Nitrate To Ammonia And Ceramic (NAC) Bench Scale Stabilization Studies

Final Report
May 1995 - May 1996

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Work Performed Under Contract No.: DE-AR21-95MC32113

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Rust Federal Services, Inc.
Clemson Technical Center
Clemson Research Park
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P.O. Box 880
Morgantown, West Virginia 26507-0880

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Executive Summary

The Department of Energy (DOE) has large quantities of sodium-nitrate based liquid wastes. The largest quantity of these wastes is in the 149 single shell tanks at Hanford which hold up to 1 million gallons each. Other high level waste tank supernatants are present at the Savannah River Plant, Rocky Flats Plant, Idaho National Engineering Laboratory, and Oak Ridge National Laboratory. These tank waste are typically 4 to 5 molar in nitrate and contain radionuclides, various salts, and heavy metals³. INEL high-level waste tank supernatant contains about 0.7 and 0.6 grams per liter of chromium and mercury, respectively. SRP high-level waste tank supernatant contains about 0.2 g/L of chromium. Other heavy metals could well be present at lower levels in these tank wastes. These wastes are currently regulated and managed by the DOE. Under the Federal Facility Compliance Act (FFCA) DOE is subject to RCRA, which would apply to these tank supernatants. Stabilization of this waste is difficult because nitrates are very mobile. Additionally, vitrification of these wastes produces large quantities of hard-to-manage NO_x emissions.

The Nitrate to Ammonia and Ceramic (NAC) process has been developed to remove a majority of the nitrate content from wastes such as these¹. In the NAC process, solid aluminum at low temperatures (50-80°C) and low energy reduce nitrate to ammonia, and a solid aluminum oxide material (referred to as NAC solid product) is formed. Utilizing the NAC process, a problematic waste stream constituent (sodium nitrate) is decomposed to ammonia gas.

This NAC process has the potential to treat the large amount of nitrate tank wastes at DOE facilities. The NAC process can also utilize the large existing inventory of scrap aluminum at DOE facilities. Some of this aluminum has been radiologically contaminated and the NAC process offers an economical disposal option for this waste.

In initial studies, the NAC solid product was calcined and sintered to form a ceramic-type waste form^{1,2}. Stabilization of radionuclides and metals was achieved². However, to take the NAC solid product to the ceramic stage requires significant energy to heat the waste to a high temperature. And at these high temperatures, volatile radionuclides may be released, creating additional containment problems. In addition, a full-scale ceramic process capable of handling large quantities of NAC solid product is currently not available. Because of these concerns and issues, alternative ways to form a solid non-leachable solid product are desired.

In this study, Rust-Clemson Technical Center spiked a 5M nitrate solution with 400-10,000 ppm of all 8 RCRA metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and 260-4,000 ppm of three semi-volatile (SVOs) RCRA organics (2,4-dinitrotoluene, 2,4,6-trichlorophenol and nitrobenzene). These amounts if completely leached from the final waste form would exceed Toxicity Characteristic Leaching Procedure (TCLP) limits by 20-100 fold. This mixture was converted to the NAC solid containing these RCRA species. The mercury and chromium levels in this spiked solution are much higher than those the ~1 ppm present in some high level waste tank supernatants. Elevated levels were added to severely try the system.

The solid product from the NAC process was stabilized using Portland Type I cement/class F flyash, sulfur polymer cement, high alumina cement, vinyl ester styrene polymer, and an

advanced polymer. Three mix ratios from each stabilization chemistry were screened for leachable constituents to determine acceptable waste loadings. Stabilized samples were subjected to unconfined compressive strength testing (UCS), ANS 16.1 leach testing for sodium, and TCLP testing for the RCRA metals and organics. The compressive strength results provide a useful indicator of structural stability. The ANS 16.1 leach procedure for sodium results indicate how tight the wasteforms are, i.e., how quickly a non-retained constituent can leach from the stabilized solid. Sodium is also a primary constituent of most high nitrate wastes. Finally, the TCLP test results indicate how well the different waste forms are able to stabilize the 8 RCRA metals. The three semivolatile organic compounds were chosen to provide a range of organic compound types which might be present in high nitrate based waste. These organics are not present in the DOE high level waste tank supernatants, but similar type organic may be present in other high nitrate waste streams.

The NAC process alone successfully stabilized many RCRA constituents. Only chromium, arsenic, selenium and 2,4,6-trichlorophenol leached above the TCLP limits.

No one solidification/stabilization (S/S) technology was a clear leader in all areas tested. The Portland cement/flyash blend was probably the overall best performer. The Portland cement blend had the highest waste loading, 71%, produced the highest unconfined compressive strength (94 psi) and had the best TCLP results (only selenium failed); but 62% of the sodium leached out over the 5 day ANS 16.1 leach.

The 50% sulfur polymer cement produced an unconfined compressive strength of 42 psi. Arsenic, selenium and 2,4,6-trichlorophenol exceeded the TCLP limits. Only 18% of the sodium leached out in the ANS 16.1 leach test.

The 50% high alumina cement mixture produced an unconfined compressive strength of 16 psi, the lowest measured in this study. Lead and 2,4,6-trichlorophenol exceeded TCLP limits. A total of 97% of the sodium leached out in the ANS 16.1 leach test.

The vinyl ester styrene formulation (waste loadings from 30 to 67%) failed to produce a solid monolith. An "advanced polymer" produced an acceptable monolith, however the waste form dissolved during the TCLP extraction. The unconfined compressive strength was not measured. At a 30% waste loading cadmium and selenium exceeded TCLP limits. A total of 25% of the sodium leached out in the ANS 16.1 leach test.

In general, S/S decreased leachability of metals and mobile ions such as sodium and increased structural strength. As such S/S can be used to stabilize RCRA contaminated NAC solid product. Portland cement stabilization is inexpensive, the materials are readily available and the technology is mature. As such Portland cement S/S should be an acceptable form of treatment for most solid NAC products. In some instances, where non-retained ions such as sodium are a concern or if selenium is present, additional pretreatment may be required to reduce leachability.

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Engineer I

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Research Scientist

TABLE OF CONTENTS

1.0 Introduction

2.0 Theory

3.0 Experimental

3.1 Preparation of NAC Solid Product

- 3.1.1 Preliminary Run
- 3.1.2 Preparation of the RCRA-Spiked Nitrate Solution
- 3.1.3 Preparation of the RCRA-Spiked NAC Solid Product

3.2 Stabilization of the NAC Solid Product

- 3.2.1 Portland Cement/Flyash Stabilization
  - 3.2.1.1 Screening Tests.
  - 3.2.1.2 Best Waste Loading Preparation.
  - 3.2.1.3 Filtrate From NAC Process Used as Makeup Water.
- 3.2.2 Sulfur Polymer Cement Stabilization
  - 3.2.2.1 Screening Tests.
  - 3.2.2.2 Best Waste Loading Preparation.
- 3.2.3 High Alumina Cement Stabilization
  - 3.2.3.1 Screening Tests.
  - 3.2.3.2 Best Waste Loading Preparation.
  - 3.2.3.3 Filtrate From NAC Process Used as Makeup Water.
- 3.2.4 Vinyl Ester Styrene Stabilization
  - 3.2.4.1 Screening Tests.
  - 3.2.4.2 Best Waste Loading Preparation

4.0 Test Methods and Results

4.1 RCRA-Spiked NAC Solid Product

4.2 Screening Tests

- 4.2.1 Portland Cement
- 4.2.2 Sulfur Polymer Cement
- 4.2.3 Advanced Polymer
- 4.2.4 High Alumina Cement

4.3 Unconfined Compressive Strength (UCS) Tests

- 4.3.1 Portland Type I Cement
- 4.3.2 Sulfur Polymer Cement
- 4.3.3 High Alumina Cement

4.4 ANS 16.1 Leach Tests

- 4.4.1 Portland Cement
- 4.4.2 Sulfur Polymer Cement
- 4.4.3 Advanced Polymer
- 4.4.4 High Alumina Cement

TABLE OF CONTENTS (Cont'd)

4.5 TCLP Tests

- 4.5.1 Portland Cement
- 4.5.2 Sulfur Polymer Cement
- 4.5.3 Advanced Polymer
- 4.5.4 High Alumina Cement

4.6 Comparison Among Stabilization Reagents

- 4.6.1 Waste Loading
- 4.6.2 TCLP Performance
- 4.6.3 Unconfined Compressive Strength Comparison
- 4.6.4 ANS 16.1 Sodium Leachability Comparison

5.0 Summary

6.0 Acknowledgements

LIST OF FIGURES

1	.....	NAC Equipment Schematic
2	.....	NAC Test program
3	.....	Portland Cement Stabilization Screen Test Schematic
4	.....	Sulfur Cement Stabilization Screen Test Schematic
5	.....	High Alumina Cement Stabilization Screen Test Schematic
6	.....	Advanced Polymer Stabilization Screen Test Schematic
7	.....	Portland Cement Compressive Strength Test #1 Results
8	.....	Portland Cement Compressive Strength Test #2 Results
9	.....	Portland Cement Compressive Strength Test Results Using NAC Filtrate
10	.....	Sulfur Polymer Cement Compressive Strength Test #1 Results
11	.....	Sulfur Polymer Cement Compressive Strength Test #2 Results
12	.....	High Alumina Cement Compressive Strength Test #1 Results
13	.....	High Alumina Cement Compressive Strength Test #2 Results
14	....	High Alumina Cement Compressive Strength Test Results Using NAC Filtrate
15	.....	ANS 16.1 Leach Test Results for Portland Cement Test #1
16	.....	ANS 16.1 Leach Test Results for Portland Cement Test #2
17	.....	ANS 16.1 Leach Test Results for Sulfur Polymer Test #1
18	.....	ANS 16.1 Leach Test Results for Sulfur Polymer Test #2
19	.....	ANS 16.1 Leach Test Results for Advanced Polymer Test #1
20	.....	ANS 16.1 Leach Test Results for Advanced Polymer Test #2
21	.....	ANS 16.1 Leach Test Results for High Alumina Cement Test #1
22	.....	ANS 16.1 Leach Test Results for High Alumina Cement Test #2
23	...	Comparison of TCLP Leachate Concentrations -- Portland Cement Stabilization versus Unstabilized Solid NAC Product
24	.....	TCLP Leachate Concentrations in Portland Cement Stabilized Samples
25	.....	TCLP Leachate Concentrations in Portland Cement Stabilized Samples Prepared with NAC Filtrate
26	Comparison of TCLP Leachate Concentrations -- Sulfur Polymer Cement Stabilization versus Unstabilized Solid NAC Product	
27	....	TCLP Leachate Concentrations in Sulfur Polymer Cement Stabilized Samples
28	.	Comparison of TCLP Leachate Concentrations -- Advanced Polymer Stabilization versus Unstabilized Solid NAC Product
29	.....	TCLP Leachate Concentrations in Advanced Polymer Stabilized Samples
30	Comparison of TCLP Leachate Concentrations -- High Alumina Cement Stabilization versus Unstabilized Solid NAC Product	
31	.....	TCLP Leachate Concentrations in High Alumina Cement Stabilized Samples
32	....	TCLP Leachate Concentrations for High Alumina Cement Stabilized Samples Prepared With and Without NAC Filtrate
33	..	Comparison of Unconfined Compressive Strength Results For Portland Cement, Sulfur Polymer Cement and High Alumina Cement Samples

LIST OF TABLES

1	..... RCRA Constituent Concentration Added to Surrogate Waste
2	..... RCRA Spike Concentrations in Various NAC Process Streams
3	.. Percent of RCRA Constituents Present in Filtrate & Solid After NAC Processing
4	..... Portland Cement Screening Test Results
5	..... Sulfur Polymer Cement Screening Test Results
6	..... Advanced Polymer Screening Test Results
7	..... High Alumina Cement Screening Test Results
8	..... Portland Cement ANS 16.1 Leach Results
9	..... Sulfur Polymer Cement ANS 16.1 Leach Results
10	..... Advanced Polymer ANS 16.1 Leach Results
11	..... High Alumina Cement ANS 16.1 Leach Results
12	..... TCLP Leach Results for Portland Cement Waste Form
13	..... TCLP Leach Results for Sulfur Polymer Cement Waste Form
14	..... TCLP Leach Results for Advanced Polymer Cement Waste Form
15	..... TCLP Leach Results for High Alumina Cement Waste Form
16	..... Comparison of TCLP Results
17	..... Comparison of ANS 16.1 Data

APPENDICES

APPENDIX A	..... Composition of High Nitrate Waste Supernates
A-1	..... Composition of ORNL Low-Level Liquid Waste
A-2	..... Composition of SRP High-Level Waste Tank Supernate
A-3	..... Composition of Hanford Plant High-Level Waste Tank Supernate
A-4	..... Composition of INEL High-Level Waste Tank Supernate
A-5	..... Composition of RFP Nitrate Salt Waste
APPENDIX B	..... Compressive Strength Test Results
APPENDIX C	..... ANS Leach Results

Nitrate to Ammonia and Ceramic (NAC) Bench Scale Stabilization Study

1.0 Introduction

The Department of Energy (DOE) has large quantities of sodium-nitrate based liquid wastes. Around 1 billion liters of high level waste tank supernatant are present at Hanford, Savannah River Plant, Rocky Flats Plant, Idaho National Engineering Laboratory, and Oak Ridge National Laboratory. The largest quantity of these wastes is in the 149 single shell tanks at Hanford which hold up to 1 million gallons each. These tank waste are typically 4 to 5 molar in nitrate and contain radionuclides, various salts, and heavy metals³. INEL high-level waste tank supernatant contains about 0.7 and 0.6 grams per liter of chromium and mercury, respectively. SRP high-level waste tank supernatant contains about 0.2 g/L of chromium. Other heavy metals could well be present at lower levels in these tank wastes. The major components present in these wastes are summarized in Appendix A (Tables A-1 through A-5). These wastes are currently regulated and managed by the DOE. Under the Federal Facility Compliance Act (FFCA) DOE is subject to RCRA, which would apply to these tank supernatants. Stabilization of this waste is difficult because nitrates are very mobile. Additionally, vitrification of these wastes produces large quantities of hard-to-manage NO_x emissions.

The Nitrate to Ammonia and Ceramic (NAC) process has been developed to remove a majority of the nitrate content from wastes such as these^{1, 6}. In the NAC process, solid aluminum at low temperatures (50-80°C) reduce nitrate to ammonia, and a solid aluminum oxide material (referred to as NAC solid product) is formed. Utilizing the NAC process, a problematic waste stream constituent (sodium nitrate) is decomposed to ammonia gas^a. In initial studies, the NAC solid product was calcined and sintered to form a ceramic-type waste form^{1, 2, 4}. Stabilization of radionuclides and metals was achieved². Work conducted to date has been on studying the NAC reaction. Initial studies looked at reaction conditions and varying reagent additions and ratios^{1, 4, 6}. More recent studies have, in addition, looked at designing a pilot scale operation^{2, 5}. The vast majority of this work has been performed at the Oak Ridge National Laboratory under the direction of Al Mattus.

This NAC process has the potential to treat the large amount of nitrate tank wastes at DOE facilities. The NAC process can also utilize the large existing inventory of scrap aluminum at DOE facilities. Some of this aluminum has been radiologically contaminated and the NAC process offers an economical disposal option for this waste.

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^aThere are several established technologies available for the management of ammonia:

- scrub into dilute acid to form ammonia salts
- cool and pressurize into liquid ammonia for reuse
- burn in a heated catalytic bed tower to form nitrogen and water vapor
- oxidize to nitric acid for reuse

Nitrate to Ammonia and Ceramic (NAC) Bench Scale Stabilization Study

Other processes that are available to treat or manage high nitrate based wastes include electrochemical destruction, biological denitrification, chemical reduction, hydrothermal processes and calcination. The advantages and disadvantages of each are summarized in a report by Taylor, et.al³. The advantages of the NAC process are that it occurs at low temperature and atmospheric pressure, destruction is essentially complete, heavy metals and strontium form insoluble precipitates, volume typically decreases by 70% (versus a 40% increase for Portland cement stabilization of the high nitrate solution), and no pretreatment will be required for the alkaline waste solutions that are stored at Hanford, ORNL and SRP.

To take the NAC solid product to the ceramic stage requires significant energy to heat the waste to a high temperature. And at these high temperatures, volatile radionuclides may be released, creating additional containment problems. In addition, a full-scale ceramic process capable of handling large quantities of NAC solid product is currently not available. Because of these concerns alternative ways to form a non-leachable solid product are desired.

In August 1994, a proposal submitted by Rust Clemson Technical Center was selected for award under the Research Opportunity Announcement (ROA). ROA's are funded by the DOE's Office of Environmental Restoration and Waste Management (EM) and managed by the Morgantown Energy Technology Center (METC). ROA's support the DOE-EM Office of Technology Development applied research efforts. The primary purpose of this study is to provide economical and environmentally acceptable methods for stabilizing NAC solids.

In this study, Rust Clemson Technical Center spiked a nitrate based solution with the eight TCLP metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and 3 TCLP semivolatile organic compounds (2,4-dinitrotoluene, 2,4,6-trichlorophenol and nitrobenzene). This mixture was subjected to the NAC process. The solid product was stabilized using sulfur polymer cement, Portland cement, high alumina cement and vinyl ester styrene polymer. Stabilized samples were subjected to TCLP, ANS 16.1 and unconfined compressive strength testing. The compressive strength results provide a useful indicator of structural stability. The ANS 16.1 leach procedure for sodium results indicate how tight the wasteforms are, i.e., how quickly a non-retained constituent can leach from the stabilized solid. Sodium is also a primary constituent of most high nitrate wastes. Finally, the TCLP test results indicate how well the different waste forms are able to stabilize the 8 RCRA metals. The three semivolatile organic compounds were chosen to provide a range of organic compound types which might be present in high nitrate based waste. These organics are not present in the DOE high level waste tank supernatants, but similar type organic may be present in other high nitrate waste streams.

Three goals for this study are:

- 1) To determine if S/S reduces the leachability of the spiked contaminants
- 2) To compare the performance of the four S/S formulations
- 3) To assess what these results mean to the NAC process

There are no specific performance criteria, although the TCLP limits are used as a benchmark.

2.0 Theory

The Nitrate to Ammonia and Ceramic (NAC) process removes a majority of the nitrate content from wastes through a reduction reaction. In the NAC process, solid aluminum at low temperatures (50-80°C) reduce nitrate to ammonia, and a solid aluminum oxide material, gibbsite, is formed. The optimal pH of nitrate wastes to be treated by this process is around 13.

The aluminum serves as a sacrificial anode, reducing the sodium nitrate in the waste to ammonia, and forming sodium aluminate and gibbsite in a process approximated by the following reaction:

This reaction is exothermic and cooling is required to maintain the reaction temperature below 80°C. The solid gibbsite material is used in subsequent testing as a waste feed (NAC solid product) for the four stabilization hosts.

3.0 Experimental Procedures

The Department of Energy (DOE) has large quantities of sodium-nitrate based liquid wastes. Around 1 billion liters of high level waste tank supernatant are present at Hanford, Savannah River Plant, Rocky Flats Plant, Idaho National Engineering Laboratory, and Oak Ridge National Laboratory. These tank waste are typically 4 to 5 molar in nitrate and contain radionuclides, various salts, and heavy metals³. INEL high-level waste tank supernatant contains about 0.7 and 0.6 grams per liter of chromium and mercury, respectively. SRP high-level waste tank supernatant contains about 0.2 g/L of chromium. Other heavy metals could well be present at lower levels in these tank wastes. These wastes are currently regulated and managed by the DOE. Under the Federal Facility Compliance Act (FFCA) DOE is subject to RCRA, which would apply to these tank supernatants.

In this study, Rust Clemson Technical Center spiked a nitrate based solution with the eight TCLP metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and 3 TCLP semivolatile organic compounds (2,4-dinitrotoluene, 2,4,6-trichlorophenol and nitrobenzene). This mixture was subjected to the NAC process. The solid product was stabilized using sulfur polymer cement, Portland cement, high alumina cement and vinyl ester styrene polymer. Stabilized samples were subjected to TCLP, ANS 16.1 and unconfined compressive strength testing.

In the NAC process, solid aluminum at low temperature (50-80°) is fed into a high nitrate, alkaline waste. For these studies a 5M nitrate solution was spiked with 400-10,000 ppm of all 8 RCRA metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and 260-4,000 ppm of three semi-volatile (SVOs) RCRA organics (2,4-dinitrotoluene, 2,4,6-trichlorophenol and nitrobenzene). Data is not available on the speciation of heavy metals in high nitrate salt solutions. Most of the metals were added as nitrate salts. Since heavy metal nitrate salts are usually very soluble, addition of the metals in this form provides a worst case scenario -- many of the metals could be present in less soluble forms.

The NAC process alone significantly reduces radionuclide leachability. In studies by Mattus, et.al., a sintered NAC product was produced from the Melton Valley Storage Tank supernate and subjected to ANS 16.1 leaching². Strontium-85, although present in the supernate, could not be detected in leachates. Cesium-137 was only slightly above background in the leachates (The ANS 16.1 leach index for cesium ranged from 12.2 to 13.7).

Stabilization of the NAC solid product was performed. Leachability of the metals and organics from these stabilized products was tested. These amounts if completely leached from the final waste form would exceed TCLP limits by 20-100 fold. The Clemson Technical Center study investigated four stabilization hosts for this NAC solid product: sulphur polymer cement, high alumina cement (the gibbsite material contains high amounts of aluminum), Portland cement/fly ash, and vinyl ester styrene resin.

Nitrate to Ammonia and Ceramic Stabilization Study

Initial screening tests were performed using various waste (NAC solid product) loadings with each stabilization host to determine the best waste loading. Once formulations were developed, stabilized waste forms were produced. These stabilized waste forms were subject to ANS 16.1 leach testing for sodium, unconfined compressive strength testing (UCS), and TCLP testing for the RCRA metals and organics.

The Clemson Technical Center's (CTC) policies and procedures have been established in a format which complies with ANS/ASQC-E4 and NQA-1. CTC has been chartered to support the characterization and analysis of radioactive, hazardous, and mixed waste. Therefore, it is the policy of CTC to meet or exceed the standards of quality expected by government agencies and industry practices.

Successful implementation of this policy requires a documented quality system and a total commitment to quality by all CTC employees. The basic mechanisms and systems required to implement this policy have been established and proven through use and verification by the Rust Federal Services Corporate Quality Assurance Group. Under this established framework, CTC has developed appropriate site specific analytical methods and procedures to verify compliance with all mandated quality assurance.

The quality system document, which is a description of the way these policies, procedures, methods, etc., meet the requirements of ANS/ASQC-E4 and NQA-1, is a controlled document administered through the CTC Quality Assurance Manager.

3.1 Preparation of NAC Solid Product

The solid product (aluminum oxide-sodium aluminate solid) was produced from the Nitrate to Ammonia and Ceramic process as described below. This product was then utilized for the stabilization studies using four hosts as described in section 3.2.

3.1.1 Preliminary Run

A solution was prepared for a preliminary shakedown run to test the NAC process and to determine operating parameters. This solution consisted of a 5 M NaNO_3 solution prepared by adding 212 g of NaNO_3 to 500 ml of deionized water. No metal or organic constituents were added. The pH of this solution was adjusted to 12.83 by adding 2 g of NaOH pellets.

This solution was mixed well and placed into a 3000 ml jacketed reaction vessel (see **Figure 1**). Heat and rapid stirring was applied to the solution until the temperature reached 51°C. Mixing was performed using a Lightning Labmaster TS2010 high shear mixer. A Lauda-RM6 heater/chiller was used to control the temperature of the jacketed reactor vessel so that the solution reached and maintained an internal temperature of 50-80°C. The temperature of the solution was continuously monitored by a thermocouple.

Ten grams of -200 mesh aluminum powder (99%) was slowly poured into the solution. The solution temperature quickly jumped to 70°C.

Figure 1
NAC Equipment Schematic
Page 6

Nitrate to Ammonia and Ceramic Stabilization Study

Coolant was then applied to the jacket surrounding the reaction flask and aluminum addition continued in 10 g increments. After each aluminum addition, the aluminum was allowed to react until the temperature quit rising. Once the temperature dropped below 55°C, more aluminum was added. Based on previous experience¹, the total aluminum to be added was set at 110% of theoretical requirements.

After 22% of the required aluminum was added, the reaction temperature was difficult to maintain below 100°C. At this point smaller amounts of aluminum (5 g and then 2 g increments) were added and allowed to react.

At 38% of the required aluminum addition, foaming became a significant problem. Water was added with a squeeze bottle to aid in controlling foam production and to slow the reaction. Foam continued to be a problem through the remainder of the run. A total of 240 mls of deionized water was added.

This produced a slurry with minimal free liquid which was removed from the reactor and placed in a metal pan for removal of free water. Using data gathered in this run, it became apparent that the 3 liter reaction flask would only be able to treat 500 mls at a time. This run also indicated the amount of aluminum required for the reaction initiation. An additional finding was that significant foam was produced. It should be noted that equipment design and process controls are necessary to manage this. Foaming is most readily decreased by increasing the amount or proportion of water.

3.1.2 Preparation of the RCRA-Spiked Nitrate Based Solution

Five (5) liters of a 5M (31%) liquid nitrate waste was prepared using a multiple of the TCLP limit concentration of 8 RCRA metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and three semi-volatile organics (SVO) as shown in **Table 1**.

The SVOs were prepared by dissolving 2.6 g of solid 2,4-dinitrotoluene ($\text{CH}_3\text{C}_6\text{H}_3(\text{NO}_2)_2$), 40 g of 2,4,6-Trichlorophenol ($\text{Cl}_3\text{C}_6\text{H}_2\text{OH}$), and 40 g of nitrobenzene ($\text{C}_6\text{H}_5\text{NO}_2$) into 200 ml of methanol. This solution was added to 2 liters of deionized water; however, it did not appear to mix completely into the water.

Metal salts were then added to the organic/water mixture in amounts shown in **Table 1**. Following this, 2125 g of NaNO_3 was added, mixed well and the volume measured (total volume = 3500 mls). An additional 1500 mls of deionized water was added. The solution was mixed well for 24 hours.

The next day NaOH pellets were added incrementally until the pH was slightly above 13. A total of 155 g of NaOH pellets were required. The solution was mixed well for an additional 24 hours at which time a subsample was withdrawn and sent for analysis of nitrate content and total RCRA constituent concentrations.

Table 1. RCRA Constituent Concentration Added to Surrogate Waste				
Metal Salt	RCRA Listing	RCRA Limit (ppm)	Multiple Amount Above TCLP Limit*	Amount of Salt Added to Final Volume of 5 Liters (g)
As ₂ O ₃	D004	5	20	53
Ba(NO ₃) ₂	D005	100	5	191
Cd(NO ₃) ₂ * 4H ₂ O	D006	1	100	55
Cr(NO ₃) ₃ * 9H ₂ O	D007	5	20	154
Pb(NO ₃) ₂	D008	5	20	81
Hg ₂ (NO ₃) ₂ * 1H ₂ O	D009	0.2	100	5
SeO ₂	D010	1	100	28
AgNO ₃	D011	5	20	31
2,4- Dinitrotoluene	D030	0.13	20	2.6
2,4,6- Trichlorophenol	D042	2.0	20	40.0
Nitrobenzene	D036	2.0	20	40.0

* The "Amount Above TCLP Limit" is in addition to the 20 fold dilution that results from TCLP Method

3.1.3 Preparation of the RCRA-Spiked NAC Solid Product

Five hundred (500) mls of the RCRA-spiked nitrate waste was placed in the reactor apparatus and mixed using the same equipment configuration as the preliminary run.

Aluminum was added (total = 110% of theoretical requirements) by adding the 200 mesh powdered aluminum in increments into the solution and allowing it to react. Heat was initially applied to the reaction flask and aluminum was added in 5 g increments and allowed to react. The reaction was measured by an initial solution temperature increase followed by a temperature decrease whereupon more aluminum was added. At 18% of the theoretical aluminum added the temperature rose above 80°C and coolant was applied to the reaction flask.

At 24% of the theoretical aluminum added, significant foam was produced and water was added to control foaming. However, foam production continued and at 82% of the theoretical aluminum added, the amount of aluminum added had to be decreased from 5 g increments to 1.5 g increments so that the foam did not spill over the top of the flask. A total of 430 mls of deionized water had been added to the solution during the reaction.

After all the aluminum was added (225 g) the solution was mixed thoroughly for several hours. The slurry was gravity filtered using a Wattman #40 filter paper and placed in an oven

at 104°C to dry. The slurry contained 37% solids. The dried solids were ground with a mortar and pestle and containerized. The filtrate had a density of 1.13 g/ml.

This process was then repeated using a 5 liter reaction flask. During this run, 750 mls of nitrate solution were reacted during which 340 g of aluminum. A total of 1055 mls of deionized water were added. This produced a slurry with 50% solids.

A third run was conducted using 1000 ml of solution in the 5 liter reaction flask. A total of 2,730 mls of deionized water was added yielding a 41% solids slurry. For runs #4, 5 and 6 a total of 2650, 4500 and 760 mls of deionized water were added to produce slurries of 59, 47 and 57% solids, respectively.

Upon drying, the solids from all six runs were homogenized in a cone blender, removed and ground to pass a #10 (2 mm) sieve. A subsample of these solids was sent for TCLP leaching, total RCRA constituent analyses, and total nitrate content. These blended solids were utilized in all subsequent stabilization studies.

The filtrates obtained from each run were combined; a portion was analyzed for total RCRA constituents, total nitrate content and density. The density was 1.14 g/ml.

3.2 Stabilization of the NAC Solid Product

The dried NAC solid product was combined with one of four stabilization reagents: Portland cement, sulfur polymer cement, vinyl ester styrene or high alumina cement.

Screening tests were performed to determine the best waste loading. In most instances, prior experience was used as a guide to determine the waste loading range. In some instances, at high waste loading a cohesive solid was not obtained, so the upper range of the waste loading was decreased. The overall project scope is summarized in **Figure 2**. Determining factors for the best waste loading were strength performance (CTC-5049^b), mixing efficiency (ease of mixing, problems with flash set, coverage of NAC solid product with stabilization reagents, creation of a cohesive monolith) and leachate performance compared to RCRA metal TCLP^c requirements (determined using a quick leach procedure).

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^bMethod CTC-5049, "Load Bearing Strength by Pocket Penetrometer," is used to determine qualitative load bearing strength. The test can be used to screen samples for their cohesive characteristics. A portion of the material is packed firmly in a small beaker. The pocket penetrometer is pressed into the sample. The penetrometer is removed, and the measurement is read directly from the instrument in tons per square foot. Final testing would be a test that measures the unconfined compressive strength.

^cThe Toxicity Characteristic Test Procedure (TCLP) is an EPA procedure that was designed to simulate the leaching a waste will undergo if disposed of in a sanitary landfill. A subsample of the waste is extracted with a buffered acetic acid solution for 18 hours. The extract is analyzed to determine if any of the forty Toxicity Characteristic (TC) constituents have exceeded concentrations specified in 40 CFR 261.24 or if the treatment standards specified in 40 CFR 268.41 have been met for the Land Disposal Restrictions program. The material is a hazardous waste if any of the TC concentrations are exceeded and requires further treatment prior to land disposal if the LDR treatment standards are not met.

Figure 2
NAC Test Program
Page 10

Based on screening test results, stabilized samples were prepared using optimal waste loadings. The stabilized samples were tested for TCLP metals and SVOs, unconfined compressive strength^d and the ANS 16.1 leach test^e.

3.2.1 Portland Cement/Flyash Stabilization

Portland Type I cement is currently being used to treat a wide variety of wastes. The material's high strength, low permeability, resistance to most chemicals, ready availability and low cost makes it an ideal candidate for waste containment. Flyash Class F acts both as a bulking agent and as a pozzolan. The resulting cement paste may have higher strength than Portland cement alone. The flyash also helps to bind additional water, decrease pH, and act as an adsorbent for metal ions.

3.2.1.1 Screening Tests

Three Portland cement waste loadings were screened: 52, 62 and 71%. For all three waste loadings, 20 g (10%) class F flyash^f and 10 g (5%) of powdered activated carbon were also added. For 52% waste loading, 110 g of NAC solid product and 70 g of Portland cement (33%) were mixed with the flyash and Darco G-60^g powdered activated carbon (200 to 325 mesh) along with 82 mls of deionized water. For 62% waste loading, 130 g of NAC solid product and 50 g of Portland cement (23%) were mixed with the flyash and activated carbon along with 89 mls of deionized water. For 71% waste loading, 150 g of NAC solid product and 30 g of Portland cement (14%) were mixed with the flyash and activated carbon and 86 mls of deionized water.

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^dThe unconfined compressive strength is a common test required by the EPA for stabilized hazardous waste and by the NRC for stabilized radioactive waste. A stabilized sample with no lateral support is compressed vertically until the structural integrity of the sample fails. The maximum loading typically is the unconfined compressive strength. For hazardous waste, the important factors are workability, minimum settling, and the ability to support landfill equipment during the operational period. Values of 25 to 50 psi are typically considered sufficient. For radioactive waste, the regulations require "a structurally stable waste form that will generally maintain its physical dimensions and form under expected disposal conditions such as the weight of overburden and compaction equipment." Values of > 60 psi are sufficient for most materials. Cement-based waste forms are an exception, values greater than 500 psi are required.

^eThe ANS 16.1 Leach Procedure is an American National Standard published by the American Nuclear Society. The solidified waste is placed in a static solution of deionized water. The water is changed out at specified time intervals. The water is tested for constituents of interest. From the results a Leachability Index (LI) is calculated, which is a measure of the rate of diffusion for each of the constituents (The higher the LI, the slower the rate of diffusion). Values above 6 are considered acceptable.

^ffly ash is a very fine ash, 1 to 50 microns in diameter, produced by combustion processes, typically using powdered coal. It is a mixture of alumina, silica, unburned carbon and various metal oxides. Composition of the two main grades of fly ash, Class C and Class F, are given in ASTM C 618. Class F fly ash contains around 5% CaO, whereas for Class C it is closer to 15%.

^gAvailable from Fisher Scientific

Each sample was covered and allowed to cure for 24 hours. Each sample was also subjected to the CTC-5016^h quick leach, and the leachates screened for RCRA metals. Results for quick leach metals from these screening tests indicated poor stabilization of selenium. Previous work performed at the CTC on other waste showed that a 50% (wt MgO/wt Portland cement) loading of MgO effectively aided in selenium stabilization. Sixty five (65) g of NAC (65%) was mixed with 10 g (10%) Portland cement, 10 g of MgO (10%), 10 g of flyash (10%), 5 g (5%) of activated carbon and 40 mls of deionized water. The mixture was covered and cured 24 hours. A quick leach was performed and analyzed for RCRA metals. Analysis indicated poor stabilization of selenium, so the addition of Na₂S was investigated.

Constituents used in this test were 75 g of NAC (70%), 15 g (14%) Portland cement, 10 g of flyash (9%), 5 g (5%) of activated carbon and 2 g of Na₂S (2%). The Na₂S was mixed with 20 mls of deionized water until dissolved. The flyash, activated carbon and NAC were then mixed into this Na₂S solution along with an additional 14 mls of deionized water.

The temperature of this mixture increased 6.8°C. When the temperature began to decrease (approx. 20 minutes) the Portland cement and an additional 9 mls of water were added. No noticeable temperature change was observed upon Portland cement addition. This mixture was covered and cured 24 hours. A quick leach was performed and analyzed for RCRA metals. The addition of sodium sulfide did not help the stabilization of selenium.

3.2.1.2 *Best Waste Loading Preparation*

Figure 3 illustrates the Portland cement tests performed. Na₂S did not decrease selenium solubility. The 71% waste loading was selected as the best waste loading. So 375 g NAC (71%) was mixed with 25 g (5%) activated carbon and 158 mls of deionized water. The temperature increased 6°C. When the temperature lowered, 50 g of flyash (10%) and 75 g of Portland cement (14%) were added along with an additional 53 mls of deionized water. The temperature of this mixture increased 1°C.

For unconfined compressive strength testing, 349 g of this mixture was placed in a 51 mm by 102 mm mold. An additional mold was filled half way with 196 g of this mixture for ANS 16.1 leach testing.

The remaining mixture (approx. 180 g) was placed in a third mold for full TCLP testing of metals and SVO's. These molds were placed, uncovered, in a humidified environment for 7 days of curing.

For quality control purposes, a duplicate sample was prepared. A total of 174 mls of water was added with the NAC and activated carbon. Then 50 mls of water was mixed with the remaining constituents.

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^hMethod CTC-5016, "Quick Leach Extraction Method," is a rapid extraction procedure that qualitatively duplicates the metals leachability of the TCLP test. Ten grams of sample is mixed with 200 ml of the appropriate extraction fluid. The mixture is stirred on a magnetic stirring plate for at least 25 minutes and until pH equilibrium has been reached. The mixture is filtered and the metals content and pH of the filtrate are measured.

Figure 3
Portland Cement Stabilization
Screen Test Schematic
Page 13

Nitrate to Ammonia and Ceramic Stabilization Study

3.2.1.3   *Filtrate From NAC Process Used as Makeup Water*

In full-scale operations, liquid residuals may be recycled. However, it may be advantageous to treat the liquid residuals, rather than recycle. To evaluate the potential for use of the filtrate obtained from the NAC process for use in stabilization as make up water, additional testing was performed. In addition, these tests indicated the potential for stabilization of the NAC slurry directly (without drying).

The filtrate density after approximately three months of storage remained 1.13 g/ml. This filtrate (68 mls) was combined with 150 g of NAC dried product and 10 g of activated carbon. A temperature increase of 4.5 °C occurred. When the reaction began to slow (approximately 20 minutes as measured by a decrease in temperature) 40 g of Portland cement, 20 g of flyash and an additional 22 mls of filtrate were added and mixed well. The temperature of the mixture rose 2°C.

The mixture was placed in a mold and cured in humidified air for one week and then utilized for full TCLP testing of RCRA metals and SVOs. An additional mold was made in a similar manner for UCS testing by adding 200 g of NAC to 13.3 g of activated carbon, 26.7 g of flyash, 53.3 g of Portland cement and 108 mls of filtrate.

3.2.2   Sulfur Polymer Cement Stabilization

Large amounts of sulfur are recovered from combustion stack gases and from the refining of natural gas and petroleum. In an attempt to develop new uses for this material, the U.S. Bureau of Mines developed a sulfur polymer cement (SPC) that consists of elemental sulfur reacted with 5% dicyclopentadiene. SPC is a thermoplastic material, not a hydraulic cement. Its low melting point (120°C) and melt viscosity (about 25 centipoise) make for easy handling. Compared with hydraulic Portland cements, SPC has a number of advantages: higher compressive strength, faster set (full strength is reached in hours rather than weeks), and resistance to most acids and bases. The sulfur cement used was "CHEMENT 2000" produced by Martin Resources, Odessa TX (1-800-584-2062, Hugh Harbour).

3.2.2.1   *Screening Tests*

Three waste loadings were evaluated (35, 50, and 65 wt%). Initially, molten SPC was added to room temperature, dried NAC in a glass beaker. The mixture flash set. Heating the NAC product in a Teflon beaker also failed when the beaker melted or dissolved (this was unexpected as the temperature was only 135°C).

A stainless steel beaker was used for all further testing. For a 35% waste loading, 10 g of Na₂S (5%) was added to 70 g of NAC. The mixture was heated to 135°C. A total of 120 g of SPC was then slowly added and mixed. The mixture was poured into a mold. The process was repeated using 50 and 65% waste loading. At the waste loading of 65% NAC, visual observations indicated that the waste was not completely encapsulated within the SPC.

Each waste loading was subjected to the CTC-5016 quick leach and the leachates were screened for RCRA metals.

Nitrate to Ammonia and Ceramic Stabilization Study

3.2.2.2 Best Waste Loading Preparation

Although all three waste loadings passed the quick leach screen for RCRA metal TCLP limits, the 65% waste loading did not produce a cohesive monolith. Therefore, the best waste loading was deemed to be 50%.

As illustrated in **Figure 4**, ten (10) g (5%) of Na_2S was added to 100 g NAC (50%) and heated to 135°C in a stainless steel beaker. A total of 90 g of SPC was then slowly added and mixed while continuously heating. This mixture was poured into a mold for ANS 16.1 testing. The process was repeated to produce a second mold for TCLP testing.

For UCS testing, 25 g of Gilson "Rediron" capping compound was melted and placed in a UCS mold (51 X 102 mm). The SPC process was repeated using 200 g NAC, 20 g Na_2S and 180 g SPC and 321 g of this mixture was poured into the mold. Gilson capping compound was poured on top of the cooled SPC mixture.

This procedure was then repeated to produce duplicate molds for TCLP, ANS 16.1 and UCS testing.

3.2.3 High Alumina Cement Stabilization

A high-alumina cement can be prepared by mixing lime ($\text{Ca}(\text{OH})_2$) with the NAC solid product (mainly Al_2O_3). The NAC solid product serves as the alumina source. High-alumina cements often flash set to form a monolith of considerable strength. Strength may decrease over time. High alumina cements may be more sensitive than Portland cement systems to corrosive attack.

3.2.3.1 Screening Tests

Three waste loadings were studied: 30, 60 and 80%. For 60% waste loading, 74 g of NAC was added to 50 g of $\text{Ca}(\text{OH})_2$ and 93 mls of deionized water. The slurry was mixed well, covered and allowed to cure for 24 hours.

Similarly, for 30% waste loading, 60 g of NAC was added to 140 g of $\text{Ca}(\text{OH})_2$ and 188 mls of deionized water. For 80% waste loading, 160 g of NAC was added to 40 g of $\text{Ca}(\text{OH})_2$ and 110 mls of deionized water. These were also mixed well, covered and allowed to cure 24 hours. Each loading was subjected to the CTC-5016 quick leach and the leachates screened for RCRA metals.

Results on quick leach metals from these screening tests indicated that TCLP limits might be exceeded for barium, lead and selenium. Na_2S and Na_2SO_4 were added to try to reduce the solubility of these problematic metals. Two (2) g of Na_2S and 1 g of Na_2SO_4 (for barium) were mixed with 30 mls of deionized water until dissolved. The mixture was added to 50 g of NAC. No temperature change was detected. Fifty (50) g of $\text{Ca}(\text{OH})_2$ and 56 mls of deionized water was then added to this mixture. A 1°C temperature change occurred upon the addition of $\text{Ca}(\text{OH})_2$. After 24 hours the sample was still fluid, so it was allowed to cure uncovered for an additional 48 hours. A quick leach was performed and the leachate analyzed for RCRA metals. Analysis indicated that lead and selenium continued to leach out above TCLP limits.

Figure 4
Sulfur Cement Stabilization Screen
Test Schematic
Page 16

Nitrate to Ammonia and Ceramic Stabilization Study

3.2.3.2 Best Waste Loading Preparation

The schematic for the high-alumina cement tests is shown in **Figure 5**. The 80% waste loading just passed the TCLP requirement for selenium and failed for barium. The 60% waste loading was close to failure with TCLP leachable barium. The best waste loading was determined to be slightly lower than the 60% waste loading. The best formulation was determined to be a 50% NAC solid product waste loading using only $\text{Ca}(\text{OH})_2$. A mixture was prepared by adding 200 g NAC with 200 g $\text{Ca}(\text{OH})_2$ and 300 mls of deionized water. The temperature of this mixture increased 2°C. The stabilization was repeated. Duplicate molds were prepared for ANS 16.1 testing, UCS testing and TCLP testing.

3.2.3.3 Filtrate From NAC Process Used as Makeup Water

In full-scale operations, liquid residuals may be recycled. However, it may be advantageous to treat the liquid residuals, rather than recycle. To evaluate the potential for use of the filtrate obtained from the NAC process for use in stabilization as make up water, additional testing was performed. In addition, these tests may indicate the potential for stabilization of the NAC slurry directly without drying.

The filtrate (256 mls) was combined with 150 g of NAC dried product and 150 g of $\text{Ca}(\text{OH})_2$ and mixed well. The temperature increased 7°C. The mixture was placed in two molds and cured in humidified air for one week and then utilized for full TCLP testing of RCRA metals and SVOs, and for UCS testing.

3.2.4 Vinyl Ester Styrene Stabilization

In the vinyl ester styrene (VES) process, the waste is dispersed into a hydrophobic liquid resin using high-shear mixing. A catalyst is added to polymerize the system. A hard monolith forms within hours. The resultant thermoset polymer is resistant to solvents, moderate heat and water. No reaction takes place with the waste components, it is an encapsulation process. The VES process is marketed by Diversified Technologies, Knoxville TN (Paul Werner 615-539-9000). Three waste loadings were evaluated: 30, 60, and 67 wt/wt%.

3.2.4.1 Screening Tests

For 30% waste loading, 130 mls of binder were mixed with 3.3 mls of catalyst for one minute. Then NAC product (200g) was slowly added to this mixture. After this, a promoter (0.13 ml) was added and mixed thoroughly for 1.5 minutes. A thermocouple was placed in this mixture and reaction temperature monitored. Only a 4.5°F increase in temperature occurred which indicated that the polymerization reaction was inhibited and that a solid monolith might not be produced.

Several other formulations were attempted and none were successful at producing an acceptable temperature increase. It was speculated that the high pH of the NAC solid product may have adversely impacted the VES. A second Diversified Technologies' polymer called "Advanced Polymer" was tested and a solid product was produced. This polymer is prepared using two proprietary reagents: DT-800 and DT-822.

Figure 5
High Alumina Cement Stabilization
Screen Test Schematic
Page 18

Nitrate to Ammonia and Ceramic Stabilization Study

For 30% waste loading, 84 g of DT-800 were added to 56 g of DT-822 and mixed well. NAC solid product (60g) was slowly added to this mixture. This mixture was poured into a plastic beaker containing 3/8" rigid tubing. (The tubing serves as molds for TCLP test requirements.) A thermocouple was placed in this mixture. The reaction temperature increased 150°F in 33 minutes, indicating an acceptable reaction rate.

This process was repeated for 60 and 67% waste loadings. For 60% waste loading, 120g of NAC, 48 g DT-800 and 32 g of DT-822 were used. The temperature increased 133°F in 18 minutes. For 67% waste loading 160g of NAC, 48 g DT-800 and 32 g of DT-822 were used. The temperature increased 170°F in 15 minutes.

After 24 hours, the solidified, cooled monoliths were broken and the solidified samples removed from the rigid tubing. It was observed that some segregation of the 30% waste loading sample had occurred with settling of the NAC product to the bottom of the solidified sample. The solids were subjected to the CTC-5016 quick leach and the leachates were screened for RCRA metals.

3.2.4.2   *Best Waste Loading Preparation*

For 30% waste loading, 252 g (42%) of DT-800 was mixed with 56 g (28%) of DT-822. NAC product (180 g) was added and mixed well as shown in **Figure 6**. A portion of this mixture (180 g) was poured into a 51 mm by 102 mm mold for UCS testing. A second mold was made using 127 g of this mixture for ANS 16.1 leach testing. The remaining mixture was poured into a third mold containing 3/8" rigid tubing for TCLP testing.

A violent reaction took place within the molds potentially due to the small surface area at the top that could allow for heat transfer. Both the TCLP mold and the UCS mold "boiled" over the top. The UCS mold was unusable but the TCLP mold was usable for TCLP testing.

The process was repeated using smaller portions to produce an additional TCLP mold and ANS 16.1 mold. No UCS mold was produced so no UCS testing was performed on this stabilization reagent.

Figure 6
Advanced Polymer Stabilization
Screen Test Schematic
Page 20

4.0 Test Methods and Results

Leach testing was performed on the NAC solid product and on the best formulations for each of the four stabilization reagents. Samples were leached using the TCLP and the abbreviated ANS 16.1 test methods, with the exception of the NAC solid product which was leached using only the TCLP test method. Additional TCLP tests were performed on Portland cement and a high alumina cement samples where filtrate was used in preparing the formulations.

Two molds were made for each stabilization reagent so that duplicate leach tests could be performed. The constituent analyzed for ANS 16.1 leachability was sodium. In this method the stabilized waste form is suspended in leachant (deionized water) for a period of time. The leachant is removed, analyzed and fresh leachant replaced at time intervals (after the start of the test) of 2 hours, 7 hours, 24 hours and days 2, 3, 4 and 5. A control was also run using deionized water and no sample.

Unconfined compressive strength testing was performed on three of the four stabilization reagents. No mold was able to be produced from the advanced polymer stabilization reagent due to heat production and an overflow of the mold and a set could never be obtained with the vinyl ester styrene resin. Two molds, 51mm by 102 mm (2" by 4"), were made for each of the three stabilization reagents, so that duplicate UCS testing could be performed. UCS testing was performed per ASTM-D1633. Molds were tested in a Soiltest model U-590 compression testing machine until failure was reached. Additional UCS tests were performed on Portland cement and a high alumina cement samples where the residual liquid (filtrate) from preparation of the NAC solid product was added to cement formulations.

4.1 RCRA-Spiked NAC Solid Product

The RCRA-spiked nitrate solution was analyzed for the spike constituents. The results are listed in **Table 2** ("waste before NAC"). This liquid had a 31% nitrate content (5 molar). The concentration of RCRA constituents in the NAC solid product are also listed in **Table 2** ("solid after NAC-total"). After NAC processing the solid contained 0.09% nitrate. Although RCRA constituent concentrations were high in the solid, only a few were soluble to concentrations above the TCLP limits: chromium, arsenic, selenium and 2,4,6-trichlorophenol, see "solid after NAC-TCLP". The NAC process alone successfully stabilized many RCRA constituents.

The NAC solid product contained no detectable amounts of nitrobenzene or 2,4-dinitrotoluene. These constituents may have been broken down into other compounds or destroyed completely under the reducing conditions present in the solution. Since the trichlorophenol remained, the two other organics may have been de-nitrated. Analyses were performed to determine potential byproducts resulting from the destruction of these SVOs. However, the high concentration of SVOs in the liquid prior to treatment resulted in dilution before treatment sample. As a result, no data pertaining to the amount of potential byproducts contained in the original solution is available. This makes comparison with products produced after the NAC reaction impossible. The 2,4,6-trichlorophenol primarily partitioned to the liquid filtrate.

Nitrate to Ammonia and Ceramic Stabilization Study

A second sample was withdrawn near the end of this study, after 3 months of storage, to determine the amount of SVOs lost due to volatilization over the course of the study. Results on this sample are listed in **Table 2**.

The percent of each RCRA constituent present in the filtrate and solid product solid are listed in **Table 3**. The data indicate a reasonable mass balance for metals (84 to 137%). No detectable levels of nitrobenzene or dinitrotoluene were found in the liquid or solid fractions. The mass balance for the trichlorophenol was 80%.

The 2,4,6-trichlorophenol remained primarily in the filtrate (53% of the initial amount). Most of the 8 RCRA metals partitioned to the solid; however, significant amounts of lead, arsenic, and selenium were present in the filtrate (10, 40 and 18% of the initial amount, respectively). All other RCRA metals were at concentrations below the TCLP limit.

The NAC solid product failed TCLP requirements for chromium, arsenic, selenium and 2,4,6-trichlorophenol, even though the percentage of these constituents that were TCLP leachable was small. As shown in **Table 3**, 0.38% of the chromium and 0.29% of the arsenic leached out in the TCLP test. Larger percentages were noted for selenium and 2,4,6-trichlorophenol, which were 2.13 and 11.9% of the total concentration detected in the NAC product, respectively.

Filtrate removed during the NAC process had concentrations of RCRA constituents shown in **Table 2**. All constituents were below the TCLP limit except lead, arsenic, selenium, and 2,4,6-trichlorophenol. A significant reduction in concentration of these elements was observed. The lead concentration was reduced 89% and arsenic, selenium and 2,4,6-trichlorophenol were reduced 57, 80 and 42%, respectively. The total reduction in nitrate from NAC processing was 99.3%. The filtrate contained 0.13% nitrate.

4.2 Screening Tests

Screening tests were performed to determine the highest waste loading achievable with each of the four stabilization technologies and to evaluate the need for formulation modifications. Screening strength tests were conducted using CTC-5049. Visual observations of mixing ease, amount of water needed and other potential problems with various waste loadings were also evaluated during the screening tests.

The most important parameter used to compare performance was the TCLP leachability of the 8 RCRA metals. Stabilized waste forms were subjected to CTC-5016, a quick leach procedure, which gives a simple and fairly accurate estimate of TCLP performance.

4.2.1 Portland Cement

Portland cement waste loadings of 52, 62 and 71 % were tested. Load bearing strength after 24 hours of curing was measured at greater than 4.5 kg/cm² for all three samples. All the samples mixed well and there were no flash set problems. Therefore, the deciding parameter for the best waste loading was TCLP performance for metal stabilization.

Table 2. RCRA Spike Concentrations in Various NAC Process Streams, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitrobenzene	2,4,6-Trichlorophenol	2,4-Dinitrotoluene
Waste Before NAC	2323	14345	3404	3703	442	9030	3303	3364	1200	2030	144
Filtrate After NAC	0.275	3.89	<0.26	2.69	0.014	919	1420	665	<0.01	1160	<0.01
Solid After NAC-Total	1990	8675	1912	1983	253	4468	1740	1851	<0.01	334	<0.01
Solid After NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.14	5.1	39.5	<0.04	40	<0.04
TCLP Limit	5	100	1	5	0.2	5	5	1	40	2	0.13
NAC Product After 3 Months									<0.01	298	<0.01

Bold/shading indicates those constituents detected in concentrations higher than the TCLP Limit.

Table 3. Percent of RCRA Constituents Present in Filtrate and Solid After NAC Processing, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitrobenzene	2,4,6-Trichlorophenol	2,4-Dinitrotoluene
Filtrate After NAC	0.01	0.03	0.00	0.07	0.00	9.50	40.1	18.4	0.00	53.3	0.00
NAC Solid Product	137	96.8	89.9	85.7	91.6	79.2	84.3	88.1	0.00	26.3	0.00
Total Accounted For	137	96.8	89.9	85.8	91.6	88.7	124	106	0.00	79.6	0.00
Percent Leachable From Solid After NAC	0.25	1.20	0.00	7.54	1.14	0.00	5.86	42.7	0.00	240	0.00

Nitrate to Ammonia and Ceramic Stabilization Study

TCLP fluid #2¹ was determined to be the appropriate fluid for these samples. Final pHs of the TCLP leachates were 11.4, 10.4 and 9.2 for the 52, 62 and 71% waste loadings, respectively. All three waste loadings stabilized seven of the eight RCRA metals to below the TCLP limits, as shown in **Table 4**. Selenium was the only metal detected above the TCLP limit.

Selenium is usually not found at environmental remediation sites and consequently minimal work has been performed with stabilization of this element. Past work performed at CTC used a 50/50 mixture of magnesium oxide (MgO) and Portland cement (wt. MgO/wt. Portland cement) for selenium stabilization. Therefore the highest waste loading (71%) was selected and an MgO/Portland cement stabilization performed to reduce selenium solubility. A quick leach was performed (final TCLP pH = 9.2) and analyzed for RCRA metals. The results listed in **Table 4** show that the MgO/Portland cement did not significantly reduce the selenium solubility and may have had a negative impact on barium leachability.

The use of sodium sulfide (Na₂S) was then tested to aid in selenium stabilization. Na₂S reduces the leachability of many metals by forming insoluble metal sulfides. The addition of Na₂S may have reduced the TCLP leachable concentrations of silver, cadmium, mercury and lead however the TCLP leachable selenium was higher with Na₂S addition than with Portland cement alone. Load bearing strength was measured at greater than 4.5 kg/cm².

The best formulation was 71% waste loading using Portland cement (14%), flyash (10%) and activated carbon (5%).

4.2.2 Sulfur Polymer Cement

Sulfur Polymer Cement (SPC) stabilized samples were prepared using waste loadings of 35 to 65% SPC with 5% sodium sulfide. The lower waste loadings of 35 and 50% produced a hard monolith that was able to bear much more than the maximum strength of 4.5 kg/cm² that can be tested by CTC-5049. The higher waste loading of 65% did not produce a solid monolith and could not be strength tested.

Initially, flash set and container problems described in section 3 of this report had to be solved. Following this, mixing of the samples for TCLP quick leach testing was performed.

TCLP fluid #1 was determined to be the appropriate fluid for these samples. Final TCLP pHs were 5.13, 5.05 and 5.73 for 35, 50 and 65% waste loadings, respectively. All three waste loadings stabilized the eight RCRA metals to below the TCLP limits as shown in **Table 5**. Because the 65% waste loading did not produce a solid monolith, 50% waste loading was determined to be best.

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¹The extraction fluid employed is a function of the alkalinity of the waste. TCLP fluid number 1 is made by adding 5.7 ml of glacial acetic acid and 64.3 ml of 1.0 N sodium hydroxide to a final volume of 1 liter of water and is used for less alkaline wastes. TCLP fluid number 2 is made by adding 5.7 ml of glacial acetic acid to a final volume of 1 liter of water and is used for more alkaline wastes.

Nitrate to Ammonia and Ceramic Stabilization Study

Table 4. Portland Cement Screening Test Results, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium
Solid After NAC-TCLP	0.247	5.19	<0.020	7.48	0.144	<0.140	5.1	39.5
TCLP Limit	5	100	1	5	0.2	5	5	1
52% Waste Loading	<0.050	2.31	<0.020	0.719	<0.0006	<0.140	0.194	4.05
62% Waste Loading	<0.050	1.89	0.027	0.0523	<0.0006	<0.140	0.182	5.3
71% Waste Loading	0.121	4.39	0.148	0.246	0.0012	0.234	0.149	3.99
MgO/PC (71% NAC)	<0.050	27.7	0.027	0.394	0.0017	<0.140	<0.225	3.32
PC & Na ₂ S (71% NAC)	<0.050	6.58	<0.020	<0.090	<0.0003	<0.140	0.296	11.4

4.2.3 Advanced Polymer

As described in Section 3 of this report, the vinyl ester styrene was unable to set properly to produce a solid monolith. TCLP fluid #1 was determined to be the appropriate fluid for the VES samples. Final leachate pHs were 5.8, and 6.1 for 30 and 60% waste loadings respectively). The advanced polymer however, did produce a solid monolith with a bearing strength $>4.5 \text{ kg/cm}^2$.

All the samples mixed well and there were no flash set problems. Therefore, the deciding parameter for the best waste loading was the TCLP quick leach performance for metal stabilization.

Quick leach testing indicated that this polymer may not be applicable for stabilization of the NAC solid product as shown in Table 6. At 67% waste loading, silver was the only metal that leached well below the TCLP limit. Chromium was slightly below the TCLP limit. The other 6 RCRA metals failed the TCLP limits.

At 60% waste loading, similar results were observed except that barium was also below the TCLP limit.

The best waste loading was 30%; all but cadmium and selenium passed the TCLP test. Both of these elements were slightly over the TCLP limit.

4.2.4 High Alumina Cement

The strength generated from 30, 60 and 80% waste loadings, using high alumina cement as a stabilization reagent, was 2.8, 3.5 and greater than 4.5 kg/cm^2 , respectively. TCLP fluid

Nitrate to Ammonia and Ceramic Stabilization Study

Table 5. Sulfur Polymer Cement Screening Test Results, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium
Solid After NAC-TCLP	0.247	5.19	<0.020	7.48	0.144	<0.140	5.1	39.5
TCLP Limit	5	100	1	5	0.2	5	5	1
35% Waste Loading	<0.05	7.51	<0.02	<0.09	<0.0015	<0.14	1.71	0.471
50% Waste Loading	<0.05	9.26	<0.02	<0.09	<0.0006	<0.14	0.964	<0.30
65% Waste Loading	<0.05	9.91	0.034	<0.09	0.0027	0.219	1.4	0.322

Table 6. Advanced Polymer Screening Test Results, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium
Solid After NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.14	5.1	39.5
TCLP Limit	5	100	1	5	0.2	5	5	1
30% Waste Loading	<0.05	10.8	1.24	0.275	0.029	4.11	0.43	1.09
60% Waste Loading	0.517	86.2	14.8	2.89	0.358	32.2	6.35	6.83
67% Waste Loading	1.31	114	18.3	4.80	0.486	49.7	11.3	9.22

#2 was determined to be the appropriate fluid for these samples. Final TCLPs pH's were 11.5, 11.7 and 10.8 for 30, 60 and 80% waste loadings, respectively.

All the waste loadings mixed well and there were no flash set problems. All three waste loadings also successfully stabilized silver, cadmium, chromium, mercury and arsenic as shown in **Table 7**. The 30 and 60% waste loadings failed the TCLP requirements for lead and selenium and the 80% waste loading failed the TCLP requirements for barium and lead.

The use of Na_2S for lead and selenium, and Na_2SO_4 for barium, was tested using an approximately 50% waste loading. After 24 hours the sample was still fluid, so it was allowed to cure uncovered for an additional 48 hours. Load bearing strength using CTC procedure was measured at 4.3 kg/cm^2 . A quick leach was performed (final leachate pH = 10.6) and the leachate analyzed for RCRA metals. As shown in **Table 7**, these additional

Nitrate to Ammonia and Ceramic Stabilization Study

reagents reduced the TCLP leachable barium to well below the TCLP limit; but lead and selenium were not. TCLP leachable selenium increased with these additives.

The 80% waste loading just passed the TCLP requirement for selenium and failed for barium. The 60% waste loading was close to failure with TCLP leachable barium. The best waste loading was determined to be slightly lower than the 60% waste loading. The best formulation was determined to be a 50% NAC solid product waste loading using only Ca(OH)_2 .

4.3 Unconfined Compressive Strength (UCS) Tests

Unconfined Compressive Strength (UCS) tests were performed on three of the four stabilization reagents. Testing was performed as per ASTM-D1633 using a Soiltest model U-590 compression apparatus. Molds were 51mm by 102 mm (2in. by 4in.).

The advanced polymer was mixed with NAC solid product and poured into an UCS mold. The advanced polymer reacted quickly causing the mixture to erupt and flow over the top of the mold. Directly following this, the remaining sample set hard, but only half of the volume remained in the mold.

4.3.1 Portland Cement

Three molds were prepared using 71% waste loading. Two molds were made without filtrate using deionized water. One mold was prepared using the filtrate obtained from the production of the NAC solid product. In an ideal larger scale process, some filtrate would be incorporated into the final waste form. After 7 days of humidified curing, the Portland cement stabilized samples did not set hard.

Table 7. High Alumina Cement Screening Test Results, ppm

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium
Solid After NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.14	5.1	39.5
TCLP Limit	5	100	1	5	0.2	5	5	1
30% Waste Loading	0.053	29.7	0.02	0.096	0.0063	9.54	<0.23	2.18
60% Waste Loading	0.089	91	<0.02	<0.09	0.0167	28.3	<0.23	1.54
80% Waste Loading	0.089	105	<0.02	<0.09	0.0441	7.89	<0.23	0.633
50% Waste Loading with Na_2S and Na_2SO_4	<0.05	5.11	<0.02	<0.09	0.009	26.5	<0.23	11.3

Nitrate to Ammonia and Ceramic Stabilization Study

Figures 7, 8 and 9 show the results of these compressive strength tests with the raw data for these tests included in **Appendix B**.

Without filtrate, compressive strengths of 106.4 and 82.8 psi (average of 94.6 psi) were attained. The mold prepared with filtrate had a maximum compressive strength of 64.1 psi.

4.3.2 Sulfur Polymer Cement

Two molds were prepared for UCS testing using sulfur polymer cement at a 50% waste loading. Due to irregularities of the surfaces (top and bottom), a capping compound was utilized as per ASTM-C617. Compressive strength was measured at 39.7 and 43.7 psi (average of 41.7 psi). **Figures 10 and 11** show the results of these compressive strength tests; the raw data for these tests are included in **Appendix B**.

These samples had low compressive strengths and would not meet a 50 psi requirement.

4.3.3 High Alumina Cement

Three molds were tested with a waste loading of 50%. The two molds were made without filtrate. One mold used filtrate as makeup water during mold preparation. After 7 days of humidified curing, these samples did not set hard.

Figures 12, 13 and 14 show the results of the compressive strength tests. The raw data for these tests is included in **Appendix A**. The molds prepared without filtrate had maximum compressive strengths of 17 and 15.2 psi (average of 16.1 psi). The mold prepared with filtrate had a maximum compressive strength of 81.4 psi.

The samples prepared with filtrate have a maximum compressive strength greater than 50 psi and had 400% more strength than the average strength of the samples made without filtrate. Without filtrate the samples did not develop enough strength to meet a potential 50 psi requirement.

4.4 ANS 16.1 Leach Tests

The ANS 16.1 method, developed by the American Nuclear Society, is a test developed to measure the leachability of radioactivity from solidified low-level radioactive wastes. Leachability is calculated two different ways. If the amount of constituent leached is less than 20% of the total, the effective diffusivity is determined by the formula:

$$D = \pi \left[\frac{a_n}{A_0} \right]^2 \left[\frac{V}{S} \right]^2 T$$

where:

D   =   effective diffusivity, cm²/s
V   =   volume of specimen, cm³

Figure 7
Portland Cement Compressive
Strength Test #1 Results
Page 29

Figure 8
Portland Cement Compressive
Strength Test #2 Results
Page 30

Figure 9
Portland Cement Compressive
Strength Test Results Using NAC
Filtrate
Page 31

Figure 10
Sulfur Polymer Cement Compressive
Strength Test #1 Results
Page 32

Figure 11
Sulfur Polymer Cement Compressive
Strength Test #2 Results
Page 33

Figure 12
High Alumina Cement Compressive
Strength Test #1 Results
Page 34

Figure 13
High Alumina Cement Compressive
Strength Test #2 Results
Page 35

Figure 14
High Alumina Cement Compressive
Strength Test Results Using NAC
Filtrate
Page 36

Nitrate to Ammonia and Ceramic Stabilization Study

- S = geometric surface area of the specimen as calculated from measured dimensions, cm²
T = leaching time represented by the following:

$$T = \left[\frac{1}{2} (t_n^{\frac{1}{2}} + t_{n-1}^{\frac{1}{2}}) \right]^2$$

If the amount of constituent leached is more than 20% of the total, the effective diffusivity is determined by the formula:

$$D = \frac{Gd^2}{t}$$

Where:

- G = a time factor for the cylinder (based on tabular data)
d = diameter of cylinder
t = elapsed time since the beginning of the first leach interval

For this project, the leachability of sodium was used as an indicator of potential radioactive constituent leachability. The abbreviated test was performed (duration of 5 days rather than 90 days).

A portion of each stabilization mixture was placed in an UCS mold (approximately halfway filled) and cured. The cured sample is suspended in leachant (deionized water). The leachant is removed, analyzed, and fresh leachant replaced at set time intervals of 0 (initial rinseate), 2, 7, 24, 48, 72, 96 and 120 hours after the start of the leach testing.

The amount of sodium in the NAC solid product prior to stabilization was determined to be 34,900 ppm, as determined by duplicate analyses.

All data and calculations for the ANS 16.1 leach test are summarized in **Appendix B**.

4.4.1 Portland Cement

After 7 days of humidified curing, the samples did not set hard. During leaching minor degradation of the samples occurred up to the fifth day with small parts of the monolith breaking off. The amount of degradation, as determined, by visual estimate was 2-4%.

At a 71% waste loading the sample contained a total concentration of 17,400 ppm or 3.30 g of sodium. The total amount of sodium that leached out of the sample after 5 days was 68% or 2.24 g.

Nitrate to Ammonia and Ceramic Stabilization Study

The leach data for this sample is reported in **Table 8**. **Figure 15** shows that this sample continued to leach sodium over time, however the effective diffusivity stabilized after 48 hours to approximately 1.17×10^{-6} cm/sec.

A duplicate sample was prepared in a similar manner. This sample also showed 2-4% degradation.

The sodium data for this sample is reported in **Table 8**. **Figure 16** shows that this sample continued to leach sodium and that the effective diffusivity fluctuated over the duration of this test. Unlike the first sample, the effective diffusivity increased after the initial two hour sample was withdrawn and continued to increase over the remainder of the test to a maximum of 6.56×10^{-7} cm/sec at the fifth day.

This sample contained a total concentration of 16,100 ppm or 3.01 g of sodium. The total amount of sodium that leached out of the sample was 56% or 1.71 g.

The average effective diffusivity of these two Portland cement stabilized samples was 9.13×10^{-7} cm/sec. The average percent sodium leached was 63%.

4.4.2 Sulfur Polymer Cement

At a 50% waste loading the sample contained a total concentration of 23,900 ppm of sodium or 3.94 g. Only 2.67 g was present on the NAC solid product. Therefore the stabilization reagents may have contributed 1.27g of sodium to the stabilized mixture. This amount is 32% of the total amount of sodium in the stabilized sample.

Table 8. Portland Cement ANS 16.1 Leach Results		
Sample	Sodium (ppm) Run #1	Sodium (ppm) Run #2
Solid Before ANS 16.1	17,400	16,100
Rinse	72.3	48
2 hrs	343	202
7 hrs	264	164
24 hrs	384	259
48 hrs	256	224
72 hrs	185	163
96 hrs	163	157
120 hrs	122	121
Solid After ANS 16.1	6,190	9,860

Figure 16
ANS 16.1 Leach Test Results for
Portland Cement Test #2
Page 40

Nitrate to Ammonia and Ceramic Stabilization Study

The leachant collected from ANS 16.1 testing for this stabilization reagent had a yellow color and smelled of sulfur. No degradation of the sample occurred during the tests.

The total amount of sodium that leached out of the sample was 19% or 0.76g sodium.

The sodium data for this sample is reported in **Table 9**. **Figure 17** shows that this sample continued to leach sodium and the effective diffusivity increased over time to a maximum value of 6.49×10^{-8} cm/sec.

A duplicate sample was prepared that contained 26,000 ppm or 4.5 g sodium. The total amount of sodium that leached out of the sample was 18% or 0.83 g.

The sodium data for this sample is reported in **Table 9**. **Figure 18** shows that this sample continued to leach sodium and the effective diffusivity increased over time to a maximum value of 5.51×10^{-8} cm/sec.

The two samples had similar results with an average effective diffusivity of 6.00×10^{-8} cm/sec. The average amount of sodium leached from the samples was 18.5%, about one third of the sodium that leached was potentially from the stabilization reagents.

4.4.3 Advanced Polymer

The advanced polymer samples degraded during leach testing. The NAC solid product was either coming to the surface of the stabilized waste form or the polymer was dissolving away. After 5 days of leach testing the samples became a soft, taffy-like, consistency with pieces of NAC solid product migrating to the surface of the stabilized samples.

Table 9. Sulfur Polymer Cement ANS 16.1 Leach Results		
Sample	Sodium (ppm) Run #1	Sodium (ppm) Run #2
Solid Before ANS 16.1	23,900	26,000
Rinse	23.60	26.5
2 hrs	58.61	70.56
7 hrs	60.94	62.92
24 hrs	156.2	161.7
48 hrs	118.8	133.1
72 hrs	112.2	105.82
96 hrs	94.49	92.84
120 hrs	89.54	86.79
Solid After ANS 16.1	17800	19700

Figure 17
ANS 16.1 Leach Test Results for
Sulfur Polymer Cement Test #1
Page 42

Figure 18
ANS 16.1 Leach Test Results for
Sulfur Polymer Cement Test #2
Page 43

Nitrate to Ammonia and Ceramic Stabilization Study

Two samples at 30% waste loading were prepared for duplicative purposes. The sodium data for both samples is reported in **Table 10**. **Figure 19** shows that sample #1 continued to leach sodium and the effective diffusivity increased over time to a maximum value of 1.35×10^{-7} cm/sec.

The initial sodium concentration in this sample was 11,700 ppm, which equates to 1.3g. The total amount of sodium that leached out of the sample was 29% or 0.25 g sodium.

Figure 20 illustrates the results for the second advanced polymer sample. This sample also continued to leach sodium over time. The effective diffusivity of this sample may have stabilized until day 4 then increased to a maximum value of 1.35×10^{-7} cm/sec.

The total amount of sodium leached from this sample was greater than 20% of the sodium content of the sample. As a result, the effective diffusivity of the final leachate had to be calculated based on tabular data as per method ANS 16.1. Because this data point was calculated in a different manner than the other data points, the effective diffusivity may have actually stabilized after 7 hours to an average effective diffusivity of 6.58×10^{-8} .

The initial concentration of sodium in this sample was 11,700 ppm or 1.3 g. The total amount of sodium that leached out of the sample was 29% or 0.25 g.

Both samples had the same average effective diffusivity of 1.35×10^{-7} cm/sec. The percent leached from each sample was very similar with an average of 26%, with about one fifth of the sodium leached from the stabilization reagents.

Table 10. Advanced Polymer ANS 16.1 Leach Results		
Sample	Sodium (ppm) Run #1	Sodium (ppm) Run #2
Solid Before ANS 16.1	11,700	9,940
Rinse	<2.00	<2.00
2 hrs	14.8	12.2
7 hrs	39.3	26.8
24 hrs	79.5	57.4
48 hrs	61.5	44.9
72 hrs	54.5	39.7
96 hrs	48.4	31.8
120 hrs	63.3	21.5
Solid After ANS 16.1	8,730	5,840

Figure 19
ANS 16.1 Leach Test Results for
Advanced Polymer Test #1
Page 45

Figure 20
ANS 16.1 Leach Test Results for
Advanced Polymer Test #2
Page 46

Nitrate to Ammonia and Ceramic Stabilization Study

4.4.4 High Alumina Cement

Two high alumina cement samples were prepared. The sodium data for both samples is reported in **Table 11**.

These samples did not set hard after 7 days of humidified curing. A slight degradation of samples was observed during leach testing. The final product had a soft, clay like consistency.

Figure 21 shows that for the first sample the effective diffusivity decreased over time to a minimum value of 3.80×10^{-6} cm/sec.

The initial concentration of sodium in this sample was 10,100 ppm sodium or 1.48 g. The total amount of sodium that leached out of the sample was 93% or 1.37 g.

Figure 22 illustrates the results for second high alumina cement sample. This sample also continued to leach sodium over time. The effective diffusivity of this sample over time had an average value of around 8.0×10^{-6} cm/sec.

The initial concentration of sodium in this sample was 9,450 ppm or 1.32 g. The total amount of sodium that leached out of the sample was 100% or 1.32 g.

4.5 TCLP Tests

4.5.1 Portland Cement

Results for full TCLP testing performed on the best waste loading (71%) are listed in **Table 12**. As illustrated in **Figure 23**, stabilization with Portland cement significantly reduced the leachable concentration of the RCRA constituents.

Table 11. High Alumina Cement ANS 16.1 Leach Results		
Sample	Sodium (ppm) Run #1	Sodium (ppm) Run #2
Solid Before ANS 16.1	10,100	9,450
Rinse	39.9	51.4
2 hrs	330	313
7 hrs	194	200
24 hrs	274	249
48 hrs	188	196
72 hrs	76.6	67.7
96 hrs	27.2	24.1
120 hrs	16.5	14.9
Solid After ANS 16.1	819	743

Figure 21
ANS 16.1 Leach Test Results for High
Alumina Cement Test #1
Page 48

Figure 22
ANS 16.1 Leach Test Results for High
Alumina Cement Test #2
Page 49

Figure 23
 Comparison of TCLP Leachate
 Concentrations - Portland Cement
 Stabilization versus Unstabilized NAC
 Solid Product
 Page 50

Table 12 . TCLP Leach Results for Portland Cement Waste Form, 71% Waste Loading

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitro- benzene	2,4,6Tri- chlorophenol	2,4-Dinitro- toluene
Raw NAC- TCLP	0.247	5.19	<0.02	7.48	0.144	<0.140	5.1	39.5	<0.04	40	<0.04
TCLP Limit	5	100	1	5	0.2	5	5	1	40	2	0.13
TCLP #1	<0.050	1.34	<0.020	1.09	0.0056	<0.140	0.365	8.22	<0.01	<0.01	<0.01
TCLP #2	<0.050	2.58	<0.020	1.38	0.0026	<0.140	<0.225	7.71	<0.01	<0.01	<0.01
TCLP Ave.	<0.050	1.96	<0.020	1.24	0.0041	<0.140	0.239 ^a	7.97	<0.01	<0.01	<0.01
PC w/Filtrate	<0.050	0.215	<0.020	2.58	0.0064	<0.140	1.67	16.8	<0.01	<0.01	<0.01

^a = average value determined using a 0.5 times "below detection limit" value (<0.225)

Values in **Bold** = exceeds TCLP Limit

Nitrate to Ammonia and Ceramic Stabilization Study

The formulation successfully reduced the leachability of the metal and organic RCRA constituents to below the TCLP limits, with the exception of selenium as shown in **Figure 24**. Although selenium was not stabilized to below the TCLP limit, an 80% reduction in selenium concentration was observed. For clarity, barium has been eliminated from this figure, however the TCLP leachable barium (1.96 ppm) was significantly below the TCLP limit (100 ppm).

Figure 25 shows that the use of filtrate as makeup water during stabilization may have increased the TCLP leachable concentrations of chromium, arsenic, and selenium and may have decreased the TCLP leachable barium. Only selenium was detected above the TCLP limit, however a 57% reduction in TCLP leachable selenium occurred in the raw NAC solid when stabilized using the filtrate liquid.

4.5.2 Sulfur Polymer Cement

Table 13 lists the TCLP results for the 50 % waste loading using sulfur polymer cement. **Figure 26** illustrates that sulfur polymer cement successfully reduced the TCLP leachable RCRA constituents with the exception of arsenic and barium, which slightly increased.

As shown in **Figure 27**, sulfur polymer cement successfully stabilized most RCRA constituents to below the TCLP limits. TCLP leachable selenium and 2,4,6-trichlorophenol were detected in concentrations higher than the TCLP limit, however, 97 and 87% reductions were detected, respectively, with the use of SPC. A 28% increase in arsenic concentration occurred upon SPC stabilization. The temperature required for sulfur polymer cement stabilization (135°C) would only partially account for the reduction observed in the 2,4,6-trichlorophenol; the boiling point for this compound is 249°C. Barium has been eliminated from this figure for clarity, however the TCLP leachable barium (12.13 ppm) was significantly below the TCLP limit (100 ppm).

4.5.3 Advanced Polymer

The TCLP results for stabilization of 30% waste loading of NAC solid product in advanced polymer are listed in **Table 14**. Both an increase and a decrease in TCLP leachability was observed in a few of the RCRA constituents as illustrated in **Figure 28**. Leachability for barium, cadmium and lead increased upon advanced polymer stabilization; leachability of other RCRA constituents decreased.

Figure 29, compares the advanced polymer stabilized NAC solid product to the TCLP limits. Only cadmium and selenium exceeded the limit. Barium results have been omitted from this figure for clarity however the 20.5 ppm barium detected in the advanced polymer stabilized NAC solid product was significantly lower than the 100 ppm barium limit.

4.5.4 High Alumina Cement

Table 15 lists the results of full TCLP testing performed on 50% waste loading using high alumina cement. **Figure 30** shows that the high alumina cement successfully stabilized a majority of the RCRA constituents. This reagent however had an adverse impact on barium and lead stabilization. Lead TCLP solubility increased upon high alumina cement stabilization. TCLP leachable barium increased 6.7 times

The temperature of the reaction using the advanced polymer (90°C) would only partially account for the reduction observed in the 2,4,6-trichlorophenol; the boiling point for this compound is 249°C.

in the stabilized waste form over the TCLP leachable concentration of the unstabilized NAC solid product. Barium has been eliminated from this figure for clarity.

Figure 24
TCLP Leachate Concentrations in
Portland Cement Stabilized Samples
Prepared with NAC Filtrate
Page 53

Figure 25
TCLP Leachate Concentrations - in
Portland Cement Stabilized Samples
Prepared with NAC Filtrate
Page 54

Figure 26
Comparison of TCLP Leachate
Concentrations - Sulfur Polymer
Cement Stabilization versus
Unstabilized NAC Solid Product
Page 55

Figure 27
TCLP Leachate Concentrations in
Sulfur Polymer Cement Stabilized
Samples
Page 56

Figure 28
 Comparison of TCLP Leachate
 Concentrations - Advanced Polymer
 Stabilization versus Unstabilized NAC
 Solid Product
 Page 57

Figure 29
TCLP Leachate Concentrations - in
Advanced Polymer Stabilized Samples
Page 58

Figure 30
 Comparison of TCLP Leachate
 Concentrations - High Alumina
 Cement Stabilization versus
 Unstabilized Also NAC Solid Product
 Page 59

Table 13. TCLP Leach Results for Sulfur Polymer Cement Waste Form, 5% Na₂S and 50% Waste Loading

Sample (ppm)	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitrobenzene	Trichlorophenol	Dinitrotoluene
Raw NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.140	5.1	39.5	<0.04	40	<0.04
TCLP Limit	5	100	1	5	0.2	5	5	1	40	2	0.13
TCLP #1	<0.050	5.56	0.022	<0.090	0.006	<0.140	7.71	1.38	<0.01	5.98	<0.01
TCLP #2	<0.050	18.7	<0.02	<0.090	0.004	<0.140	5.39	1.24	<0.01	4.15	<0.01
TCLP Ave	<0.050	12.13	^a 0.016	<0.090	0.005	<0.140	6.55	1.31	<0.01	5.07	<0.01

^a = average value determined using a 0.5 times "below detection limit" value (<0.020)

Table 14. TCLP Leach Results for Advanced Polymer Cement Waste Form, 30% Waste Loading

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitro-benzene	2,4,6-Trichlorophenol	2,4-Dinitrotoluene
Solid After NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.14	5.1	39.5	<0.04	40	<0.04
TCLP Limit	5	100	1	5	0.2	5	5	1	40	2	0.13
TCLP #1	0.089	21.4	1.16	0.185	0.098	2.14	0.723	2.42	<0.01	<0.01	<0.01
TCLP #1	0.072	19.6	1.31	0.318	0.080	1.50	0.852	2.04	<0.01	<0.01	<0.01
TCLP Ave.	0.081	20.5	1.24	0.252	0.089	1.82	0.788	2.23	<0.01	<0.01	<0.01

Table 15. TCLP Leach Results for High Alumina Cement Waste Form, 50% Waste Loading

Sample	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitro- benzene	2,4,6- Trichlorophenol	2,4-Dinitrotoluene
Solid After NAC-TCLP	0.247	5.19	<0.02	7.48	0.144	<0.1 4	5.1	39.5	<0.04	40	<0.04
TCLP Limit	5	100	1	5	0.2	5	5	1	40	2	0.13
Ca(OH) ₂ TCLP #1	0.075	74.7	<0.02	<0.09	0.045	33.4	<0.2	<0.3	<0.01	8.50	<0.01
Ca(OH) ₂ TCLP #2	0.066	70.2	<0.02	<0.09	0.034	30.9	<0.2	<0.3	<0.01	6.86	<0.01
TCLP Ave.	0.071	72.5	<0.02	<0.09	0.040	32.2	<0.2	<0.3	<0.01	7.68	<0.01
Ca(OH) ₂ w/Filtrate	<0.05	79.7	<0.02	<0.09	0.004	58.7	<0.2	0.43	<0.01	31.80	<0.01

Nitrate to Ammonia and Ceramic Stabilization Study

Although lead and barium leachability increased upon high alumina cement stabilization, all RCRA constituents were below the TCLP limits with the exception of lead and 2,4,6-trichlorophenol as shown in **Figure 31**. For clarity, barium has been eliminated from this figure; however the TCLP leachable barium (72.5 ppm) was below the TCLP limit (100 ppm). Although 2,4,6-trichlorophenol was not stabilized to below the TCLP limit, an 83% reduction in 2,4,6-trichlorophenol concentration was observed.

Figure 32 shows that the use of filtrate as makeup water during stabilization may have increased the TCLP leachable concentrations of barium, lead, and 2,4,6-trichlorophenol. However, only lead and 2,4,6-trichlorophenol were detected above the TCLP limit.

4.6 Comparison Among Stabilization Reagents

4.6.1 Waste Loading

The highest waste loading was the Portland cement matrix at a 71 % NAC solid product waste loading using 14 % Portland cement, 10 % type F flyash, and 5 % activated carbon. Both the sulfur polymer cement and high alumina cement had 50 % waste loadings. The sulfur polymer cement also had a 5 % Na_2S . The lowest waste loading was the advanced polymer with a 30 % NAC solid product waste loading.

4.6.2 TCLP Performance

Table 16 compares the TCLP performance (average of two tests for each reagent with the exception of the filtrate tests) for each stabilization reagent. Portland cement performed the best. Only selenium exceeded the TCLP limit. With the use of the filtrate obtained from the NAC process, the amount of TCLP leachable selenium doubled; all the other RCRA constituents remained below the TCLP limits.

The second best TCLP performance was obtained using the advanced polymer. Only cadmium and selenium were detected in concentrations higher than the TCLP limit. High alumina cement and sulfur polymer cement performed poorly. The sulfur cement had TCLP leachable concentrations of arsenic, selenium and 2,4,6-trichlorophenol slightly higher than the TCLP limit. The high alumina cement failed the TCLP requirements for lead and 2,4,6-trichlorophenol. The high concentration of TCLP leachable barium in the high alumina cement stabilized NAC solid product may also indicate a potential problem with this element.

4.6.3 Unconfined Compressive Strength Comparison

Unconfined compressive strength (UCS) test results are illustrated in **Figure 33**. No UCS molds were prepared for the advanced polymer. The highest compressive strength was obtained with Portland cement at 94.1 psi. The second highest compressive strength of 81.4 psi was obtained with the high alumina cement utilizing the NAC filtrate as makeup water. By comparison, the non-filtrate high alumina cement had the lowest strength of 16.1 psi.

The Portland cement with filtrate sample had a lower strength than the Portland cement alone. The Portland cement sample had the third highest strength at 64.1 psi. The sulfur polymer cement sample had the second from lowest strength at 41.7 psi.

Figure 31
 TCLP Leachate Concentrations in High
 Alumina Cement Stabilized Samples
 Page 63

Figure 32
TCLP Leachate Concentrations for
High Alumina Cement Stabilized
Samples Prepared With & Without
NAC Filtrate
Page 64

Figure 33
Comparison of Unconfined Compressive
Strength Results for Portland Cement, Sulfur
Polymer Cement & High Alumina Cement
Samples
Page 65

Table 16. Comparison of TCLP Results

Waste Form*	Concentration of RCRA Constituent in TCLP Leachate, ppm										
	Silver	Barium	Cadmium	Chromium	Mercury	Lead	Arsenic	Selenium	Nitrobenzene	2,4,6-Trichlorophenol	2,4-Dinitrotoluene
PCT, 71% W.L.	<0.05	1.96	<0.02	1.24	0.0041	<0.14	0.24	7.97	<0.01	<0.01	<0.01
SPC, 5% Na ₂ S + 50% W.L.	<0.05	12.1	0.016	<0.09	0.0052	<0.14	6.55	1.31	<0.01	5.07	<0.01
AP, 30% W.L.	0.081	20.5	1.24	0.25	0.089	1.82	0.79	2.23	<0.01	<0.01	<0.01
HAC, 50% W.L.	0.071	72.5	<0.02	<0.09	0.040	32.2	<0.23	<0.30	<0.01	7.68	<0.01
PC w/ Filtrate, 71% W.L.	<0.05	0.22	<0.02	2.58	0.0064	<0.14	1.67	16.8	<0.01	<0.01	<0.01
HAC w/ Filtrate, 50% W.L.	<0.05	79.7	<0.02	<0.09	0.0038	58.7	<0.22	0.427	<0.01	31.80	<0.01
TCLP Limit	5.0	100	1.0	5.0	0.2	5.0	5.0	1.0	40	2.0	0.13

** Bold/italic indicates those concentrations exceeding TCLP Limits

** PC = Portland cement, SPC = Sulfur polymer cement, AP = Advanced Polymer, HAC = High alumina cement

4.6.4   ANS 16.1 Sodium Leachability Comparison

Table 17 compares the sodium leach test data for all four stabilization reagents. The lowest (best) effective diffusivity, 6.00×10^{-8} cm/s, was obtained from the sulfur polymer cement stabilized NAC solid product. A total of 19% of the sodium leached out over the five day period. The advanced polymer was second best in effective diffusivity at 13.5×10^{-8} cm/s and 25% sodium leached. The next highest effective diffusivity was the Portland cement at 91.5×10^{-8} cm/s, 62% of the sodium leached from the stabilized waste. The high alumina cement had the highest effective diffusivity and the most sodium leached from the stabilized waste. During leach testing, 97% of the sodium leached for an effective diffusivity of 5.57×10^{-8} cm/s at day five. The amount of sodium leached from the waste forms ranged from 10,000 to 25,000 ppm.

Table 17. Comparison of ANS 16.1 Data

	Effective Diffusivity ($\times 10^{-8}$ cm/s) over time							Before Leach Test Sodium Conc. (ppm)	Cumulative Percent Leached
	2hr	7hr	24hr	48hr	72hr	96hr	120hr		
Portland Cement, 71% W.L.	112	105	99.6	90.5	86.9	90.8	91.5	6,750	62.4
SPC, 5% Na ₂ S + 50% W.L.	2.2	2.6	5.1	4.0	5.1	5.3	6.0	24,950	18.8
Advanced Polymer, 30% W.L.	0.9	7.0	8.9	6.7	8.9	9.0	13.5	10,820	25.3
High Alumina Cement, 50% W.L.	786	682	605	668	693	668	557	9,775	96.5

5.0 Summary

NAC solid product was solidified using four stabilization/solidification technologies. The solid product was spiked with large amounts of RCRA constituents to produce a matrix that would challenge these S/S technologies.

The NAC process alone successfully stabilized many RCRA constituents. Although spike concentrations were very high in the solid, only chromium, arsenic, selenium and 2,4,6-trichlorophenol were soluble to concentrations above the TCLP limits. The percent of each constituent that leached out of the NAC solid product was 7.54%, 5.86%, 42.7% and 240%, respectively (the later result is suspect, it is greater than typical method variability).

No one S/S technology was a clear leader in all test areas (unconfined compressive strength, TCLP, ANS 16.1 for sodium). The Portland cement blend and the Portland cement blend with filtrate from the NAC treatment were probably the overall best performers. The Portland cement blend had the highest waste loading, 71%, produced the highest unconfined compressive strength (94 psi) and had the best TCLP results (only selenium failed); but 62% of the sodium leached out over the 5 day ANS 16.1 leach. The Portland cement blend with filtrate produced an unconfined compressive strength of 64 psi and only selenium failed the TCLP. The ANS 16.1 leach test was not performed on this formulation.

The 50% sulfur polymer cement produced a product with an unconfined compressive strength of 42 psi. Arsenic, selenium and 2,4,6-trichlorophenol exceeded TCLP limits. Only 18% of the sodium leached out over the 5 day ANS 16.1 leach.

The 50% high alumina cement produced an unconfined compressive strength of 16 psi, the lowest measured in this study. When filtrate from the NAC treatment was used in the formulation, an unconfined compressive strength of 81 psi was achieved. Lead and 2,4,6-trichlorophenol exceeded TCLP limits. 97% of the sodium leached out over the 5 day ANS 16.1 leach.

The vinyl ester styrene formulation failed to produce a solid monolith. Waste loadings ranged from 30 to 67%. A second formulation using an "advanced polymer" supplied by Diversified Technologies produced an acceptable monolith for leach testing, however the wasteform dissolved during the TCLP extraction. An unconfined compressive strength was not measured because the sample "boiled over" and did not form a good monolith for UCS testing. At a 30% waste loading cadmium and selenium exceeded TCLP limits. A total of 25% of the sodium leached out over the 5 day ANS 16.1 leach.

Portland cement stabilization is inexpensive, the materials are readily available and the technology is mature. A recent comparison has been made between the technological and economic benefits of Portland cement, sulfur polymer cement and two other competing technologies⁷. Portland cement stabilization fared well. S/S with the portland cement blend

Nitrate to Ammonia and Ceramic Stabilization Study

decreased the leachability of metals and mobile ions such as sodium and provided moderate structural strength. As such Portland cement S/S should be an acceptable form of treatment for most solid NAC products. In some instances, where non-retained ions such as sodium are a concern or if selenium is present, additional pretreatment may be required to reduce leachability.

Additional areas which could be addressed to further the NAC technology are:

- 1) A review and summary of the high nitrate waste streams (DOE and non-DOE) which could benefit from the NAC treatment process. The summary should include a detailed listing of the constituents, salts, radionuclides, metals, organics, etc.
- 2) Studies on reducing the solubility of selenium and non-retained ions such as sodium.
- 3) A economic evaluation of the NAC process, including S/S using a Portland cement blend.

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Nitrate to Ammonia and Ceramic Stabilization Study

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Appendix A

Table A-1
Composition of ORNL Low-Level Liquid Waste
Melton Valley Storage Tank (MVST) Supernate
(Average composition of 10 tanks)

Volume = 830,000 L
 Density = 1.23 g/mL
 pH = 12.5

CONTAMINANT	CONCENTRATION	
	(g/L)	(Bq/L)
NITRATE	270	
SODIUM	88	
POTASSIUM	24	
CARBONATE	6.9	
CALCIUM	3.4	
CHLORIDE	2.9	
MAGNESIUM	0.7	
TOTAL ORGANIC CARBON	0.6	
URANIUM	0.2	
¹³⁷ Cs		4.8E8
⁹⁰ Sr		4.1E7
¹³⁴ Cs		5.0E6
⁶⁰ Co		3.4E6
¹⁰⁶ Ru		8.7E5
GROSS ALPHA		3.3E5
¹⁴ C		1.9E5

Source: M.B. Sears, et al., *Sampling and Analysis of Radioactive Liquid Wastes and Sludges in the Melton Valley and evaporator Facility Storage Tanks* at ORNL, ORNL/TM-11652, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, September 1990.

Nitrate to Ammonia and Ceramic Stabilization Study

Table A-2
Composition of SRP High-Level
Waste Tank Supernate
(Results from Tank No. 2, F-Area)

Volume = 380,000,000 L

Density = 1.41 g/mL

pH = 14.5

CONTAMINANT	CONCENTRATION	
	(g/L)	(Bq/L)
SODIUM	214	
NITRATE	149	
NITRITE	133	
HYDROXIDE	76.5	
ALUMINUM	18.9	
CARBONATE	<6.0	
PHOSPHATE	3.8	
CHLORIDE	2.1	
SULFATE	1.9	
CHROMIUM	0.2	
¹³⁷ Cs		1.3E11
¹³⁴ Cs		5.0E9
¹⁰⁶ Ru		2.3E9
⁹⁰ Sr		1.7E6
GROSS ALPHA		< 8.0E3

Source: R.S. Ondrejcin, *Chemical Compositions of Supernates Stored in SRP High Level Waste Tanks*, DP-1347/UC-70, E.I. duPont de Nemours & Co., Savannah River Laboratory, August 1974.

Table A-3
Composition of Hanford Plant
High-Level Waste Tank Supernate^a

Volume = 600,000,000 L
Density = 1.3 g/mL
pH = 14

CONTAMINANT	CONCENTRATION	
	(g/L)	(Bq/L)
NITRATE	183	
SODIUM	115	
HYDROXIDE	32	
NITRITE	23	
PHOSPHATE	8.0	
CARBONATE	3.9	
SULFATE	2.8	
TOTAL ORGANIC CARBON	2.6	
ALUMINUM	2.3	
POTASSIUM	1.8	
FLUORIDE	1.3	
CHLORIDE	0.06	
¹³⁷ Cs		9.4E8
⁹⁰ Sr		3.1E7
⁹⁹ Tc		9.4E5
²⁴¹ Am		2.5E5
²³⁹ Pu		2.5E4

^aVolume and concentration data is based on dissolving the existing solid salt cake and supernate into a 5 M sodium solution.

Source: *Final Environmental Impact Statement: Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes*, DOE/EIS-0113, December 1987.

Nitrate to Ammonia and Ceramic Stabilization Study

Table A-4
Composition of INEL
High-Level Waste Tank Supernate
(Results from Tank WM-183)

Volume = 7,500,000 L
Density = 1.22 g/mL
pH = 0.2

CONTAMINANT	CONCENTRATION	
	(g/L)	(Bq/L)
NITRATE	279	
SODIUM	17.9	
ALUMINUM	14.0	
POTASSIUM	3.9	
IRON	3.0	
HYDROGEN ION	1.8	
CALCIUM	1.6	
FLUORIDE	0.8	
CHROMIUM	0.7	
MERCURY	0.6	
¹³⁷ Cs		9.9E9
⁹⁰ Sr		8.2E9
¹⁵⁴ Eu, ¹⁵⁵ Eu		1.3E8
¹⁴⁴ Ce		8.7E7
⁶⁰ Co		1.8E6

Source: Chris Kent, Idaho National Engineering Laboratory, Idaho Falls, ID, personal communication to P.A. Taylor, Oak Ridge National Laboratory, Oak Ridge, Tenn., February 4, 1993.

Nitrate to Ammonia and Ceramic Stabilization Study

Table A-5
Composition of RFP
Nitrate Salt Waste

Volume = 23,000,000 L
Density = 1.01 g/mL
pH = acidic

CONTAMINANT	CONCENTRATION	
	(g/L)	(Bq/L)
NITRATE	3.1	
SODIUM	1.6	
CHLORIDE	1.4	
SULFATE	1.4	
POTASSIUM	1.1	
CARBONATE	0.7	
CALCIUM	0.5	
FLUORIDE	0.3	
IRON	0.3	
PLUTONIUM (TOTAL)		500

Source: A. Faucet, Rocky Flats Plant, Golden, Colorado, personal communication to P.A. Taylor, Oak Ridge National Laboratory, Oak Ridge, Tenn., March 24, 1993.

Appendix B

Sample Name: PC 1

Description: Portland Cement Test #1

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.10 cm
Initial Volume (Vo) 206.33 cm³
Initial Mass (Kg) 0.346 kg

Test Data

LC-2

LC-8

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.5	3.9	5.0	0.0050	0.0013	20.45	0.19	0.20	2.7
1.0	6.1	10.0	0.0100	0.0025	20.48	0.30	0.31	4.2
2.0	10.5	15.0	0.0150	0.0038	20.51	0.51	0.52	7.3
2.8	14.0	20.0	0.0200	0.0050	20.53	0.68	0.70	9.7
3.4	16.7	30.0	0.0300	0.0075	20.58	0.81	0.83	11.5
4.0	19.3	35.0	0.0350	0.0088	20.61	0.94	0.96	13.3
5.0	23.7	38.0	0.0380	0.0096	20.63	1.15	1.18	16.3
6.0	28.1	40.0	0.0400	0.0101	20.64	1.36	1.39	19.4
6.5	30.3	41.0	0.0410	0.0103	20.64	1.47	1.50	20.9
7.0	32.5	42.0	0.0420	0.0106	20.65	1.57	1.61	22.4
8.5	39.1	45.0	0.0450	0.0113	20.66	1.89	1.94	26.9
10.0	45.7	48.0	0.0480	0.0121	20.68	2.21	2.26	31.4
11.0	50.1	51.0	0.0510	0.0128	20.69	2.42	2.48	34.4
12.0	54.5	53.0	0.0530	0.0133	20.70	2.63	2.69	37.4
12.5	56.7	55.0	0.0550	0.0138	20.71	2.74	2.80	38.9
14.0	63.3	59.0	0.0590	0.0148	20.74	3.05	3.12	43.4
15.0	67.7	62.0	0.0620	0.0156	20.75	3.26	3.34	46.3
16.0	72.0	64.0	0.0640	0.0161	20.76	3.47	3.55	49.3
18.0	80.8	69.0	0.0690	0.0174	20.79	3.89	3.98	55.3
19.0	85.2	72.0	0.0720	0.0181	20.80	4.10	4.19	58.2
20.0	89.6	74.0	0.0740	0.0186	20.82	4.31	4.41	61.2
21.0	94.0	76.0	0.0760	0.0191	20.83	4.51	4.62	64.2
22.0	98.4	79.0	0.0790	0.0199	20.84	4.72	4.83	67.1
24.0	107.2	87.0	0.0870	0.0219	20.89	5.13	5.25	72.9
25.0	111.6	90.5	0.0905	0.0228	20.90	5.34	5.46	75.9
26.0	116.0	93.5	0.0935	0.0235	20.92	5.54	5.67	78.8
27.0	120.4	96.0	0.0960	0.0241	20.93	5.75	5.88	81.7
28.0	124.8	100.0	0.1000	0.0251	20.96	5.95	6.09	84.6
28.5	127.0	104.0	0.1040	0.0262	20.98	6.05	6.19	86.0
29.0	129.2	105.5	0.1055	0.0265	20.99	6.16	6.30	87.5
29.5	131.4	108.0	0.1080	0.0272	21.00	6.26	6.40	88.9
30.0	133.6	110.0	0.1100	0.0277	21.01	6.36	6.51	90.4
31.0	138.0	116.0	0.1160	0.0292	21.04	6.56	6.71	93.2
32.0	142.4	121.0	0.1210	0.0304	21.07	6.76	6.91	96.0
32.5	144.6	123.0	0.1230	0.0309	21.08	6.86	7.02	97.5
33.0	146.8	125.0	0.1250	0.0314	21.09	6.96	7.12	98.9
34.0	151.2	126.5	0.1265	0.0318	21.10	7.16	7.33	101.8
35.0	155.6	129.0	0.1290	0.0324	21.11	7.37	7.54	104.7
35.6	158.2	131.0	0.1310	0.0329	21.12	7.49	7.66	106.4

COMMENT:

Sample Name: PC 2

Description: Portland Cement Test #2

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.10 cm
Initial Volume (Vo) 206.33 cm³
Initial Mass (Kg) 0.341 kg

Test Data

LC-2 LC-8

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.5	3.9	5.0	0.0050	0.0013	20.45	0.19	0.20	2.7
1.0	6.1	9.0	0.0090	0.0023	20.47	0.30	0.31	4.2
1.5	8.3	13.0	0.0130	0.0033	20.50	0.41	0.42	5.8
2.0	10.5	15.0	0.0150	0.0038	20.51	0.51	0.52	7.3
2.5	12.7	17.0	0.0170	0.0043	20.52	0.62	0.63	8.8
3.0	14.9	18.0	0.0180	0.0045	20.52	0.73	0.74	10.3
3.5	17.1	20.0	0.0200	0.0050	20.53	0.83	0.85	11.8
4.0	19.3	21.0	0.0210	0.0053	20.54	0.94	0.96	13.4
5.0	23.7	25.0	0.0250	0.0063	20.56	1.15	1.18	16.4
6.0	28.1	27.0	0.0270	0.0068	20.57	1.37	1.40	19.4
7.0	32.5	30.0	0.0300	0.0075	20.58	1.58	1.62	22.4
8.0	36.9	32.0	0.0320	0.0080	20.59	1.79	1.83	25.5
9.0	41.3	34.0	0.0340	0.0086	20.60	2.00	2.05	28.5
10.0	45.7	35.5	0.0355	0.0089	20.61	2.22	2.27	31.5
11.0	50.1	38.0	0.0380	0.0096	20.63	2.43	2.48	34.5
12.0	54.5	39.5	0.0395	0.0099	20.63	2.64	2.70	37.5
13.0	58.9	42.0	0.0420	0.0106	20.65	2.85	2.92	40.5
14.0	63.3	44.0	0.0440	0.0111	20.66	3.06	3.13	43.5
15.0	67.7	46.0	0.0460	0.0116	20.67	3.27	3.35	46.5
16.0	72.0	48.0	0.0480	0.0121	20.68	3.48	3.57	49.5
17.0	76.4	49.5	0.0495	0.0124	20.69	3.70	3.78	52.5
18.0	80.8	51.5	0.0515	0.0130	20.70	3.91	4.00	55.5
19.0	85.2	53.0	0.0530	0.0133	20.70	4.12	4.21	58.5
20.0	89.6	55.0	0.0550	0.0138	20.71	4.33	4.43	61.5
21.0	94.0	57.0	0.0570	0.0143	20.73	4.54	4.64	64.5
22.0	98.4	60.0	0.0600	0.0151	20.74	4.75	4.86	67.4
22.5	100.6	61.0	0.0610	0.0153	20.75	4.85	4.96	68.9
23.0	102.8	64.0	0.0640	0.0161	20.76	4.95	5.07	70.4
23.5	105.0	65.0	0.0650	0.0163	20.77	5.06	5.17	71.9
24.0	107.2	66.0	0.0660	0.0166	20.77	5.16	5.28	73.3
25.0	111.6	70.0	0.0700	0.0176	20.79	5.37	5.49	76.3
25.5	113.8	74.0	0.0740	0.0186	20.82	5.47	5.59	77.7
26.0	116.0	76.0	0.0760	0.0191	20.83	5.57	5.70	79.2
26.5	118.2	80.0	0.0800	0.0201	20.85	5.67	5.80	80.6
27.0	120.4	85.0	0.0850	0.0214	20.87	5.77	5.90	82.0
27.3	121.7	90.0	0.0900	0.0226	20.90	5.82	5.96	82.8
27.3	121.7	95.0	0.0950	0.0239	20.93	5.82	5.95	82.6
27.3	121.7	100.0	0.1000	0.0251	20.96	5.81	5.94	82.5
26.5	118.2	105.0	0.1050	0.0264	20.98	5.63	5.76	80.1
26.0	116.0	110.0	0.1100	0.0277	21.01	5.52	5.65	78.5
25.0	111.6	115.0	0.1150	0.0289	21.04	5.31	5.43	75.4
20.0	89.6	130.0	0.1300	0.0327	21.12	4.24	4.34	60.3

COMMENT:

Sample Name: PCF 1

Description: Portland Cement with filtrate Test #1

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.10 cm
Initial Volume (Vo) 206.33 cm³
Initial Mass (Kg) 0.362 kg

Test Data

LC-2		LC-8						
Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.5	3.9	5.0	0.0050	0.0013	20.45	0.19	0.20	2.7
1.0	6.1	8.0	0.0080	0.0020	20.47	0.30	0.31	4.3
1.3	7.4	10.0	0.0100	0.0025	20.48	0.36	0.37	5.2
1.5	8.3	12.0	0.0120	0.0030	20.49	0.41	0.42	5.8
1.8	9.6	15.0	0.0150	0.0038	20.51	0.47	0.48	6.7
2.0	10.5	18.0	0.0180	0.0045	20.52	0.51	0.52	7.3
2.5	12.7	20.0	0.0200	0.0050	20.53	0.62	0.63	8.8
3.0	14.9	22.0	0.0220	0.0055	20.54	0.73	0.74	10.3
3.5	17.1	24.0	0.0240	0.0060	20.55	0.83	0.85	11.8
4.0	19.3	26.0	0.0260	0.0065	20.56	0.94	0.96	13.3
4.5	21.5	27.0	0.0270	0.0068	20.57	1.05	1.07	14.9
5.0	23.7	28.0	0.0280	0.0070	20.57	1.15	1.18	16.4
5.5	25.9	30.0	0.0300	0.0075	20.58	1.26	1.29	17.9
6.0	28.1	31.5	0.0315	0.0079	20.59	1.36	1.40	19.4
6.5	30.3	33.0	0.0330	0.0083	20.60	1.47	1.50	20.9
7.0	32.5	35.0	0.0350	0.0088	20.61	1.58	1.61	22.4
7.5	34.7	36.0	0.0360	0.0091	20.61	1.68	1.72	23.9
8.0	36.9	37.0	0.0370	0.0093	20.62	1.79	1.83	25.4
8.5	39.1	38.0	0.0380	0.0096	20.63	1.90	1.94	26.9
9.0	41.3	40.0	0.0400	0.0101	20.64	2.00	2.05	28.4
10.0	45.7	42.0	0.0420	0.0106	20.65	2.21	2.26	31.4
11.0	50.1	44.0	0.0440	0.0111	20.66	2.42	2.48	34.4
12.0	54.5	46.0	0.0460	0.0116	20.67	2.64	2.70	37.5
13.0	58.9	48.0	0.0480	0.0121	20.68	2.85	2.91	40.5
14.0	63.3	51.0	0.0510	0.0128	20.69	3.06	3.13	43.4
15.0	67.7	54.0	0.0540	0.0136	20.71	3.27	3.34	46.4
16.0	72.0	56.0	0.0560	0.0141	20.72	3.48	3.56	49.4
17.0	76.4	58.0	0.0580	0.0146	20.73	3.69	3.77	52.4
18.0	80.8	62.0	0.0620	0.0156	20.75	3.90	3.99	55.4
19.0	85.2	65.0	0.0650	0.0163	20.77	4.10	4.20	58.3
20.0	89.6	71.0	0.0710	0.0179	20.80	4.31	4.41	61.2
20.5	91.8	75.0	0.0750	0.0189	20.82	4.41	4.51	62.7
20.7	92.7	80.0	0.0800	0.0201	20.85	4.45	4.55	63.2
21.0	94.0	90.0	0.0900	0.0226	20.90	4.50	4.60	63.9
21.1	94.5	95.0	0.0950	0.0239	20.93	4.51	4.62	64.1
21.1	94.5	100.0	0.1000	0.0251	20.96	4.51	4.61	64.1
21.1	94.5	105.0	0.1050	0.0264	20.98	4.50	4.61	64.0
21.1	94.5	110.0	0.1100	0.0277	21.01	4.50	4.60	63.9
21.0	94.0	115.0	0.1150	0.0289	21.04	4.47	4.57	63.5
20.5	91.8	123.0	0.1230	0.0309	21.08	4.36	4.46	61.9
19.0	85.2	130.0	0.1300	0.0327	21.12	4.04	4.13	57.4
16.0	72.0	140.0	0.1400	0.0352	21.17	3.40	3.48	48.4
8.0	36.9	170.0	0.1700	0.0428	21.34	1.73	1.77	24.6
6.5	30.3	200.0	0.2000	0.0503	21.51	1.41	1.44	20.0

COMMENT:

Sample Name:

SPC 1

Description:

Sulfur Polymer Cement Test #1

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do)	5.10	cm
Initial Area (Ao)	20.43	cm ²
Initial Height (Ho)	9.20	cm
Initial Volume (Vo)	187.94	cm ³

Test Data

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.1	2.2	4.0	0.0040	0.0011	20.45	0.11	0.11	1.5
0.5	3.9	9.0	0.0090	0.0025	20.48	0.19	0.20	2.7
1.0	6.1	15.0	0.0150	0.0041	20.51	0.30	0.31	4.2
2.0	10.5	22.0	0.0220	0.0061	20.55	0.51	0.52	7.3
2.5	12.7	25.0	0.0250	0.0069	20.57	0.62	0.63	8.8
3.0	14.9	26.0	0.0260	0.0072	20.58	0.72	0.74	10.3
4.0	19.3	30.0	0.0300	0.0083	20.60	0.94	0.96	13.3
4.5	21.5	30.5	0.0305	0.0084	20.60	1.04	1.07	14.8
5.0	23.7	34.0	0.0340	0.0094	20.62	1.15	1.18	16.3
6.0	28.1	37.5	0.0375	0.0104	20.64	1.36	1.39	19.3
7.0	32.5	43.0	0.0430	0.0119	20.67	1.57	1.61	22.3
8.0	36.9	51.0	0.0510	0.0141	20.72	1.78	1.82	25.3
8.3	38.2	53.0	0.0530	0.0146	20.73	1.84	1.89	26.2
9.0	41.3	57.0	0.0570	0.0157	20.75	1.99	2.04	28.3
10.0	45.7	61.0	0.0610	0.0168	20.78	2.20	2.25	31.2
11.0	50.1	63.0	0.0630	0.0174	20.79	2.41	2.46	34.2
11.5	52.3	64.0	0.0640	0.0177	20.80	2.51	2.57	35.7
12.0	54.5	65.0	0.0650	0.0179	20.80	2.62	2.68	37.2
12.5	56.7	66.0	0.0660	0.0182	20.81	2.72	2.79	38.7
12.7	57.4	66.0	0.0660	0.0182	20.81	2.76	2.82	39.2
12.9	58.2	67.0	0.0670	0.0185	20.81	2.80	2.86	39.7

COMMENT:

Sample Name:

SPC 2

Description:

Sulfur Polymer Cement Test #2

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do)	5.10	cm
Initial Area (Ao)	20.43	cm ²
Initial Height (Ho)	9.40	cm
Initial Volume (Vo)	192.03	cm ³

Test Data

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.3	3.0	6.0	0.0060	0.0016	20.46	0.15	0.15	2.1
0.7	4.8	9.0	0.0090	0.0024	20.48	0.23	0.24	3.3
1.0	6.1	10.0	0.0100	0.0027	20.48	0.30	0.31	4.2
1.5	8.3	11.0	0.0110	0.0030	20.49	0.41	0.42	5.8
2.0	10.5	13.0	0.0130	0.0035	20.50	0.51	0.52	7.3
2.5	12.7	13.5	0.0135	0.0036	20.50	0.62	0.63	8.8
3.5	17.1	15.0	0.0150	0.0041	20.51	0.83	0.85	11.9
4.0	19.3	15.0	0.0150	0.0041	20.51	0.94	0.96	13.4
4.5	21.5	16.0	0.0160	0.0043	20.52	1.05	1.07	14.9
5.0	23.7	16.0	0.0160	0.0043	20.52	1.16	1.18	16.4
6.0	28.1	17.0	0.0170	0.0046	20.52	1.37	1.40	19.5
7.0	32.5	18.0	0.0180	0.0049	20.53	1.58	1.62	22.5
8.0	36.9	20.0	0.0200	0.0054	20.54	1.80	1.84	25.5
9.0	41.3	21.0	0.0210	0.0057	20.54	2.01	2.06	28.6
10.0	45.7	22.0	0.0220	0.0059	20.55	2.22	2.27	31.6
11.0	50.1	22.0	0.0220	0.0059	20.55	2.44	2.49	34.6
11.5	52.3	23.0	0.0230	0.0062	20.56	2.54	2.60	36.1
12.5	56.7	23.0	0.0230	0.0062	20.56	2.76	2.82	39.2
12.8	58.0	23.5	0.0235	0.0064	20.56	2.82	2.89	40.1
13.0	58.9	24.0	0.0240	0.0065	20.56	2.86	2.93	40.7
13.5	61.1	24.5	0.0245	0.0066	20.56	2.97	3.04	42.2
14.0	63.3	24.5	0.0245	0.0066	20.56	3.08	3.15	43.7

COMMENT:

Sample Name: CaOH1

Description: CaOH Test #1

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.20 cm
Initial Volume (Vo) 208.37 cm³
Weight 0.230 kg

Test Data

LC-2

LC-8

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.3	3.0	5.0	0.0050	0.0012	20.45	0.15	0.15	2.1
0.5	3.9	10.0	0.0100	0.0025	20.48	0.19	0.20	2.7
0.7	4.8	15.0	0.0150	0.0037	20.50	0.23	0.24	3.3
0.9	5.7	20.0	0.0200	0.0050	20.53	0.28	0.28	3.9
1.1	6.6	25.0	0.0250	0.0062	20.56	0.32	0.33	4.5
1.4	7.9	30.0	0.0300	0.0075	20.58	0.38	0.39	5.4
2.2	11.4	40.0	0.0400	0.0100	20.63	0.55	0.57	7.8
2.5	12.7	44.0	0.0440	0.0110	20.65	0.62	0.63	8.7
3.0	14.9	50.0	0.0500	0.0125	20.69	0.72	0.74	10.2
3.7	18.0	60.0	0.0600	0.0149	20.74	0.87	0.89	12.3
4.0	19.3	64.0	0.0640	0.0159	20.76	0.93	0.95	13.2
4.4	21.1	70.0	0.0700	0.0174	20.79	1.01	1.04	14.4
4.7	22.4	80.0	0.0800	0.0199	20.84	1.07	1.10	15.3
5.0	23.7	84.0	0.0840	0.0209	20.86	1.14	1.16	16.1
5.2	24.6	90.0	0.0900	0.0224	20.90	1.18	1.20	16.7
5.3	25.0	100.0	0.1000	0.0249	20.95	1.19	1.22	17.0
5.3	25.0	110.0	0.1100	0.0274	21.00	1.19	1.22	16.9
5.2	24.6	115.0	0.1150	0.0286	21.03	1.17	1.20	16.6
4.8	22.8	120.0	0.1200	0.0299	21.06	1.08	1.11	15.4
4.1	19.7	125.0	0.1250	0.0311	21.08	0.94	0.96	13.3
3.0	14.9	138.0	0.1380	0.0344	21.16	0.70	0.72	10.0
2.6	13.2	150.0	0.1500	0.0374	21.22	0.62	0.63	8.8
2.3	11.8	200.0	0.2000	0.0498	21.50	0.55	0.56	7.8

COMMENT:

Sample Name: CaOH2

Description: CaOH Test #2

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.20 cm
Initial Volume (Vo) 208.37 cm³
Weight 0.230 kg

Test Data

LC-2

LC-8

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.5	3.9	5.0	0.0050	0.0012	20.45	0.19	0.20	2.7
0.8	5.2	10.0	0.0100	0.0025	20.48	0.26	0.26	3.6
1.1	6.6	15.0	0.0150	0.0037	20.50	0.32	0.33	4.5
1.4	7.9	20.0	0.0200	0.0050	20.53	0.38	0.39	5.5
1.6	8.8	25.0	0.0250	0.0062	20.56	0.43	0.44	6.1
2.0	10.5	30.0	0.0300	0.0075	20.58	0.51	0.52	7.3
2.5	12.5	40.0	0.0400	0.0100	20.63	0.61	0.62	8.6
2.2	11.4	44.0	0.0440	0.0110	20.65	0.55	0.56	7.8
3.0	14.9	50.0	0.0500	0.0125	20.69	0.72	0.74	10.2
3.5	17.1	60.0	0.0600	0.0149	20.74	0.83	0.84	11.7
3.7	18.0	64.0	0.0640	0.0159	20.76	0.87	0.89	12.3
4.2	20.2	70.0	0.0700	0.0174	20.79	0.97	0.99	13.8
4.6	21.9	80.0	0.0800	0.0199	20.84	1.05	1.08	15.0
4.6	21.9	84.0	0.0840	0.0209	20.86	1.05	1.08	14.9
4.7	22.4	90.0	0.0900	0.0224	20.90	1.07	1.10	15.2
4.7	22.4	100.0	0.1000	0.0249	20.95	1.07	1.09	15.2
4.7	22.4	110.0	0.1100	0.0274	21.00	1.07	1.09	15.1
4.3	20.6	115.0	0.1150	0.0286	21.03	0.98	1.00	13.9
3.9	18.9	120.0	0.1200	0.0299	21.06	0.90	0.92	12.7
3.7	18.0	125.0	0.1250	0.0311	21.08	0.85	0.87	12.1
3.6	17.6	138.0	0.1380	0.0344	21.16	0.83	0.85	11.8
3.6	17.6	150.0	0.1500	0.0374	21.22	0.83	0.85	11.8
3.5	16.9	200.0	0.2000	0.0498	21.50	0.79	0.80	11.2

COMMENT:

Sample Name: CaOH-F1

Description: CaOH with Filtrate Test #1

Unconfined Compressive Strength

Initial Data

Initial Diameter (Do) 5.10 cm
Initial Area (Ao) 20.43 cm²
Initial Height (Ho) 10.20 cm
Initial Volume (Vo) 208.37 cm³
Weight 0.230 kg

Test Data

LC-2

LC-8

Load Dial in 0.0001"	Axial Load in kg	Strain Dial in 0.001"	Total Strain in inches	Unit Strain	Corrected Area cm ²	Stress kg/cm ²	Stress ton/ft ²	Stress psi
0.0	1.7	0.0	0.0000	0.0000	20.43	0.00	0.00	0.0
0.5	3.9	5.0	0.0050	0.0012	20.45	0.19	0.20	2.7
1.3	7.4	10.0	0.0100	0.0025	20.48	0.36	0.37	5.2
1.9	10.1	15.0	0.0150	0.0037	20.50	0.49	0.50	7.0
3.6	17.6	20.0	0.0200	0.0050	20.53	0.85	0.87	12.1
5.0	23.7	24.0	0.0240	0.0060	20.55	1.15	1.18	16.4
6.0	28.1	25.0	0.0250	0.0062	20.56	1.37	1.40	19.4
7.0	32.5	26.0	0.0260	0.0065	20.56	1.58	1.62	22.5
8.3	38.2	28.0	0.0280	0.0070	20.57	1.86	1.90	26.4
9.0	41.3	28.0	0.0280	0.0070	20.57	2.01	2.05	28.5
10.0	45.7	29.0	0.0290	0.0072	20.58	2.22	2.27	31.5
10.5	47.9	31.0	0.0310	0.0077	20.59	2.33	2.38	33.0
11.0	50.1	32.0	0.0320	0.0080	20.59	2.43	2.49	34.6
12.0	54.5	35.0	0.0350	0.0087	20.61	2.64	2.70	37.6
13.0	58.9	34.0	0.0340	0.0085	20.60	2.86	2.92	40.6
13.8	62.4	38.0	0.0380	0.0095	20.62	3.02	3.09	43.0
14.5	65.5	40.0	0.0400	0.0100	20.63	3.17	3.25	45.1
15.0	67.7	40.0	0.0400	0.0100	20.63	3.28	3.35	46.6
16.0	72.0	42.0	0.0420	0.0105	20.64	3.49	3.57	49.6
17.0	76.4	43.0	0.0430	0.0107	20.65	3.70	3.79	52.6
18.0	80.8	45.0	0.0450	0.0112	20.66	3.91	4.00	55.6
19.0	85.2	47.0	0.0470	0.0117	20.67	4.12	4.22	58.6
20.0	89.6	49.0	0.0490	0.0122	20.68	4.33	4.43	61.6
21.0	94.0	52.0	0.0520	0.0129	20.70	4.54	4.65	64.6
21.3	95.3	57.0	0.0570	0.0142	20.72	4.60	4.71	65.4
22.0	98.4	67.0	0.0670	0.0167	20.77	4.74	4.85	67.3
23.0	102.8	74.0	0.0740	0.0184	20.81	4.94	5.05	70.2
24.0	107.2	80.0	0.0800	0.0199	20.84	5.14	5.26	73.1
25.0	111.6	87.0	0.0870	0.0217	20.88	5.34	5.47	76.0
25.6	114.2	96.0	0.0960	0.0239	20.93	5.46	5.59	77.6
26.0	116.0	106.0	0.1060	0.0264	20.98	5.53	5.66	78.6
26.5	118.2	115.0	0.1150	0.0286	21.03	5.62	5.75	79.9
27.1	120.8	126.0	0.1260	0.0314	21.09	5.73	5.86	81.4
20.0	89.6	140.0	0.1400	0.0349	21.17	4.23	4.33	60.2

COMMENT:

Appendix C

Portland Cement #1								
Dynamic Leaching Test ANSI 16.1								
(Note: Use these calcs. if $\text{Sum}\{a(n)\} > 0.2$)			Cylinder					
			Length, (cm)	5.70				
Species: Na			Diameter, (cm)	5.10		len./dia. =	1.12	
			Volume, (cm	116.38				
			Sample Wt.(k	0.20				
			Surface, (cm	132.18				
Leachate Volume, (L)	1.32		V/S Ratio	0.88				
			[V/S]^2, (cm2	0.78				
Rinse Vol. (L)	1.44							
Rinse Conc. (mg/L)	72.30	Pi =	3.14					
A(o){subsample}(mg/k	17,400							
Adjusted A(o), (mg)	3,296				A(o) is taken from a subsample unrinsed			
Final conc. (mg/kg)	6,190				Adjusted A(o) takes subsample A(o) and removes rinse conc.			
Final wt. (kg)	0.183							
Leach				Leachate				
Interval	del t, hr	Cum. t, hr	Cum. t, sec	Conc. (mg/L)			A(n), (mg)	A(n)/A(o)
1	2	2	7,200	343			453.10	0.14
2	5	7	25,200	264			348.74	0.11
3	17	24	86,400	384			507.26	0.15
4	24	48	172,800	256			338.18	0.10
5	24	72	259,200	185			244.39	0.07
6	24	96	345,600	163			215.32	0.07
7	24	120	432,000	122			161.16	0.05
						sum	2,268.16	
Cumulative			Effective	Cum.		mass bal	104.86	
Fraction			Diffusivity	Percent				
Leached	1/t	"G"	(cm/s)	Leached				
0.14	1.39E-04		1.60E-06	13.75	Note: this eff. diff. uses other formula for $\text{sum } a(n) < 0.2$			
0.24	3.97E-05	1.48E-03	1.53E-06	24.33	Note: "G" from procedure charts			
0.40	1.16E-05	4.70E-03	1.41E-06	39.72				
0.50	5.79E-06	8.10E-03	1.22E-06	49.98				
0.57	3.86E-06	1.14E-02	1.14E-06	57.39				
0.64	2.89E-06	1.56E-02	1.17E-06	63.92				
0.69	2.31E-06	1.95E-02	1.17E-06	68.81				

Portland Cement #2									
Dynamic Leaching Test ANSI 16.1									
(Note: Use these calcs. if Sum{a(n)} > 0.2)			Cylinder						
			Length, (cm)	5.7					
Species: Na			Diameter, (cm)	5.1		len./dia. =	1.12		
			Volume, (cm)	116.38					
			Sample Wt. (kg)	0.193					
			Surface, (cm)	132.18					
Leachate Volume, (L)	1.321		V/S Ratio	0.88					
			[V/S]^2, (cm ²)	0.78					
Rinse Vol. (L)	1.437								
Rinse Conc. (mg/L)	48	Pi =	3.14						
A(o){subsample} (mg/kg)	16,100								A(o) is ta
Adjusted A(o), (mg)	3,045								Adjusted
Final conc. (mg/kg)	9,860								
Final wt. (kg)	0.193								
Leach				Leachate					
Interval	del t, hr	Cum. t, hr	Cum. t, sec	Conc. (mg/L)			A(n), (mg)	A(n)/A(o)	
1	2	2	7,200	202			266.84	0.09	
2	5	7	25,200	164			216.64	0.07	
3	17	24	86,400	259			342.14	0.11	
4	24	48	172,800	224			295.90	0.10	
5	24	72	259,200	163			215.32	0.07	
6	24	96	345,600	157			207.40	0.07	
7	24	120	432,000	121			159.84	0.05	
						sum	1,704.09		
Cumulative			Effective	Cum.		mass bal	562.31		
Fraction			Diffusivity	Percent					
Leached	1/t	"G"	(cm/s)	Leached					
0.09	1.39E-04		6.50E-07	8.76		Note: this eff. diff. uses other formula for sum a{n} < 0.			
0.16	3.97E-05		5.65E-07	15.88		Note: this eff. diff. uses other formula for sum a{n} < 0.			
0.27	1.16E-05	1.92E-03	5.78E-07	27.12		Note: "G" from procedure charts			
0.37	5.79E-06	3.92E-03	5.90E-07	36.83					
0.44	3.86E-06	5.91E-03	5.93E-07	43.91					
0.51	2.89E-06	8.52E-03	6.41E-07	50.72					
0.56	2.31E-06	1.09E-02	6.56E-07	55.97					

Sulfur Polymer Cement #1							
Dynamic Leaching Test ANSI 16.1							
(Note: Use these calcs. if $\text{Sum}\{a(n)\} < 0.2$)			Cylinder				
			Length, (cm)	4.3			
Species: Na			Diameter, (cm)	5.1			
			Volume, (cm ³)	87.80			
			Sample Wt. (k)	0.166			
			Surface, (cm ²)	109.75			
Leachate Volume, (L)	1.098		V/S Ratio	0.80			
			[V/S] ² , (cm ²)	0.64			
Rinse Vol. (L)	1						
Rinse Conc. (mg/L)	23.60	Pi =	3.1416				
A(o){subsample}(mg/k)	23,900				A(o) is taken from a subsample unrinsed		
Adjusted A(o), (mg)	3,943.8				Adjusted A(o) takes subsample A(o) and removes rins		
Final conc. (mg/kg)	17,800						
Final wt. (kg)	0.166						
Leach					Leachate		
Interval	del T, hr	Cum. T, hr	Cum. T, sec	T	Conc. (mg/L)	A(n), (mg)	A(n)/A(o)
1	2	2	7200	1,800	58.96	64.74	0.0164
2	5	7	25200	14,835	60.94	66.91	0.0170
3	17	24	86400	51,231	156.20	171.51	0.0435
4	24	48	172800	125,894	118.80	130.44	0.0331
5	24	72	259200	213,818	112.20	123.20	0.0312
6	24	96	345600	300,849	94.49	103.75	0.0263
7	24	120	432000	387,596	89.54	98.31	0.0249
					sum	758.86	
Cumulative		Effective	Interval		Cum.	mass bal	(230.14)
Fraction		Diffusivity	Leach	Average	Percent		
Leached	1/del T(n)	(cm/s)	Index	LI	Leached		
0.0164	1.39E-04	1.88E-08	7.73	7.73	1.64		
0.0334	5.56E-05	2.65E-08	7.58	7.65	3.34		
0.0769	1.63E-05	5.20E-08	7.28	7.53	7.69		
0.1099	1.16E-05	3.71E-08	7.43	7.50	10.99		
0.1412	1.16E-05	5.62E-08	7.25	7.45	14.12		
0.1675	1.16E-05	5.61E-08	7.25	7.42	16.75		
0.1924	1.16E-05	6.49E-08	7.19	7.39	19.24		

Sulfur Polymer Cement #2							
Dynamic Leaching Test ANSI 16.1							
(Note: Use these calcs. if $\text{Sum}\{a(n)\} < 0.2$)			Cylinder				
			Length, (cm)	4.7			
Species: Na			Diameter, (cm)	5.1			
			Volume, (cm ³)	95.96			
			Sample Wt. (k)	0.175			
			Surface, (cm ²)	116.16			
Leachate Volume, (L)	1.16		V/S Ratio	0.83			
			[V/S] ² , (cm ²)	0.68			
Rinse Vol. (L)	1						
Rinse Conc. (mg/L)	26.5	Pi =	3.1416				
A(o){subsample}(mg/k)	26,000						
Adjusted A(o), (mg)	4,523.5				A(o) is taken from a subsample unrinsed		
Final conc. (mg/kg)	19,700				Adjusted A(o) takes subsample A(o) and removes rin		
Final wt. (kg)	0.175						
Leach					Leachate		
Interval	del T, hr	Cum. T, hr	Cum. T, sec	T	Conc. (mg/L)	A(n), (mg)	A(n)/A(o)
1	2	2	7200	1,800	70.56	81.85	0.0181
2	5	7	25200	14,835	62.92	72.99	0.0161
3	17	24	86400	51,231	161.70	187.57	0.0415
4	24	48	172800	125,894	133.10	154.40	0.0341
5	24	72	259200	213,818	105.82	122.75	0.0271
6	24	96	345600	300,849	92.84	107.69	0.0238
7	24	120	432000	387,596	86.79	100.68	0.0223
					sum	827.93	
Cumulative		Effective	Interval		Cum.	mass bal	(248.1)
Fraction		Diffusivity	Leach	Average	Percent		
Leached	1/del T(n)	(cm/s)	Index	LI	Leached		
0.01809	1.39E-04	2.44E-08	7.61	7.61	1.81		
0.03423	5.56E-05	2.56E-08	7.59	7.60	3.42		
0.01738	1.63E-05	5.04E-08	7.30	7.50	7.57		
0.10983	1.16E-05	4.21E-08	7.38	7.47	10.98		
0.13696	1.16E-05	4.52E-08	7.34	7.44	13.70		
0.16077	1.16E-05	4.90E-08	7.31	7.42	16.08		
0.18303	1.16E-05	5.51E-08	7.26	7.40	18.30		

Advanced Polymer #1									
Dynamic Leaching Test ANSI 16.1									
(Note: Use these calcs. if $\text{Sum}\{a(n)\} > 0.2$)				Cylinder					
				Length, (cm)	4.0				
Species: Na				Diameter, (cm)	5.1	len./dia. =	0.78		
				Volume, (cm)	81.67				
				Sample Wt. (g)	0.113				
				Surface, (cm)	104.95				
Leachate Volume, (L)	1.05			V/S Ratio	0.78				
				$[V/S]^2, (\text{cm}^2)$	0.61				
Rinse Vol. (L)	1.132								
Rinse Conc. (mg/L)	0	Pi =	3.14						
A(o){subsample}(mg/	11,700								
Adjusted A(o), (mg)	1,322					A(o) is taken from a subsample unrinsed			
Final conc. (mg/kg)	8730					Adjusted A(o) takes subsample A(o) and removes rins			
Final wt. (kg)	0.133								
Leach				Leachate					
Interval	del t, hr	Cum. t, hr	Cum. t, sec	onc. (mg/L)			A(n), (mg)	A(n)/A(o)	
1	2	2	7,200	14.8			15.54	0.01	
2	5	7	25,200	39.3			41.27	0.03	
3	17	24	86,400	79.5			83.48	0.06	
4	24	48	172,800	61.5			64.58	0.05	
5	24	72	259,200	54.5			57.23	0.04	
6	24	96	345,600	48.4			50.82	0.04	
7	24	120	432,000	63.3			66.47	0.05	
						sum	379.37		
Cumulative			Effective	Cum.		mass bal	218.36		
Fraction			Diffusivity	Percent					
Leached	1/t	"G"	(cm/s)	Leached					
0.01	1.39E-04		9.13E-09	1.18	Note: this eff. diff. uses other formula				
0.04	3.97E-05		8.49E-08	4.30	Note: this eff. diff. uses other formula				
0.11	1.16E-05		1.04E-07	10.61	Note: this eff. diff. uses other formula				
0.15	5.79E-06		7.65E-08	15.49	Note: this eff. diff. uses other formula				
0.20	3.86E-06		1.02E-07	19.82	Note: this eff. diff. uses other formula				
0.24	2.89E-06	1.48E-03	1.11E-07	23.67	Note: "G" from procedure charts				
0.29	2.31E-06	2.25E-03	1.35E-07	28.69					

Advanced Polymer #2									
Dynamic Leaching Test ANSI 16.1									
(Note: Use these calcs. if $\text{Sum}\{a(n)\} > 0.2$)				Cylinder					
				Length, (cm)	4.0				
Species: Na				Diameter, (cm)	5.1	len./dia. =	0.78		
				Volume, (cm ³)	81.67				
				Sample Wt. (kg)	0.113				
				Surface, (cm ²)	104.95				
Leachate Volume, (L)	1.05			V/S Ratio	0.78				
				[V/S] ² , (cm ²)	0.61				
Rinse Vol. (L)	1.132								
Rinse Conc. (mg/L)	0	PI =	3.14						
A(o){subsample} (mg/kg)	9,940								
Adjusted A(o), (mg)	1,123					A(o) is taken from a subsample unrinsed			
Final conc. (mg/kg)	5840					Adjusted A(o) takes subsample A(o) and removes rinse conc.			
Final wt. (kg)	0.133								
Leach				Leachate					
Interval	del t, hr	Cum. t, hr	Cum. t, sec	Conc. (mg/L)			A(n), (mg)	A(n)/A(o)	
1	2	2	7,200	12.2			12.81	0.01	
2	5	7	25,200	26.8			28.14	0.03	
3	17	24	86,400	57.4			60.27	0.05	
4	24	48	172,800	44.9			47.15	0.04	
5	24	72	259,200	39.7			41.69	0.04	
6	24	96	345,600	31.8			33.39	0.03	
7	24	120	432,000	21.5			22.58	0.02	
						sum	246.02		
Cumulative			Effective	Cum.		mass bal	(100.49)		
Fraction			Diffusivity	Percent					
Leached	1/t	"G"	(cm/s)	Leached					
0.01	1.39E-04		8.59E-09	1.14	Note: this eff. diff. uses other formula				
0.04	3.97E-05		5.47E-08	3.65	Note: this eff. diff. uses other formula				
0.09	1.16E-05		7.49E-08	9.01	Note: this eff. diff. uses other formula				
0.13	5.79E-06		5.65E-08	13.21	Note: this eff. diff. uses other formula				
0.17	3.86E-06		7.51E-08	16.92	Note: this eff. diff. uses other formula				
0.20	2.89E-06		6.78E-08	19.89	Note: this eff. diff. uses other formula				
0.22	2.31E-06	1.23E-03	1.35E-07	21.90	Note: "G" from procedure charts				

High Alumina Cement #1									
Dynamic Leaching Test ANSI 16.1									
(Note: Use these calcs. if $\text{Sum}\{a(n)\} > 0.2$)			Cylinder						
			Length, (cm)	5.20					
Species: Na			Diameter, (cm)	5.10		len./dia. =	1.02		
			Volume, (cm ³)	106.17					
			Sample Wt. (k)	0.152					
			Surface, (cm ²)	124.17					
Leachate Volume, (L)	1.24		V/S Ratio	0.86					
			[V/S] ² , (cm ²)	0.73					
Rinse Vol. (L)	1.346								
Rinse Conc. (mg/L)	39.9	Pi =	3.14						
A(o){subsample}(mg/	10,100								
Adjusted A(o), (mg)	1,481.5				A(o) is taken from a subsample unrinsed				
Final conc. (mg/kg)	819				Adjusted A(o) takes subsample A(o) and removes rinse conc.				
Final wt. (kg)	0.183								
Leach				Leachate					
Interval	del t, hr	Cum. t, hr	Cum. t, sec	onc. (mg/L)			A(n), (mg)	A(n)/A(o)	
1	2	2	7,200	330.0			409.20	0.28	
2	5	7	25,200	194.0			240.56	0.16	
3	17	24	86,400	274.0			339.76	0.23	
4	24	48	172,800	188.0			233.12	0.16	
5	24	72	259,200	76.6			94.98	0.06	
6	24	96	345,600	27.2			33.73	0.02	
7	24	120	432,000	16.5			20.46	0.01	
						sum	1,371.81		
Cummulative			Effective	Effective	Cum.	mass bal	40.19		
Fraction			Diffusivity	Diffusivity	Percent				
Leached	1/t	"G"	(cm/s)	(cm/s)	Leached				
0.28	1.39E-04	1.92E-03	6.94E-06	6.94E-06	27.62	Note: "G" from procedure charts			
0.44	3.97E-05	5.91E-03	6.10E-06	6.10E-06	43.86				
0.67	1.16E-05	1.79E-02	5.39E-06	5.39E-06	66.79				
0.83	5.79E-06	3.65E-02	5.49E-06	5.49E-06	82.53				
0.89	3.86E-06	4.95E-02	4.97E-06	4.97E-06	88.94				
0.91	2.89E-06	5.55E-02	4.18E-06	4.18E-06	91.22				
0.93	2.31E-06	6.31E-02	3.80E-06	3.80E-06	92.60				