion exchange
LAW	low-activity waste (Hanford)
LI	leachability index
LSM	laboratory-scale melter
ND	not detected
NIST	National Institute of Standards and Technology
NQA	Nuclear Quality Assurance
ORP	oxidation reduction potential (E_h)
PA	performance assessment
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
R&D	research and development
SHE	standard hydrogen electrode
WRPS	Washington River Protection Solutions, LLC
WWFTP	WRPS waste form testing program
XRD	X-ray diffraction

Units of Measure

Å	angstrom(s)
°C	temperature in degree Celsius [T(°C) = T(K) − 273.15]
cm	centimeter(s)
d	day(s)
g	gram(s)
h	hour(s)
kg	kilogram(s)
kV	kilovolt(s)
L	liter(s)
m	meter(s)
M	molarity, mole(s)/liter
mA	milliampere
Mg	megagram(s)
mg	milligram(s)
mL	milliliter(s)
mm	millimeter(s)
mV	millivolt(s)
nA	nanoampere
nm	nanometer(s)
ppb	parts per billion
ppm	parts per million
s	second(s)
S	Siemens
wt%	weight percent
µ	micro (prefix, 10^{-6})

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1.0 Introduction

The direct feed low-activity waste (DFLAW) operations involve concentrating the Hanford low-activity waste (LAW) melter off-gas waste stream by evaporation with a new evaporator at the Effluent Management Facility (EMF). Once evaporated, the concentrate will be sent back to the LAW vitrification facility melter feed tank for recycling, with a minor amount directed without evaporation to double-shell tanks when evaporation at the EMF is unavailable. The evaporated concentrate waste stream is expected to contain variable, high levels of halides and sulfate that can limit immobilized LAW glass waste loading due to their low solubility in glass. As a result, these components could strain LAW melter performance and increase required production volumes during the Hanford mission life cycle. Furthermore, co-mingled radionuclides, technetium-99 (^{99}Tc) and iodine-129 (^{129}I), in the evaporated concentrate waste stream volatilize in the LAW melter and are expected to accumulate in the off-gas waste streams. To this end, the purpose of this research program is to examine alternative disposition paths for the evaporator concentrate waste stream that bypass recycling to the LAW vitrification facility melter (McCabe et al. 2016), thus eliminating recycling of the identified problematic components and decreasing the efficiency of the integrated operations of the LAW melter. Technology development and maturation activities conducted within this program will support alternative disposition path investigations for the EMF evaporator bottoms wastes, and the results will be used to assess whether a developed cementitious waste form can meet the waste acceptance criteria for disposal at the onsite Hanford Integrated Disposal Facility (IDF).

In fiscal year (FY) 2019, Washington River Protection Solutions, LLC (WRPS) contracted with Pacific Northwest National Laboratory (PNNL) to advance the development of solidification/immobilization of EMF evaporator bottoms liquid waste in cementitious waste forms for onsite disposal at the Hanford IDF. Activities described in this report include demonstration of waste form performance for cementitious waste forms produced from the off-gas condensate collected during a continuous laboratory-scale melter (LSM) run with an actual AP-105 Hanford tank LAW sample (Dixon et al. 2018; Cantrell et al. 2018). This work supports the WRPS Chief Technology Office objective of identifying options for alternative treatment and disposition of Hanford Tank Waste Treatment and Immobilization Plant secondary liquid waste from the DFLAW process.

1.1 Performance Demonstration of EMF Evaporator Bottoms Cementitious Waste Forms

In FY18, vitrification testing was performed using PNNL's continuous LSM on a sample of actual LAW from Hanford tank AP-105. The off-gas condensate from the AP-105 LSM run was collected and immobilized as cementitious waste forms using the Cast Stone formulation (8 wt% ordinary Portland cement, 45 wt% Class F fly ash, and 47 wt% blast furnace slag). Two of the formulated waste form specimens were then subjected to U.S. Environmental Protection Agency (EPA) Method 1311, *Toxicity Characteristic Leaching Procedure (TCLP)*, to demonstrate the feasibility of an alternative solidification treatment using a cementitious waste form and waste form qualification for off-site disposition of an EMF evaporator bottoms waste stream without recycling back to the LAW melter feed tank (EPA 1992). Results from those tests showed both specimens passing Universal Treatment Standards for inorganic constituents in non-wastewater (40 CFR 268.48) by at least an order of magnitude (Cantrell et al. 2018).

From this LAW AP-105 LSM run, two concentrated off-gas condensate cementitious waste form samples remained: one 2" × 4" monolith and one 2" × ≈2" monolith (Cantrell et al. 2018). These samples presented an opportunity to conduct additional performance testing on a cementitious waste form immobilizing melter condensate from actual Hanford tank waste, the results of which may be used to additionally qualify these waste forms for on-site disposal at the Hanford IDF. Demonstration of waste form performance thus involved performing EPA Method 1315 leach testing in deionized water (DIW,

ASTM D1193-06(2018) Type II Reagent Water) on both remaining samples (for reproducibility). The intended use of the test results is to establish baseline testing metrics for an evaporated melter off-gas condensate sample produced from an actual tank waste sample and to compare with previous laboratory testing data collected from immobilized simulant evaporator concentrate samples. The test objectives also included waste form characterization with X-ray diffraction (XRD) for mineralogical composition and digital autoradiography for radionuclide distribution. The outcome of this testing effort is described in detail in this report.

1.2 Objectives

The overall objectives of the EMF evaporator bottoms waste form testing program task in this report are to:

- Provide contaminant release and waste form characterization data based on actual treated Hanford waste streams for cementitious waste forms formulated from off-gas condensate (Cantrell et al. 2018) collected from a continuous LSM test using AP-105 Hanford tank LAW (Dixon et al. 2018). Data may be used for performance assessment (PA) and risk assessment evaluations for waste form disposal in the Hanford IDF.

1.3 Report Contents and Organization

This report details the testing approach, results, and conclusions from the performance demonstration of EMF evaporator bottoms cementitious waste forms sub-task and contains five sections and an appendix. Section 1 provides an introduction and describes key objectives and quality assurance (QA) procedures of the tests conducted for this study. Section 2 summarizes the characterization and analysis techniques used for solution and solid samples. Section 3 details EPA Method 1315 observed diffusivity leach tests (EPA 2013), and Section 4 presents the physical properties of the cementitious waste forms after leaching for 63 days. Section 5 provides a summary, including conclusions and recommendations for future work, and Section 6 contains a list of references cited in the report. Additional data and calculations performed for the EPA Method 1315 test are included in Appendix A.

1.4 Quality Assurance

This work was funded by WRPS under contract 36437-161, *Secondary Waste Cast Stone Formulation and Waste Form Qualification*. The work was conducted as part of PNNL Project 73717 (a part of Master Project 68334), Liquid Secondary Waste Formulation Development.

This work was performed in accordance with the WRPS Waste Form Testing Program (WWFTP) QA program. The WWFTP QA program is based on the requirements of NQA-1-2008, Quality Assurance Requirements for Nuclear Facility Applications, and NQA-1a-2009, Addenda to ASME NQA-1-2008 Quality Assurance Requirements for Nuclear Facility Applications, graded on the approach presented in NQA-1-2008, Part IV, Subpart 4.2, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development”. The WWFTP QA program consists of the WWFTP Quality Assurance Plan (QA-WWFTP-001) and associated procedures that provide detailed instructions for implementing NQA-1 requirements for R&D work.

The WWFTP QA Program works in conjunction with PNNL’s laboratory-level Quality Management Program, which is based upon the requirements as defined in the United States Department of Energy (DOE) Order 414.1D, Quality Assurance, and 10 CFR 830, Nuclear Safety Management, Subpart A, “Quality Assurance Requirements”. Performance of this work and preparation of this report were assigned the technology level “Applied Research”. All staff members contributing to the work have

technical expertise in the subject matter and received QA training before performing quality-affecting work. The “Applied Research” technology level provides adequate controls to ensure that the activities were performed correctly and that all client QA expectations were addressed in performing the work.

2.0 Characterization and Analysis Methods

This section describes the techniques used for solution and solid analyses of the two cementitious waste form specimens tested under the EPA Method 1315 leach procedure. All techniques described here are methods and procedures performed at PNNL.

2.1 Solution Analysis

The following instruments were used for analyzing leachate solutions to identify and measure the concentration of detectable species or elements.

2.1.1 pH and Electrical Conductivity Measurement

The pH of the leachate solutions was measured with a solid-state YSI Inc. (YSI) pH electrode and a pH meter (YSI MultiLab 4010-3). Before measurement, the pH probe was calibrated with National Institute of Standards and Technology (NIST)-traceable buffers (pH = 7.0, 10.0, and/or 13.0 at 25°C). The precision of each pH measurement was ±0.10 pH units. A YSI conductivity sensor was used to measure the electrical conductivity (EC) of leachate solutions. The cell constant of the sensor was calibrated using a 1,413 µS/cm standard, and then checked with a range of potassium chloride standard solutions, ranging from 100 to 10,000 µS/cm, and a blank containing DIW. Calibration checks were repeated after every set of 10 samples analyzed and at the end of analyses performed each day.

2.1.2 Alkalinity Measurement

The alkalinity (mg/L as $CaCO_3$) was measured using a standard acid titration method (total alkalinity at pH = 4.5). The alkalinity measurement procedure is equivalent to the U.S. Geological Survey method in the *National Field Manual for the Collection of Water-Quality Data* (USGS 2004).

2.1.3 Oxidation Reduction Potential (E_h) Measurement

A YSI 4210 oxidation reduction potential (ORP) probe (connected to a YSI MultiLab 4010-3 meter) was used to measure the ORP of the leachate solutions (Manahan 1994). The calibration of the probe was verified with ZoBell's ORP/Redox standard solution (Hach, +224.0 mV at 20°C). The E_h values discussed in this report were corrected to E_h standard hydrogen electrode values by adding +211 mV to the value measured by a YSI probe with the 3 M KCl reference (Nordstrom and Wilde 2005).

2.1.4 Analysis of Cations, Anions, ^{99}Tc, and ^{127}I

Concentrations of major cations in leachate solutions were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES), while major anions were analyzed using ion chromatography (IC). Concentrations of ^{99}Tc and ^{127}I were analyzed using inductively coupled plasma mass spectrometry (ICP-MS).

2.2 Solid Analysis

The instruments described below were used for identifying elements and minerals within select waste form specimens.

2.2.1 X-Ray Diffraction Analysis

The mineralogy of a select specimen after leach testing was determined using a Rigaku Miniflex II XRD unit equipped with a Cu Kα radiation (λ = 1.5418 Å with 30 kV and 15 mA) source. A portion of the selected specimen was homogenized by grinding in an agate mortar and pestle. Then ≈10 wt% TiO_2 standard was mixed in as an internal standard and the specimen was re-homogenized with the mortar and pestle. The powdered sample was then loaded into zero background quartz sample holders, held within custom containers with Kapton windows to prevent dispersion of the radiological powder before scanning from 3 to 100 degrees 2θ. Mineral identification was performed using Jade software (Materials Data Inc., California) with the International Centre for Diffraction Data XRD database. Quantification was performed by the whole pattern fitting (Rietveld) method using Topas software (v5, Bruker AXS, Germany) with the pattern for each phase calculated from published crystal structures International Centre for Diffraction Data, Newtown Square, PA, USA). The phase fractions were scaled to 100% and absolute quantities of minerals, and amorphous material by difference, were determined with reference to the TiO_2 standard.

2.2.2 Single Particle Digital Autoradiography

The ionizing-radiation Quantum Imaging Detector (iQID) assesses the spatial distribution of ^{99}Tc within the LSM-FY18-CS-1 monolith. Further information regarding development and use of the technique can be found in Miller et al. (2014, 2015). The bottom face of the monolith was analyzed using the iQID for 48 hours encased in Mylar film.

3.0 EPA Method 1315 Leach Testing

The EPA Method 1315 leach test measures the observed diffusivity of species of interest using a semi-dynamic leaching procedure. The observed diffusion coefficient accounts for all physical and chemical retention factors influencing mass transfer of the constituent of concern and is calculated according to Fick's second law of diffusion. Leach testing was performed on the remaining two cementitious waste form specimens used to immobilize off-gas condensate (after concentration) from the FY18 LAW AP-105 continuous LSM run. Specimens were leached for a minimum of 63 days in DIW in accordance with the instructions and approach described in EPA Method 1315 (EPA 2013). Observed diffusivities were calculated for key constituents including technetium, iodide, nitrate, and sodium.

3.1 Methods and Materials

The two Cast Stone monoliths used for the EPA Method 1315 test are herein referred to as LSM-FY18-CS-1 (2" × 4" monolith) and LSM-FY18-CS-2 (2" × ≈2" monolith). LSM-FY18-CS-1 was cured 28 days within a plastic form and under >80% relative humidity before removing the form and archiving until use. This 28 day cure period and curing environment is the standard used in previous formulation efforts that used simulated waste streams. Archived samples are stored in an open plastic bag inserted into a second sealed plastic bag containing a moist paper towel. The total archive time was 253 days for LSM-FY18-CS-1. In contrast, monolith LSM-FY18-CS-2 was cured in its plastic form for 269 days before removing the form and archiving for twelve days until analysis. Hydration reactions are known to continue past the initial 28-day cure period, but are expected to be similar between the two monoliths due to the humid environment that is maintained even while archived.

The EPA Method 1315 test is a semi-dynamic leach test that consists of submerging a monolith in leachant at a fixed ratio of liquid-volume-to-solid geometric surface area. To start the EPA Method 1315 test, each monolith was placed into the center of a leaching vessel containing sufficient leachant (DIW) to maintain a solution-to-solid geometric surface area ratio of 9 ± 1 mL/cm^2. Monolith stands and holders were used to maximize the contact area of the monolith with the leaching solution. The surface area of each monolith and the DIW target volumes were calculated before starting the EPA Method 1315 leach test based on physical measurements determined for each specimen. Specifically, the diameter of each specimen was measured at the bottom, middle, and top, and the specimen length was measured at three rotational orientations mutually separated by ~120 degrees from an arbitrary starting location using a caliper. These measurements were averaged to determine the average specimen diameter and length for calculating total surface area.

Appropriate containers (2 L plastic buckets) with lids were used to fully immerse each monolith in the leaching solution. Leachate sampling was performed at fixed intervals, with cumulative leach times of 0.08, 1, 2, 7, 14, 28, 42, 49, and 63 days. At each sampling interval, the monolith was removed from the leaching solution, the monolith mass was recorded after draining as much surface water as possible, and then the monolith was placed in a new 2 L bucket containing fresh DIW leachant. The contacted leachate pH, E_h, EC, and alkalinity were measured and recorded for each time interval. The remaining leachate was subsampled into several aliquots (each ~20 mL) for subsequent analysis. Analysis focused on leached components for which observed diffusivities are needed (e.g., ^{99}Tc, ^{127}I, NO_3^-, and Na^+) and overall chemical composition. Analytical methods used included ICP-OES for cation concentrations, ICP-MS for ^{99}Tc and ^{127}I concentrations, and IC for anion concentrations.

Initial concentrations, C_0, of the constituents of interest in the pre-leached monoliths, specifically ^{99}Tc, ^{127}I, NO_3^-, and Na^+, are given in Table 3.1. Initial ^{99}Tc, ^{127}I, NO_3^- and Na^+ concentrations in the cured monoliths were calculated from concentrations and densities measured and reported by Cantrell et al.

2018 for the LAW AP-105 waste melter off-gas condensate. The final evaporate used to prepare the monoliths was re-analyzed this FY for NO_3^- concentration and a slightly higher concentration was measured. The increase was likely due to evaporation of the legacy sample and, as such, the calculated NO_3^- concentration was used. Additionally, due to the limited specimens available, a direct measurement of the dry fraction (moisture content) could not be made; therefore, a dry fraction of 0.73 was assumed based on measurements made on simulated cementitious waste forms with the Cast Stone formulation and reported in Saslow et al. 2018. Relevant input values and equations required to carry out these calculations are provided in Appendix A.

Table 3.1. Initial Concentrations, C_0, of ^{99}Tc, ^{127}I, NO_3^-, and Na^+ used in Diffusivity Calculations

Specimen	^{99}Tc (mg/kg-dry)	^{127}I (mg/kg-dry)	NO_3^- (mg/kg-dry)	Na^+ (mg/kg-dry)
LSM-FY18-CS-1	12.93	4.50	86,080	5,290
LSM-FY18-CS-2	13.01	4.53	86,610	5,320

The observed diffusivities for ^{99}Tc, ^{127}I, NO_3^-, and Na^+ were calculated using the analytical solution for Fick's second law and Eq. (3.1) for simple radial diffusion from a cylinder into an infinite bath as detailed by EPA Method 1315 (EPA 2013). The observed diffusion coefficient, D_{obs}, accounts for all physical and chemical retention factors influencing mass transfer of the constituent of interest. This is opposed to the synonymously used term "effective" diffusivity coefficient that only accounts for the intrinsic diffusivity due to physical properties. In this report, the term "observed diffusion coefficient" is used and is equivalent to the symbol D used in ANSI/ANS-16.1 (ANSI/ANS-16.1-2003), and the symbol D_e used in the ASTM C1308-08 (2017) method. In some literature, this parameter, the D_{obs} value in Eq. (3.1) is called the apparent diffusion coefficient, D_a (see, for example, Grathwohl 1998). All of these names are equivalent and are "quantified" in standard leach tests.

$$D_{obs(i)} = 10000 * \pi\left[\frac{M_{ti}}{2\rho C_0\,(\sqrt{t_i}-\sqrt{t_{i-1}})}\right]^2 \tag{3.1}$$

where
$D_{obs(i)}$ = observed diffusivity of a specific constituent for leaching interval i (m^2/s)
M_{ti} = mass of specific constituent released during leaching interval i (mg/m^2)
t_i = cumulative contact time after leaching interval i (s)
t_{i-1} = cumulative contact time after the previous leaching interval, $i - 1$ (s)
C_o = initial concentration of constituent in the dry grout (mg/kg-dry)
ρ = grout dry bulk density (kg-dry/m^3), determined as oven dried mass divided by the calculated volume of the monolith.

The leachability index (LI), a unitless parameter derived from the interval effective diffusion coefficient values (D_i, here using D_{obs}), is calculated using Eq. (3.2), in which β is a defined constant (1.0 cm^2/s) from ANSI/ANS-16.1 (ANSI/ANS-16.1-2003). A low diffusivity results in a larger LI.

$$LI_i = \frac{1}{n}\sum_1^n[\log\left(\frac{\beta}{D_i}\right)]_n \tag{3.2}$$

3.2 Results and Discussion

Monoliths used in EPA Method 1315 leach testing were photographed before leaching and after the 63-day leach period had elapsed to record observations of cracking and monolith degradation. For both specimens, visible cracking or degradation was not observed and the difference in specimen color before

an after leaching is due to specimen wetting (Figure 3.1). The calculated observed diffusivity coefficients (D_{obs}) and LI values for ^{99}Tc, ^{127}I, NO_3^-, and Na^+ through 63 cumulative leaching days are provided in Table 3.2. Calculated D_{obs} values for ^{99}Tc, ^{127}I, NO_3^-, and Na^+ are also shown graphically in Figure 3.2. Duplicate cast stone monoliths are differentiated by the test number followed by either 1 or 2 for DIW-leached monoliths: LSM-FY18-CS-1 and LSM-FY18-CS-2. Control leachate samples, from buckets containing only DIW, were also collected at each sampling interval to determine the background concentrations of ^{99}Tc, ^{127}I, NO_3^-, and Na^+. Background concentrations for all four constituents were mostly non-detect for all sampling intervals. In instances where a positive background value was measured in only one of the control blanks, this was assumed to be a result of cross-contamination, and for the calculations, the background was assumed to be non-detect. However, if a positive value was determined for both control blanks, e.g. Na+, 28 day sampling, the highest concentration recorded was used to perform a background correction. No non-detect, zero, or negative leachate concentration values were encountered in the specimen leachates for all four constituents during the cumulative 63-day leaching test.

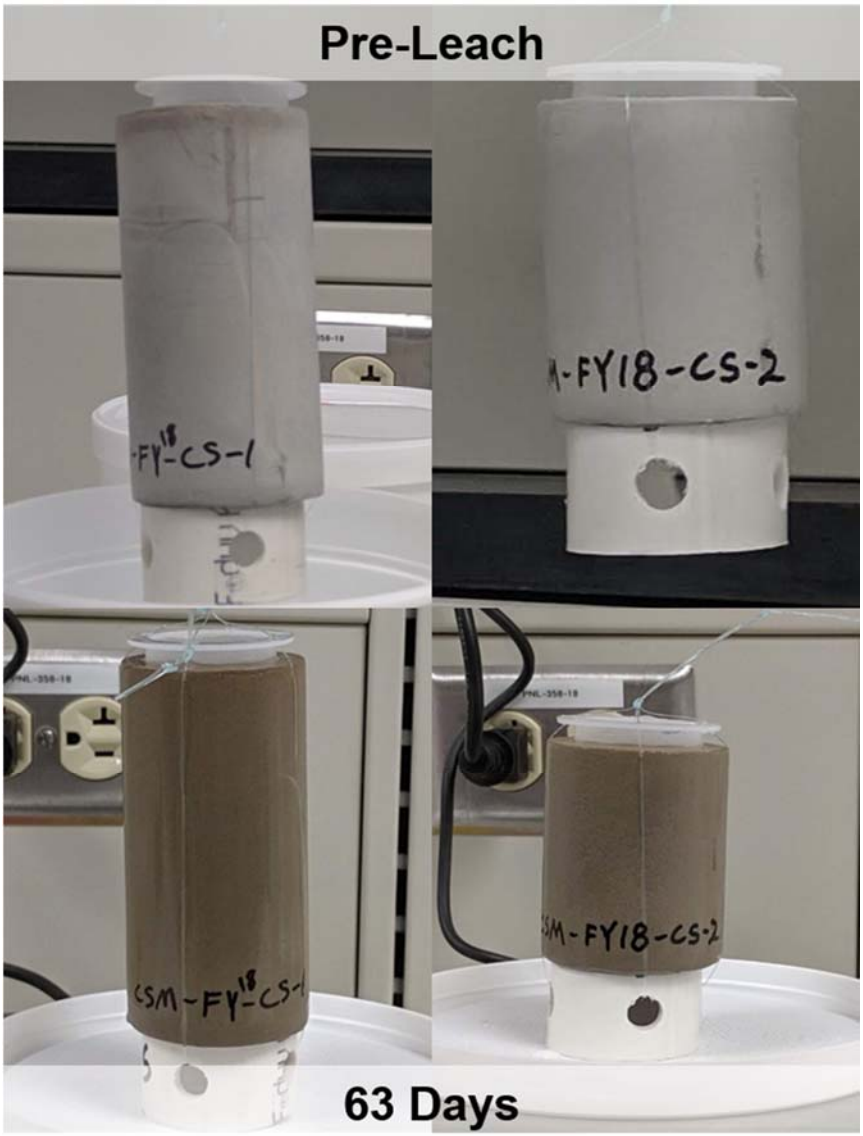

Figure 3.1. Cast Stone specimens used in EPA Method 1315 leach testing were photographed before leaching (Pre-Leach, top row) and after the 63-day leach period had elapsed (63 Days, bottom row). Specimens included LSM-FY18-CS-1 (left) and LSM-FY18-CS-2 (right). Each 63-day leached specimen is darker in color because it is still damp from the DIW leaching solution.

Table 3.2. Diffusivity and LI Values of ^{99}Tc, ^{127}I, NO_3^-, and Na^+ in DIW Leaching Solution

Cumulative Leach Time (day)	LSM-FY18-CS-1 for ^{99}Tc		LSM-FY18-CS-2 for ^{99}Tc		LSM-FY18-CS-1 for ^{127}I		LSM-FY18-CS-2 for ^{127}I		LSM-FY18-CS-1 for NO_3^-		LSM-FY18-CS-2 for NO_3^-		LSM-FY18-CS-1 for Na^+		LSM-FY18-CS-2 for Na^+	
	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]	D_{obs} (cm^2/s)	LI [-]
0.08	2.34E-13	12.6	2.29E-12	11.6	1.89E-11	10.7	9.21E-11	10.0	1.99E-10	9.7	8.67E-10	9.1	2.96E-08	7.5	1.31E-07	6.9
1.0	1.33E-12	11.9	4.19E-12	11.4	5.72E-11	10.2	4.70E-11	10.3	5.37E-10	9.3	4.91E-10	9.3	6.76E-08	7.2	7.23E-08	7.1
2.0	7.35E-13	12.1	2.71E-12	11.6	2.64E-11	10.6	1.94E-11	10.7	2.72E-10	9.6	2.12E-10	9.7	3.94E-08	7.4	3.58E-08	7.4
7.0	1.13E-12	11.9	2.49E-12	11.6	2.11E-11	10.7	8.90E-12	11.1	2.41E-10	9.6	1.05E-10	10.0	3.63E-08	7.4	1.88E-08	7.7
14.0	1.38E-12	11.9	2.80E-12	11.6	1.71E-11	10.8	6.02E-12	11.2	1.87E-10	9.7	7.15E-11	10.1	3.28E-08	7.5	1.36E-08	7.9
28.0	2.08E-12	11.7	3.98E-12	11.4	1.31E-11	10.9	5.89E-12	11.2	1.51E-10	9.8	6.73E-11	10.2	2.27E-08	7.6	1.20E-08	7.9
42.0	2.56E-12	11.6	4.43E-12	11.4	1.19E-11	10.9	5.85E-12	11.2	1.29E-10	9.9	6.58E-11	10.2	2.13E-08	7.7	1.28E-08	7.9
49.0	3.36E-12	11.5	5.22E-12	11.3	1.03E-11	11.0	5.53E-12	11.3	1.19E-10	9.9	6.52E-11	10.2	2.06E-08	7.7	1.27E-08	7.9
63.0	4.54E-12	11.3	6.60E-12	11.2	1.05E-11	11.0	6.08E-12	11.2	1.17E-10	9.9	6.86E-11	10.2	1.96E-08	7.7	1.26E-08	7.9

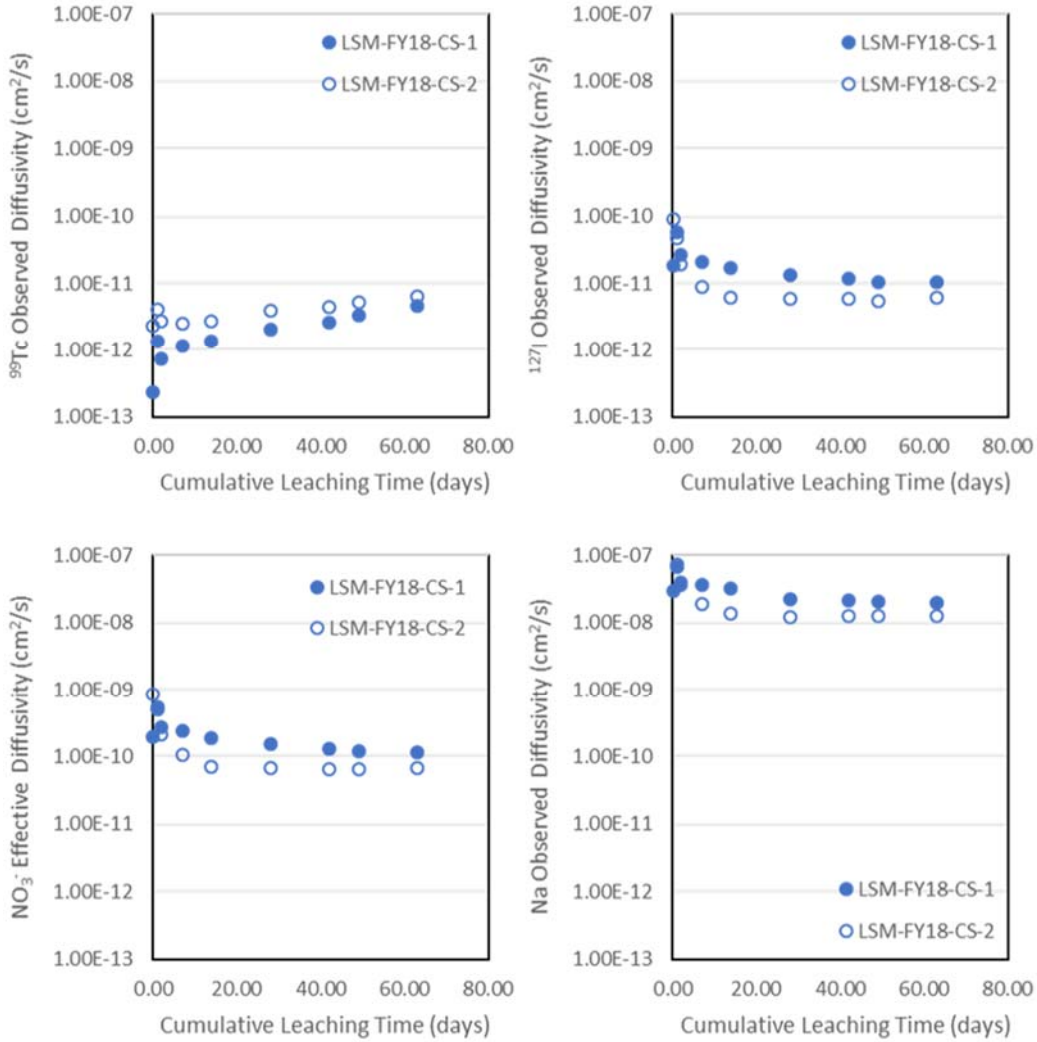

Figure 3.2. Observed diffusivity values of ^{99}Tc (top, left), ^{127}I (top, right), NO_3^- (bottom, left) and Na^+ (bottom, right) from LSM Cast Stone specimens leached for a cumulative 63 days in DIW.

A time-invariant average D_{obs} value was calculated for the four constituents by averaging the D_{obs} values determined for leach samples between 28 and 63 days. Average D_{obs} values are provided in Table 3.3, in addition to the fraction of total constituent mass released after the 63-day cumulative leach period relative to the initial mass of constituent in the monolith before leaching. Because the fraction of total released mass of ^{99}Tc during early leach periods, 0.08 to 14 days, is less than 20% of the total initial mass of ^{99}Tc, the time-invariant ^{99}Tc D_{obs} value was determined from the later leach periods, between 28 and 63 days. This approach is supported by the less significant effect of early leaching on full-sized cementitious waste forms to be disposed of in the IDF. In addition, average ^{99}Tc D_{obs} values with their uncertainty ranges can cover the minor artifacts that might result from the early stages of leaching (e.g., surface wash off), if there are any. For consistency, this approach to calculating average D_{obs} values is used for all four constituents.

Averaged ^{99}Tc D_{obs} values for individual monoliths from the cumulative 28- to 63-day leaching in DIW were 3.13×10^{-12} (LSM-FY18-CS-1) and 5.06×10^{-12} cm^2/s (LSM-FY18-CS-2) (Table 3.3). Both average ^{99}Tc D_{obs} values for individual monoliths showed lower D_{obs} values than highly mobile non-reactive

constituents, e.g., Na^+ with D_{obs} values measured at 1.25×10^{-8} (LSM-FY18-CS-1) and 2.10×10^{-8} cm^2/s (LSM-FY18-CS-2). Similarly, averaged ^{127}I D_{obs} values were 5.84×10^{-12} (LSM-FY18-CS-1) and 1.14×10^{-11} cm^2/s (LSM-FY18-CS-2) for ^{127}I and 6.67×10^{-11} (LSM-FY18-CS-1) and 1.29×10^{-10} cm^2/s (LSM-FY18-CS-2) for NO_3^-. When compared to the ^{99}Tc and ^{127}I D_{obs} values measured for simulated EMF evaporator bottoms waste immobilized using the Cast Stone formulation (Saslow et al. 2018), the D_{obs} values measured here are one to two orders of magnitude lower for ^{99}Tc and ^{127}I. Specifically, reported ^{99}Tc D_{obs} values for simulated Cast Stone specimens fell between 5.29×10^{-11} and 5.48×10^{-12} cm^2/s, the high end being one order of magnitude higher than those reported here. ^{127}I D_{obs} values for simulated specimens were 5.49×10^{-10} and 5.52×10^{-10} cm^2/s, nearly two orders of magnitude higher than the D_{obs} values reported here for ^{127}I.

Conversely, despite a lower Na^+ concentration in the specimens studied here (≈5,300 mg/kg-dry) compared to the Na^+ concentration in the simulated EMF evaporator bottoms waste (26,600 mg/kg-dry), Na^+ D_{obs} values calculated here are an order of magnitude higher than simulated Na^+ D_{obs} values, 1.63×10^{-9} and 1.75×10^{-9} cm^2/s. NO_3^- D_{obs} values were not determined for simulated Cast Stone samples due to the absence of NO_3^- in the simulated EMF evaporator bottoms waste stream. The D_{obs} values for NO_3^- measured here were lower than previously measured NO_3^- D_{obs}, an example being the LAW Cast Stone screening tests (Westsik et al. 2013) where NO_3^- D_{obs} ranged from ~1×10^{-7} cm^2/s to 1×10^{-9} cm^2/s. The differences in D_{obs} values between Cast Stone specimens immobilizing LSM concentrate and simulated EMF evaporator bottoms waste may be due to differences in the waste stream chemistry. Specifically, the starting LSM condensate does not contain detectable levels of nitrite (NO_2^-) and has less chloride, sulfate, and sodium compared to the simulant used in FY18 (Cantrell et al. 2018; Saslow et al. 2018); the simulant did not contain nitrate.

If the total fraction of a constituent's mass released from the monoliths is less than 20% over the course of EPA Method 1315 leach testing, then the D_{obs} values determined are valid and meet the semi-infinite source term assumption and observed diffusion coefficient calculations defined by Eq (3.1) and per discussion in ANSI/ANS-16.1-2003. Thus, D_{obs} corrections for inventory depletion are not necessary. For all monoliths (see Table 3.3) leached in DIW, the total fraction of ^{99}Tc, ^{127}I, and NO_3^- mass leached from monoliths did not exceed 20% of the initial mass of ^{99}Tc, ^{127}I, and NO_3^-, respectively, over the 63-day cumulative leaching period. However, the total fraction of Na^+ leached reached between 0.431 and 0.459 of the original Na^+ mass in each specimen at the end of the 63-day leach period.

Table 3.3. Calculated Averaged D_{obs} Values of ^{99}Tc, ^{127}I, NO_3^-, and Na^+ from the Cumulative 28-Day to 63-Day Leaching in DIW with Fraction of Released Mass in Individual Cast Stone Specimens*

	DIW Leaching Solution							
Specimen [(a)]	^{99}Tc D_{obs} [cm^2/s]	F[(b)]	^{127}I D_{obs} [cm^2/s]	F	NO_3^- D_{obs} [cm^2/s]	F	Na^+ D_{obs} [cm^2/s]	F
LSM-FY18-CS-1	3.13×10^{-12}	0.004	1.14×10^{-11}	0.011	1.29×10^{-10}	0.037	2.10×10^{-8}	0.459
LSM-FY18-CS-2	5.06×10^{-12}	0.006	5.84×10^{-12}	0.010	6.67×10^{-11}	0.033	1.25×10^{-8}	0.431
Simulated EMF Bottoms Cast Stone (Saslow et al. 2018)	$\approx 5 \times 10^{-11}$	≈0.03	$\approx 5 \times 10^{-10}$	≈0.09	-	-	$\approx 2 \times 10^{-9}$	≈0.13

* Calculated D_{obs} values should be used with caution when based on calculated starting concentrations rather than actual measured values.

(a) Dry density for each specimen is 1.32 g-dry/cm^3 assuming a 0.73 dry fraction as measured on specimens formulated using simulated EMF evaporator bottoms (Saslow et al. 2018)

(b) F indicates fraction of total mass released for each constituent in DIW leaching solution compared to initial mass of constituent in each monolith after 63 days leaching.

As observed in previous work (Um et al. 2016; Saslow et al. 2017, 2018), some release of ^{99}Tc, ^{127}I, and Na^+ did not follow a pure diffusion trend, showing a low slope beyond the acceptable limit for the EPA 1315 Method (a slope of 0.5 ± 0.15). This limit is reached particularly in LSM-FY18-CS-1 for ^{99}Tc and in LSM-FY18-CS-2 for ^{127}I. Deviations from the diffusion-controlled slope may be due to additional chemical reactions. Therefore, the calculated diffusivity values in Table 3.2 and Table 3.3 should be used with caution. In addition, the cumulative releases of ^{99}Tc, ^{127}I, NO_3^-, and Na^+ as a function of leaching time are also reported for qualitative understanding of release in Appendix A, Table A.3 and Table A.4. Conformance to or deviation from a diffusion-driven release mechanism is shown for each contaminant in Figure 3.3.

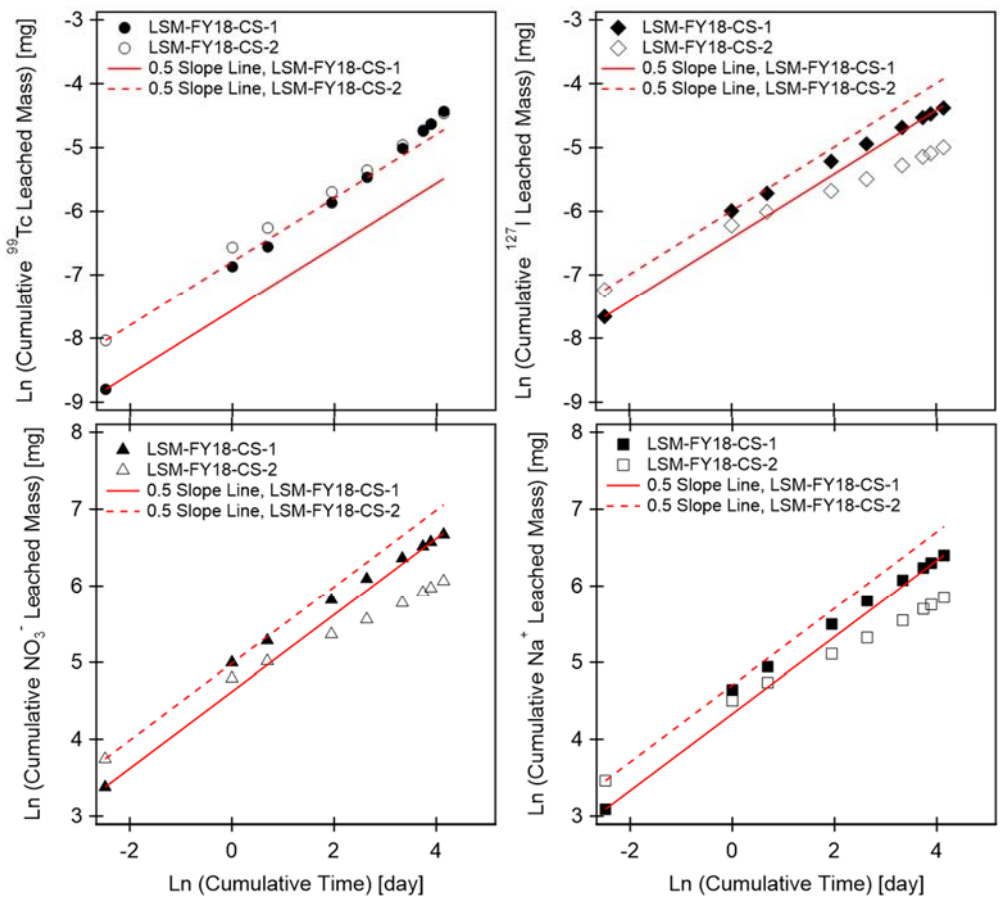

Figure 3.3. Logarithm of the cumulative ^{99}Tc (top, left), ^{127}I (top, right), NO_3^- (bottom, left), and Na^+ (bottom, right) release plotted vs. the logarithm of cumulative time for monoliths leached for 63 days in DIW using EPA Method 1315 leach testing. The red line has a slope of 0.5 and models a diffusion-controlled release mechanism.

Additional cations and anions measured in EPA 1315 Method leaching tests can be found in Appendix A, Table A.3 and Table A.4. Other measurements, including pH, EC, ammonia, and alkalinity, were made for each leachate and individual monolith at each leaching interval. The measured pH in the DIW leachates showed a range between 10.3 and 11.6. The measured ECs in DIW leaching solutions were initially low, 0.09 to 0.46 mS/cm over the first 2 days of leaching, but increased to within the range of

0.50 to 0.79 mS/cm from the 7-day sampling through the 42-day sampling in both monoliths. At the end of the leach test, EC decreased to levels between 0.29 and 0.48 mS/cm on the 49-day and 63-day sampling events. This deviates from previous results with simulants, where the EC measured values were only observed to increase beyond the 7-day sampling event. Alkalinity (measured as $CaCO_3$) values increased and decreased according to the same trends observed in EC measurements. The increase is due to the release of hydroxyl and carbonate ions, and the late decrease in alkalinity is attributed to precipitation of carbonate minerals (e.g., calcite). Additional pH values and other measurements are found in Appendix A, Table A.5.

4.0 Solid Phase Characterization

After the 63-day EPA Method 1315 leach test sampling, specimen LSM-FY18-CS-1 was processed for solid phase characterization analysis to determine the distribution of ^{99}Tc within the waste form (digital autoradiography, iQID) and the bulk mineralogy of the specimen post-leaching (XRD). These findings are detailed in the following sections.

4.1 Digital Autoradiography

Single particle digital autoradiography was used to image ^{99}Tc distribution within monolith LSM-FY18-CS-1 after leaching for 63 days in DIW. The iQID instrument observes ^{99}Tc distribution within the waste form by monitoring β-decay events. Further information regarding development and use of the technique can be found in Miller et al. (2014, 2015). Briefly, the bottom face of the 2” × 4” monolith was analyzed using the iQID over a 48-hour interval. Areas that appear brighter in iQID images correlate to regions with higher Tc concentrations. From Figure 4.1, ^{99}Tc does not appear to have concentrated in localized areas, but rather is dispersed evenly throughout the outer areas of the waste form near the outer wall. Some migration from the waste form center may have occurred based on the darker region at the center of the iQID image. However, the migration of ^{99}Tc in LSM-FY18-CS-1 is less extreme compared to simulated waste forms studied previously (Saslow et al. 2018) where ^{99}Tc was observed to concentrate at the exterior wall after leaching and appeared absent in the majority of the waste form’s interior.

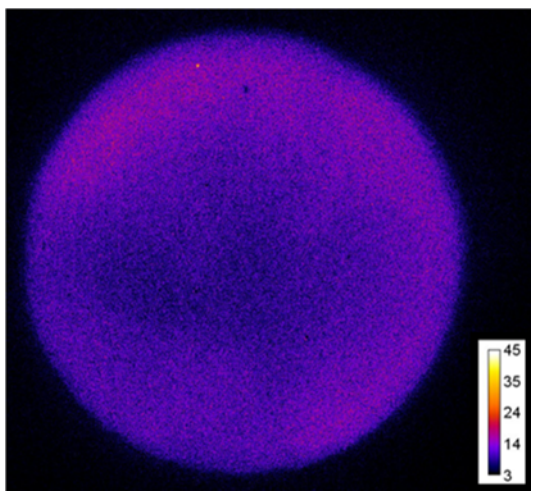

Figure 4.1. iQID image of LSM-FY18-CS-1 following 63-day leaching in DIW (bottom face). Areas that appear brighter correlate to regions with a higher number of β-decay events recorded over the 48-day collection period (see color scale bar, bottom right).

4.2 X-Ray Diffraction

An XRD pattern was collected from size-reduced material prepared from monolith LSM-FY18-CS-1 (Figure 4.2) to determine the mineralogical composition after leaching for 63 days in DIW. As seen in previous waste forms, much of the waste form consists of an amorphous phase (86.0 wt%), likely as a calcium silicate hydrate (CSH). The remaining material consisted of 2.5 wt% ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}$•$26H_2O$], 0.1 wt% calcite [$CaCO_3$], and 2.3 wt% quartz [$SiO_2$]. A small amount (<0.5 wt%) of unidentified crystalline phase was also present. The presence of 9.1 wt% rutile/anatase [TiO_2] is due to the internal TiO_2 standard added before XRD analysis and is included for the purpose of determining the relative weight percent of each mineral phase.

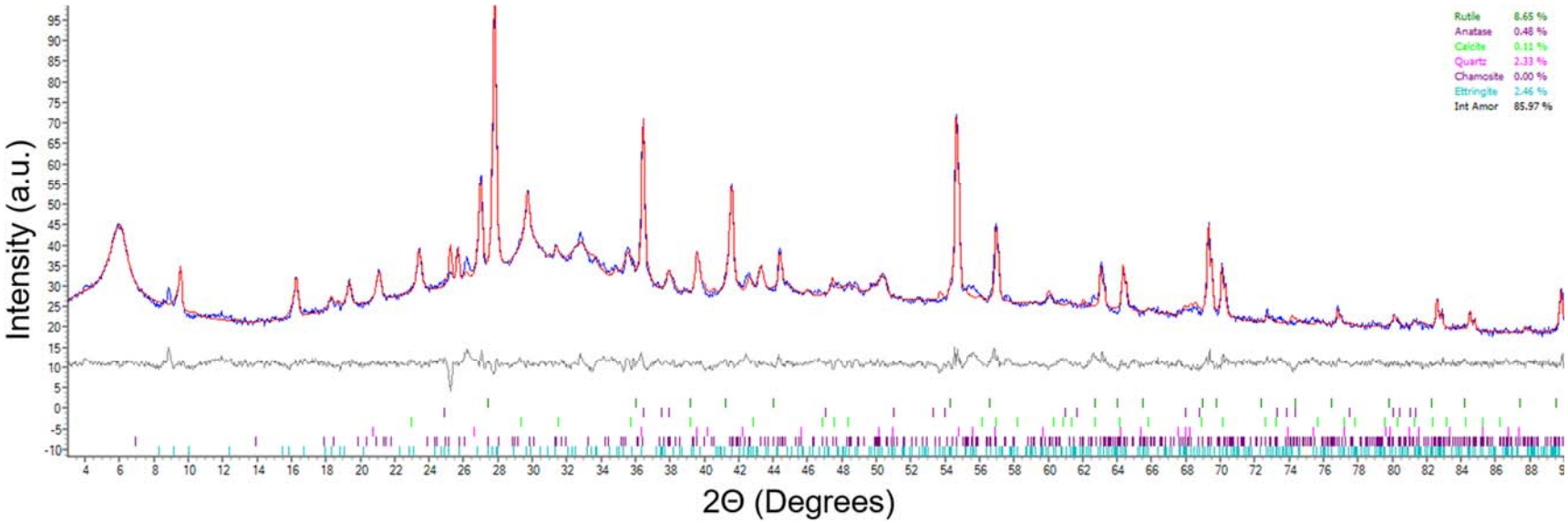

Figure 4.2. XRD pattern and analysis for LSM-FY18-CS-1. The diffraction pattern is shown in blue, the fit to the data in red, and the difference pattern in grey. The associated peaks for phases found to contribute to the final fit are shown at the bottom for their respective colors provided in the legend (top, left).

5.0 Summary and Recommendations

This section summarizes the key conclusions from EPA Method 1315 leach testing and solid phase characterization of cementitious waste forms immobilizing evaporated off-gas condensate collected from the FY18 continuous LSM test using actual AP-105 tank LAW. The results help establish baseline testing metrics for an evaporated melter off-gas condensate produced from actual tank waste, provide waste form data for comparison to previous laboratory tests collected from simulated evaporator concentrate samples, and improve the technical defensibility of waste form performance estimates. Recommendations for further testing to provide additional information for waste form development and to support future IDF PA maintenance are also addressed.

Specific waste form qualification testing efforts described in this report include

1. determination of observed diffusivity (D_{obs}) values for ^{99}Tc, ^{127}I, NO_3^-, and Na^+ in DIW using EPA Method 1315 to assess the immobilization potential of Cast Stone immobilized evaporated off-gas condensate; and,

2. solid phase characterization of a select specimen to determine radionuclide distribution and bulk mineralogy after specimen leaching for 63 days.

5.1 Conclusions

EPA Method 1315 leach testing was performed on the two remaining concentrated off-gas condensate cementitious waste form samples from the LAW AP-105 continuous LSM run (Cantrell et al. 2018). Both specimens used the Cast Stone formulation to immobilize evaporated off-gas condensate as part of FY18 testing efforts. These monoliths remained intact during the 63-day leach period, showing no signs of cracking. For ^{99}Tc, D_{obs} values for monoliths leached in DIW fluctuated during early leach periods, within the first 2 days, but then gradually increased through the cumulative 63-day leach period. This deviates from the general trend observed in previous FY18 testing efforts where the Cast Stone specimens formulated using simulated EMF evaporator bottoms showed a decreasing trend in ^{99}Tc D_{obs} values during later leaching periods. Regardless, ^{99}Tc D_{obs} values after 28-day leaching for Cast Stone monoliths tested herein are an order of magnitude lower than previously tested simulated specimens and measured to be 3.13×10^{-12} and 5.06×10^{-12} cm^2/s. This decrease in ^{99}Tc D_{obs} was also determined for specimens with a higher ^{99}Tc mass loading, ≈13 mg/kg-dry compared to ≈8 mg/kg-dry as determined for the simulated specimens studied previously.

For ^{127}I, the mass loading in the specimens made from evaporated AP-105 off-gas condensate is ≈4.5 mg/kg-dry and ≈50% less than the amount present in previously studied simulated Cast Stone waste forms, up to 9.4 mg/kg-dry. For ^{127}I, D_{obs} values were calculated to be up to two orders of magnitude lower than simulated waste forms, with values of 5.84×10^{-12} and 1.14×10^{-11} cm^2/s. NO_3^- D_{obs} values also were calculated to fall between 6.67×10^{-11} and 1.29×10^{-10} cm^2/s. ^{99}Tc, ^{127}I, and NO_3^- were determined to release a fraction of their respective initial mass between 0.003 and 0.037 over the 63-day leach period. However, Na^+, which is readily released via diffusion processes from cementitious waste forms, lost fractions up to 0.459 of the initial Na^+ mass in the waste form over the 63-day leach period. This loss corresponded to D_{obs} values of 1.25×10^{-8} and 2.10×10^{-8} cm^2/s. The differences in D_{obs} values between Cast Stone specimens immobilizing LSM concentrate and simulated EMF evaporator bottoms waste may be due to differences in the waste stream chemistry. Specifically, varying concentrations of sodium, nitrite, chloride, sulfate, and nitrate (Saslow et al. 2018; Cantrell et al. 2018). Note that throughout the 63-day leach period, some periods of ^{99}Tc and ^{127}I release did not follow a pure diffusion trend, suggesting additional chemical reactions may influence contaminant leaching from the waste form. As such, the

calculated and reported diffusivity values should be used with care since the EPA Method 1315 assumes diffusion-controlled contaminant release.

Solid phase characterization of one representative specimen, LSM-FY18-CS-1, was performed using XRD to determine the bulk mineralogical composition and iQID to identify regions or hot spots of concentrated ^{99}Tc within the waste form after leaching in DIW for 63 days. Based on the iQID image collected from the bottom face of the monolith, ^{99}Tc is relatively dispersed throughout the waste form. Localized areas of high ^{99}Tc, especially around the exterior wall, were not observed in LSM-FY18-CS-1 as seen in previously studied simulated Cast Stone waste forms. From XRD analysis, much of the waste form consists of an amorphous phase (86.0 wt%), likely as a CSH. The remaining material consisted of 2.5 wt% ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O$], 0.1 wt% calcite [$CaCO_3$], and 2.3 wt% quartz [$SiO_2$].

5.2 Recommendations

The results described herein help establish baseline testing metrics for an evaporated melter off-gas condensate produced from actual LAW tank waste that improve the technical defensibility of waste form performance estimates for the Cast Stone formulation. Recommendations for additional studies to provide more technical defensibility for waste form performance are listed below:

1. In FY18, LSM efforts also produced off-gas condensate from processed actual LAW AP-107 tank waste. By evaporating the collected off-gas condensate using the methods described by Cantrell et al. (2018), immobilizing the concentrated evaporate as a cementitious waste form, e.g., Cast Stone, and performing EPA Method 1315 leach tests on cured waste forms, this proposed effort would provide an additional dataset to compare with the AP-105 data and data from simulated waste forms in an attempt to elucidate the improvements observed for ^{127}I and NO_3^- release. An additional data set would also enhance the technical defensibility of using Cast Stone as a waste form for off-gas condensate waste streams.

2. Due to limited volume of evaporated condensate from the continuous LSM AP-105 melter run, limited Cast Stone specimens were generated. Provided there is sufficient volume of AP-107 off-gas condensate, after evaporation, generating hydrated lime-based cementitious waste forms for EPA Method 1315 leach testing is recommended, in addition to using the Cast Stone formulation. Performing identical analyses on the previously proposed hydrated lime formulation would provide additional input on alternative waste form performance and assess the limits of radionuclide and contaminants of concern retention.

6.0 References

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Appendix A – Additional Data

A.1 Initial Off-Gas Condensate Composition, Pre-Evaporation (Cantrell et al. 2018)

Table A.1. Initial Off-Gas Condensate Composition Before Evaporation, Values Taken from Cantrell et al. 2018

ICP-OES Results			ICP-MS Results			IC Results		
Analyte	*Result (µg/L)*	*EQL (µg/L)*	*Analyte*	*Result (µg/L)*	*EQL (µg/L)*	*Analyte*	*Result (mg/L)*	*EQL (mg/L)*
Aluminum (Al)	36,500	165	Antimony (Sb)	ND	5.4	Bromide (Br^-)	ND	50
Antimony (Sb)	ND	298	Arsenic (As)	288	42	Chloride (Cl^-)	937	25
Arsenic (As)	ND	415	Barium (Ba)	79.6	3.1	Fluoride (F^-)	22.7	10
Barium (Ba)	67.4	32.8	Cadmium (Cd)	28	7	Nitrate (NO_3^-)	17,100	500
Beryllium (Be)	ND	15.4	Copper (Cu)	84	8.7	Nitrite (NO_2^-)	ND	50
Bismuth (Bi)	ND	470	Cesium (Cs)	26,200	128	Phosphate (PO_4^{3-})	ND	75
Boron (B)	194,000	2,520	Chromium (Cr)	13,400	346	Sulfate (SO_4^{2-})	85.7	75
Cadmium (Cd)	ND	42.3	Lead (Pb)	65.4	2.4	Total Cyanide	8.01	0.125
Calcium (Ca)	14,200	336	Molybdenum (Mo)	1,150	5.3			
Chromium (Cr)	11,500	23.2	Mercury (Hg)	21.5	3.3			
Cobalt (Co)	ND	40.9	Rhenium (Re)	312	3			
Copper (Cu)	126	78.5	Ruthenium (Ru)	998	4.7			
Gadolinium (Gd)	ND	500	Selenium (Se)	1,190	136			
Iron (Fe)	30,000	100	Silver (Ag)	13.7	3.8			
Lead (Pb)	ND	138	Thorium (Th)	ND	4.8			
Lithium (Li)	375	240	Uranium (U)	21.7	7.1			
Magnesium (Mg)	812	27	129-I	461	41			
Manganese (Mn)	178	23.9	99-Tc	2,570	3.3			
Molybdenum (Mo)	989	98.8						
Nickel (Ni)	323	140						
Phosphorous (P)	2,500	408						
Potassium (K)	71,200	1610						
Rhenium (Re)	326	99.4						
Silicon (Si)	41,400	5,480						
Sodium (Na)	1,050,000	4,470						
Strontium (Sr)	ND	62.8						
Sulfur (S)	39,700	477						
Titanium (Ti)	2,130	23.7						
Vanadium (V)	ND	85.3						
Zinc	51,700	61.6						
Zirconium	2,390	19.1						

ESL: Estimated Quantitation Limit
ND: not detected above the EQL

A.2 Initial Constituent Concentration Calculations

Initial concentrations of ^{99}Tc, ^{127}I, NO_3^-, and Na^+ in the Cast Stone specimens used to perform U.S. Environmental Protection Agency (EPA) Method 1315 leach testing were calculated using input values from previously published reports (Cantrell et al. 2018 and Saslow et al. 2018) and Eqs. (A.1) through (A.5).

$$\text{Cast Stone Concentration}\left(\frac{\text{mg}}{\text{m}^3}\right) = \frac{\text{Cast Stone Concentration}\left(\frac{\text{Ci}}{m^3}\right) * 1000\left(\frac{\text{mg}}{\text{g}}\right)}{\text{Specific Activity of } ^{99}Tc \text{ or } ^{129}I\ \left(\frac{\text{Ci}}{\text{g}}\right)} \tag{A.1}$$

$$\text{Dry Cast Stone Concentration}\left(\frac{\text{mg}}{\text{Kg}-\text{dry}}\right) = \frac{\text{Cast Stone Concentration}\left(\frac{\text{mg}}{\text{m}^3}\right)}{\text{Monolith Density}-\text{dry}\left(\frac{\text{Kg}-\text{dry}}{\text{m}^3}\right)} \tag{A.2}$$

$$Cast\ Stone\ Concentration\ \left(\frac{mg}{m^3}\right) = \frac{Concentration\ in\ Condensate\ \left(\frac{\mu g}{L}\right) * Mass\ ratio\ of\ Condensate{:}Evaporate\ \left(\frac{g}{g}\right) * Mass\ Ratio\ of\ Evaporate{:}Cast\ Stone\ \left(\frac{g}{g}\right) * Cast\ Stone\ Density\ \left(\frac{g}{mL}\right)}{1000\ \left(\frac{ml}{L}\right) * Condensate\ Density\ \left(\frac{g}{mL}\right) * 0.000001\ \left(\frac{m^3}{mL}\right) * 1000\ \left(\frac{\mu g}{mg}\right)} \tag{A.3}$$

$$^{127}I\ Cast\ Stone\ Concentration\ \left(\frac{mg}{kg-dry}\right) = {}^{129}I\ Cast\ Stone\ Concentration\ \left(\frac{mg}{kg-dry}\right) * (Ratio\ of\ ^{127}I{:}\ ^{129}I\ in\ AP-105\ Condensate) \tag{A.4}$$

$$\left(Ratio\ of\ ^{127}I{:}\ ^{129}I\ in\ AP-105\ Condensate\right) = \frac{893\frac{\mu g}{L}\ (Measured\ by\ ICP-MS)}{461\frac{\mu g}{L}\ (from\ PNNL-27765)} = 1.937 \tag{A.5}$$

Table A.2. Values Supporting Calculation of the Initial Constituent Concentration in Test Specimens

Initial Concentrations for LSM-FY18-CS-1

Constituent	Specific Activity	Cast Stone Concentration	Cast Stone Concentration	Dry Cast Stone Concentration	Dry Fraction
Unit	*Ci/g*	*Ci/m³*	*mg/m³*	*mg/Kg-dry*	
Input Source	PNNL-27765, Table 4	PNNL-27765, Table 5	Eq. A.1	Eq. A.2, A.4, A.5	PNNL-26570, Table 5.3
Tc-99	1.70E-02	0.29	17117.65	12.93	0.73
I-129	1.77E-04	0.0005	3073.45	2.32	0.73
I-127	-	-	-	4.50	-

Constituent	Concentration in Condensate	Condensate Density	Mass Ratio of Condensate: Evaporate	Mass Ratio of Evaporate: Cast Stone	Cast Stone Density	Dry Fraction	Cast Stone Concentration	Dry Cast Stone Concentration
Unit	*µg/L*	*g/L*	*g/g*	*g/g*	*g/mL*		*mg/m³*	*mg/Kg-dry*
Input Source	PNNL-27765, Tables 1 and 3	PNNL-27765, Section 2.2	PNNL-27765, Section 2.2	PNNL-27765, Section 3.1.2	PNNL-27765, Section 3.1.2	PNNL-26570, Table 5.3	Eq. A.3	Eq. A.2
Na^+	1.05E06	1.01	10.68	0.37	1.703	0.73	6996092	5285
NO_3^-	1.71E+07	1.01	10.68	0.37	1.703	0.73	113936365	86078

Initial Concentrations for LSM-FY18-CS-2

Constituent	Specific Activity	Cast Stone Concentration	Cast Stone Concentration	Dry Cast Stone Concentration	Dry Fraction
Unit	*Ci/g*	*Ci/m³*	*mg/m³*	*mg/Kg-dry*	
Input Source	PNNL-27765, Table 4	PNNL-27765, Table 5	Eq. A.1	Eq. A.2, A.4, A.5	PNNL-26570, Table 5.3
Tc-99	1.70E-02	0.29	17117.65	13.01	0.73
I-129	1.77E-04	0.0005	3073.45	2.34	0.73
I-127	-	-	-	4.53	-

Constituent	Concentration in Condensate	Condensate Density	Mass ratio of Condensate: Evaporate	Mass Ratio of Evaporate: Cast Stone	Cast Stone Density	Dry Fraction	Cast Stone Concentration	Dry Cast Stone Concentration
Unit	*µg/L*	*g/L*	*g/g*	*g/g*	*g/mL*		*mg/m³*	*mg/Kg-dry*
Input Source	PNNL-27765, Tables 1 and 3	PNNL-27765, Section 2.2	PNNL-27765, Section 2.2	PNNL-27765, Section 3.1.2	PNNL-27765, Section 3.1.2	PNNL-26570, Table 5.3	Eq. A.3	Eq. A.2
Na^+	1.05E+06	1.01	10.68	0.37	1.703	0.73	6996092.61	5318
NO_3^-	1.71E+07	1.01	10.68	0.37	1.703	0.73	113936365	86609

A.3 Additional Results for Solution Concentrations of Cations and Anions from Environmental Protection Agency (EPA) Method 1315 Leach Tests

Table A.3. Concentrations of Major Anions, ^{99}Tc, and ^{127}I Measured in Leachates from EPA Method 1315 Tests. EQL is estimated quantification limit; ND indicates "not detected"; cumulative release of ^{99}Tc, ^{127}I, and NO_3^- (%) are shown in parentheses.

Sample ID	Cl^- (µg/mL)*		NO_3^- (µg/mL)*		NO_2^- (µg/mL)*		SO_4^- (µg/mL)*		^{99}Tc (µg/L)*		^{127}I (µg/L)*	
	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL
LSM-FY18-DI-BLK1-0.08d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	0.0378
LSM-FY18-DI-BLK1-1d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	0.0378
LSM-FY18-DI-BLK1-2d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	0.0378
LSM-FY18-DI-BLK1-7d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	0.0378
LSM-FY18-DI-BLK1-14d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	0.0378
LSM-FY18-DI-BLK1-28d	ND	0.375	ND	0.75	ND	0.75	1.15	0.25	ND	0.026	ND	0.0378
LSM-FY18-DI-BLK1-42d	ND	0.375	ND	0.75	ND	0.75	1.21	0.25	ND	0.026	0.155	0.0378
LSM-FY18-DI-BLK1-49d	ND	0.375	ND	0.75	ND	0.75	1.18	0.25	ND	0.026	ND	ND
LSM-FY18-DI-BLK1-63d	ND	0.375	ND	0.75	ND	0.75	0.775	0.25	ND	0.026	ND	ND
LSM-FY18-DI-BLK2-0.08d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	ND
LSM-FY18-DI-BLK2-1d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	ND
LSM-FY18-DI-BLK2-2d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	ND
LSM-FY18-DI-BLK2-7d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	ND
LSM-FY18-DI-BLK2-14d	ND	1.25	ND	2.5	ND	2.5	ND	3.75	ND	0.033	ND	ND
LSM-FY18-DI-BLK2-28d	ND	0.375	ND	0.75	ND	0.75	1.14	0.25	ND	0.026	ND	ND
LSM-FY18-DI-BLK2-42d	ND	0.375	ND	0.75	ND	0.75	1.18	0.25	ND	0.026	ND	ND
LSM-FY18-DI-BLK2-49d	ND	0.375	1.18	0.75	ND	0.75	1.18	0.25	ND	0.026	ND	ND
LSM-FY18-DI-BLK2-63d	ND	0.375	ND	0.75	ND	0.75	0.65	0.25	ND	0.026	ND	ND
LSM-FY18-CS-1-0.08d	ND	1.25	17.1 (0.01)	2.5	ND	2.5	ND	3.75	0.088 (0.00)	0.033	0.275 (0.04)	0.275
LSM-FY18-CS-1-1d	3.95	1.25	69.2 (0.07)	2.5	ND	2.5	ND	3.75	0.518 (0.03)	0.033	1.18 (0.22)	1.18

Sample ID	Cl^- (µg/mL)*		NO_3^- (µg/mL)*		NO_2^- (µg/mL)*		SO_4^- (µg/mL)*		^{99}Tc (µg/L)*		^{127}I (µg/L)*	
	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL
LSM-FY18-CS-1-2d	1.58	1.25	28.7 (0.09)	2.5	ND	2.5	ND	3.75	0.224 (0.04)	0.033	0.467 (0.29)	0.467
LSM-FY18-CS-1-7d	4.43	1.25	80.2 (0.16)	2.5	ND	2.5	ND	3.75	0.825 (0.09)	0.033	1.24 (0.49)	1.24
LSM-FY18-CS-1-14d	3.5	1.25	62.9 (0.21)	2.5	ND	2.5	ND	3.75	0.812 (0.13)	0.033	0.995 (0.64)	0.995
LSM-FY18-CS-1-28d	4.31	0.375	80 (0.27)	0.75	ND	0.75	3.06	0.25	1.41 (0.21)	0.026	1.23 (0.83)	1.23
LSM-FY18-CS-1-42d	3.1	0.375	56.7 (0.32)	0.75	ND	0.75	2.9	0.25	1.2 (0.27)	0.026	0.9 (0.96)	0.9
LSM-FY18-CS-1-49d	1.31	0.375	23.8 (0.34)	0.75	ND	0.75	2.35	0.25	0.6 (0.30)	0.026	0.366 (1.02)	0.366
LSM-FY18-CS-1-63d	2.21	0.375	42.5 (0.37)	0.75	ND	0.75	3.32	0.25	1.26 (0.37)	0.026	0.665 (1.12)	0.665
LSM-FY18-CS-2-0.08d	1.86	1.25	35.7 (0.03)	2.5	ND	2.5	ND	3.75	0.274 (0.02)	0.033	0.608 (0.10)	0.608
LSM-FY18-CS-2-1d	3.49	1.25	66.2 (0.09)	2.5	ND	2.5	4.14	3.75	0.913 (0.07)	0.033	1.07 (0.29)	1.07
LSM-FY18-CS-2-2d	1.34	1.25	25.3 (0.11)	2.5	ND	2.5	ND	3.75	0.428 (0.10)	0.033	0.400 (0.36)	0.4
LSM-FY18-CS-2-7d	2.85	1.25	53 (0.16)	2.5	ND	2.5	ND	3.75	1.22 (0.17)	0.033	0.806 (0.50)	0.806
LSM-FY18-CS-2-14d	2.12	1.25	38.9 (0.20)	2.5	ND	2.5	ND	3.75	1.15 (0.24)	0.033	0.59 (0.60)	0.59
LSM-FY18-CS-2-28d	2.96	0.375	53.4 (0.25)	0.75	ND	0.75	2.88	0.25	1.94 (0.36)	0.026	0.825 (0.74)	0.825
LSM-FY18-CS-2-42d	2.3	0.375	40.5 (0.28)	0.75	ND	0.75	2.82	0.25	1.57 (0.45)	0.026	0.631 (0.85)	0.631
LSM-FY18-CS-2-49d	1	0.375	17.6 (0.30)	0.75	ND	0.75	2.66	0.25	0.744 (0.49)	0.026	0.268 (0.90)	0.268
LSM-FY18-CS-2-63d	1.8	0.375	32.6 (0.33)	0.75	ND	0.75	3.64	0.25	1.51 (0.59)	0.026	0.507 (0.99)	0.507

* Initial anion concentrations in the melter off-gas condensate (pre-evaporation): Cl^- = 937 µg/mL, NO_3^- = 17,100 µg/mL, NO_2^- = ND, and SO_4^{2-} = 85.7 µg/mL

Table A.4. Concentrations of Major Cations Measured in Leachates from EPA Method 1315 Tests. EQL is estimated quantification limit; ND indicates "not detected"; cumulative release of Na (%) is shown in parentheses.

	Al (µg/L)		Ca (µg/L)		Mg (µg/L)		K (µg/L)		Si (µg/L)		Na (µg/L)	
Sample ID	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL
LSM-FY18-DI-BLK1-0.08d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-1d	ND	82.4	340	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-2d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-7d	ND	82.4	ND	168	16.2	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-14d	ND	82.4	616	168	26.6	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-28d	ND	82.4	ND	168	15.5	13.5	ND	806	ND	274	253	223
LSM-FY18-DI-BLK1-42d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-49d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK1-63d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-0.08d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-1d	ND	82.4	193	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-2d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-7d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-14d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-28d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	249	223
LSM-FY18-DI-BLK2-42d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-49d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-DI-BLK2-63d	ND	82.4	ND	168	ND	13.5	ND	806	ND	274	ND	223
LSM-FY18-CS-1-0.08d	346	82.4	542	168	ND	13.5	940	806	ND	274	12,800 (1.67)	223
LSM-FY18-CS-1-1d	2010	82.4	9300	168	36	13.5	3630	806	1300	274	47,700 (7.90)	223
LSM-FY18-CS-1-2d	1220	82.4	10,500	168	131	13.5	1700	806	1540	274	21,200 (10.67)	223
LSM-FY18-CS-1-7d	3300	82.4	29,600	168	194	13.5	4580	806	7260	274	60,500 (18.57)	223
LSM-FY18-CS-1-14d	2890	82.4	28,300	168	150	13.5	3930	806	7490	274	51,200 (25.26)	223
LSM-FY18-CS-1-28d	3470	82.4	31,200	168	100	13.5	4570	806	8480	274	60,500 (33.12)	223
LSM-FY18-CS-1-42d	3000	82.4	25,100	168	113	13.5	3450	806	7320	274	44,700 (38.96)	223
LSM-FY18-CS-1-49d	2050	82.4	17,300	168	188	13.5	1580	806	4770	274	19,200 (41.47)	223
LSM-FY18-CS-1-63d	2760	82.4	25,500	168	160	13.5	2510	806	6540	274	33,800	223

Sample ID	Al (µg/L)		Ca (µg/L)		Mg (µg/L)		K (µg/L)		Si (µg/L)		Na (µg/L)	
	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL	Result	EQL
											(45.88)	
LSM-FY18-CS-2-0.08d	617	82.4	761	168	ND	13.5	1940	806	ND	274	26,900 (3.95)	223
LSM-FY18-CS-2-1d	2350	82.4	10,600	168	51	13.5	3290	806	1870	274	49,300 (11.20)	223
LSM-FY18-CS-2-2d	1590	82.4	12,300	168	145	13.5	1630	806	2020	274	20,200 (14.16)	223
LSM-FY18-CS-2-7d	3250	82.4	31,200	168	223	13.5	3200	806	6960	274	43,500 (20.56)	223
LSM-FY18-CS-2-14d	2790	82.4	31,100	168	211	13.5	2570	806	7640	274	32,900 (25.39)	223
LSM-FY18-CS-2-28d	3140	82.4	30,000	168	135	13.5	3240	806	8570	274	44,100 (31.83)	223
LSM-FY18-CS-2-42d	2870	82.4	15,200	168	145	13.5	2770	806	7400	274	34,700 (36.93)	223
LSM-FY18-CS-2-49d	1920	82.4	16,800	168	252	13.5	1250	806	4470	274	15,100 (39.15)	223
LSM-FY18-CS-2-63d	2530	82.4	20,500	168	227	13.5	1910	806	6120	274	27,100 (43.13)	223

Table A.5. Results of Alkalinity, Electrical Conductivity (EC), Oxidation-Reduction Potential (E_h), and pH in Leachates from EPA Method 1315 Tests

Sample ID	pH	E_h (mV)[a]		EC (mS/cm)		Alkalinity (µg/mL)	
		Result	EQL	Result	EQL	Result	EQL
LSM-FY18-DI-BLK1-0.08d	6.32	329	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-1d	6.56	311	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-2d	6.40	209	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-7d	6.08	231	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-14d	5.93	369	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-28d	6.05	197	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-42d	5.98	188	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-49d	6.26	208	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK1-63d	6.13	266	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-0.08d	6.12	330	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-1d	6.38	314	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-2d	6.18	232	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-7d	5.86	260	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-14d	5.95	310	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-28d	5.86	219	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-42d	5.81	213	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-49d	6.08	216	-1000	ND	0.0100	ND	23.5
LSM-FY18-DI-BLK2-63d	6.00	274	-1000	ND	0.0100	ND	23.5
LSM-FY18-CS-1-0.08d	10.30	176	-1000	0.0902	0.0100	ND	23.5
LSM-FY18-CS-1-1d	10.90	-49.0	-1000	0.41	0.0100	78.6	23.5
LSM-FY18-CS-1-2d	11.00	-29.4	-1000	0.333	0.0100	59.2	23.5
LSM-FY18-CS-1-7d	11.50	-101	-1000	0.776	0.0100	170	23.5
LSM-FY18-CS-1-14d	11.40	-108	-1000	0.678	0.0100	148	23.5
LSM-FY18-CS-1-28d	11.60	-40.0	-1000	0.786	0.0100	168	23.5
LSM-FY18-CS-1-42d	11.50	-65.6	-1000	0.604	0.0100	113	23.5
LSM-FY18-CS-1-49d	11.20	23.1	-1000	0.325	0.0100	91.2	23.5
LSM-FY18-CS-1-63d	11.30	-42.1	-1000	0.475	0.0100	104	23.5
LSM-FY18-CS-2-0.08d	10.70	110	-1000	0.315	0.0100	36.4	23.5
LSM-FY18-CS-2-1d	11.00	-44.0	-1000	0.464	0.0100	93.1	23.5
LSM-FY18-CS-2-2d	11.00	-47.6	-1000	0.264	0.0100	54.8	23.5
LSM-FY18-CS-2-7d	11.50	-96.0	-1000	0.624	0.0100	128	23.5
LSM-FY18-CS-2-14d	11.40	-112	-1000	0.548	0.0100	112	23.5
LSM-FY18-CS-2-28d	11.50	-79.6	-1000	0.626	0.0100	133	23.5
LSM-FY18-CS-2-42d	11.40	-73.4	-1000	0.503	0.0100	97.2	23.5
LSM-FY18-CS-2-49d	11.10	-40.2	-1000	0.258	0.0100	61.4	23.5
LSM-FY18-CS-2-63d	11.20	-48.8	-1000	0.376	0.0100	88.3	23.5

(a) E_h values are not standard hydrogen electron (SHE) corrected. Add +211 mV to SHE correct these values.

A.4 References

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