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POLYETHYLENE ENCAPSULATION OF SINGLE-SHELL TANK LOW-LEVEL WASTES

ANNUAL PROGRESS REPORT

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ABSTRACT

This report describes work supported by the UST-ID, conducted at Brookhaven National Laboratory (BNL), to develop and demonstrate a polyethylene waste encapsulation process for low-level radioactive (LLW) and hazardous mixed wastes (HMW) stored in underground tanks. During FY 1992, studies were completed on the effects of elevated temperature on waste form integrity, strength and leachability. No changes in waste form integrity or compressive yield strength were detected after storing polyethylene waste forms containing 50, 60 and 70 wt% sodium nitrate at 70°C for 3 months. Leaching of polyethylene waste forms with similar nitrate salt loadings at temperatures up to 70°C resulted in slight increases in leachability (< a factor of 2), compared with leaching at ambient temperatures. Leaching of sodium nitrate from polyethylene waste forms was diffusion-controlled, enabling extrapolation of laboratory leach data to full-scale waste forms over long time periods. Full-scale polyethylene waste forms containing 50 to 70 wt% nitrate salt could be expected to leach a total of 5% to 17% of the original contaminant source term after 300 years of leaching under worst-case (70°C, fully saturated) conditions. This is about 25 to 75 times lower leachability than conventional cement grout waste forms containing a maximum of 20 wt% nitrate salts.

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1. INTRODUCTION

For the past 50 years, the U.S. Department of Energy (DOE) and its predecessor agencies have stored large volumes of defense-related radioactive and mixed wastes in underground tanks. Initially, these tanks were constructed of single steel walls surrounded by reinforced concrete and are known as single-shell tanks (SSTs). Over time, the highly corrosive contents caused many of the tanks to begin to leak.

As part of its effort to remediate leaking and potentially leaky tanks, DOE's Office of Technology Development (OTD) has established the Underground Storage Tank Integrated Demonstration (UST-ID). The overall objectives of the UST-ID include facilitating the development and demonstration of enhanced technologies that will lead to improved treatment and stabilization of underground storage tank wastes. The host site for the UST-ID is Hanford, but the program addresses potential use of these emerging technologies in remediation of tanks at five DOE facilities: Hanford, Fernald, Idaho (Idaho National Engineering Laboratory), Oak Ridge, and Savannah River. In order to meet its objectives, the UST-ID supports technology development in six focus areas including: 1) waste characterization, 2) high- and low-level waste treatment and disposal, 3) retrieval, transfer, and storage, 4) waste separation, 5) in situ treatment and disposal, and 6) site closure. [1] The Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) mandates that a demonstration of a full-scale SST closure be completed by 2004. An interim milestone includes identification of closure methods including waste treatment and disposal by 1999.[2] In an effort to meet these milestones, the UST-ID is supporting efforts to develop technologies leading to successful treatment and stabilization of SSTs.

This report describes work supported by the UST-ID, conducted at Brookhaven National Laboratory (BNL), to develop and demonstrate a polyethylene waste encapsulation process for low-level radioactive (LLW) and hazardous mixed wastes (HMW) stored in underground tanks.

1.1 The Polyethylene Encapsulation Process

The polyethylene process was developed several years ago at BNL for solidification of LLW such as evaporator concentrate salts and ion exchange resins.[3,4] Recently, it has been successfully applied for treatment of hazardous and mixed waste streams such as sodium nitrate salts and sludges.[5,6] Polyethylene is an inert thermoplastic material with a melting point of 120°C and processing temperature range of 120 - 150°C. As such, it is not susceptible to chemical interactions between the waste and binder and always results in a monolithic solid waste form on cooling. In contrast, grout solidification processes (currently considered the base-line technology for SST LLW) require a chemical hydration reaction for setting and curing. Thus, cement binders are susceptible to chemical interactions with the waste that can limit both the types of waste that are compatible and the amount of waste that can be incorporated. Small variations in waste composition during processing (which are likely based on the heterogeneous nature of SST LLW) may require frequent adjustment of solidification formulations and quality control testing. Polyethylene processing is less dependent on waste chemistry, enabling a wider range of acceptable waste types, improved waste loadings, and easier processing under heterogeneous waste conditions. In general, polyethylene encapsulation can be accomplished with greater efficiency (more waste encapsulated per drum) and with better waste form performance than is possible using conventional encapsulation technologies such as hydraulic cement-based grouts. For example, as much as 70 dry wt% sodium nitrate can be encapsulated in polyethylene, compared with 13 - 20 wt% in portland cement.

Extensive waste form performance testing has been completed including compressive strength, water immersion, thermal cycling, radioactive and hazardous constituent leachability, radiation stability and biodegradation.[3,6,7] In each case, waste form performance exceeded regulatory criteria by a wide margin. Scale-up feasibility has been confirmed by processing simulated nitrate wastes at product output rates up to 900 kg/hr (2000 lbs/hr). Based on results of bench-scale processing and performance testing, a production-scale technology demonstration of the polyethylene encapsulation process for nitrate salt wastes is planned under a parallel BNL effort, the Polymer Solidification Program, sponsored by DOE OTD.

Polyethylene encapsulation has been identified as a potential treatment option for SST LLW at Hanford by several Westinghouse Hanford Co. (WHC) and independent investigations including: the "Technology Program Plan for Closure of the Single-Shell Tank Operable Units"[8], the "Third Party Technical Workshop on Hanford SST Waste and Residuals"[9], the WHC "Systems Engineering Study for the Closure of Single-Shell Tanks"[10], the "Preliminary Assessment of Candidate Immobilization Technologies for Retrieved Single-Shell Tank Wastes"[11], and the "Tank Waste Remediation System (TWRS) LLW Disposal Technology Working Group".[12]

1.2 Characterization of Single Shell Tank Wastes

The UST-ID Program encompasses more than 332 underground storage tanks with a total volume capacity in excess of 750,000 m^3 (1.98 x 10^8 gal.). The USTs range in size from 0.114 to 7,500 m^3 (30 gal. to 2 million gal.), with an average volume between 1,890 and 3,790 m^3 (0.5 to 1 million gal.). The overall volume of wastes currently stored in USTs at the five DOE sites is about 370,000 m^3 (98 million gal.).[13]

The Hanford site contains 149 SSTs used until 1971 for storage of highly radioactive and chemically hazardous liquid wastes and sludges. They comprise about 62% of the total volume of wastes currently stored in USTs at the five DOE sites.[13] Approximately half the tanks are currently leaking. They contain about 200,000 MT of waste (predominantly sodium nitrate) with a total radioactive inventory of about 60 MCi. Table 1.1 provides an estimate of the nonradioactive chemical constituents and their relative quantities found in a typical SST following jet pumping to remove supernatant liquid. Most of the activity results from Cs-137 (~20%) and Sr-90 (~78%) and their daughter products.[14] Typically, tanks contain about one million gallons of saltcake (~35 wt%), sludge (~60 wt%) and interstitial liquid (~5 wt%). The high loadings of fission products in a typical tank result in radiation dose rates of 300 to 700 rad/hour and temperatures ranging from 51 to 63°C. 11 of the 149 SSTs have been designated as "High Heat Load" tanks. Estimated heat loads in these tanks range from 11.72 to 43.96 kW (42,000 to 150,000 BTU/hour) resulting in temperatures measured between 37 and 92°C. [15]

Several options for SST waste processing prior to solidification in a final waste form are currently under consideration. These include: 1) sludge washing in which sludges and solids are separated from supernatant liquids and then washed in caustic solutions to remove soluble salts, 2) TRUEX processing in which solids are dissolved in acid and the TRU constituents are removed using the TRUEX process, and 3) the null alternative in which no isotopic separation is performed and tank wastes are homogenized in a lag storage area prior to solidification. The first two options involve partitioning of the SST wastes into a large volume low-level waste fraction and a small volume high level and/or transuranic waste fraction. The sludge washing option would result in a volume reduction of the fission products in the LLW, thus reducing the thermal load of these wastes. The null alternative would not reduce the fission product fraction, but would result in a more even distribution of the heat load, dampening out peak heat loads evident in the "High Heat Load" tanks. Assuming the null alternative is chosen and no further radionuclide separation is conducted, an anticipated average temperature range of 50 - 70°C is assumed for the purposes of this investigation.

Table 1.1 Estimated Mass of Nonradioactive Chemical Components of Existing SST Wastes[(a)]

Chemical	Total Bulk Sludge (t)	Total Bulk Saltcake (t)	Interstitial Liquid (t)
$NaNO_3$	20,000	110,000	2,500
$NaNO_2$	3,000	2,300	1,900
Na_2CO_3	1,700	730	70
NaOH	4,200	2,000	740
$NaAlO_2$	950	1,900	1,500
Na_2SO_4	740	1,700	
Na_3PO_4	12,500	2,100	280
Cancrinite	2,700		
$Al(OH)_3$	2,300		
$Ce(OH)_3$	320		
$Cr(OH)_3$	190		
$Cd(OH)_2$	5		
$Fe(OH)_3$	1,200		
$Sr(OH)_2$	50		
$BiPO_4$	380		
$CaCO_3$	320		
F^-	800		5
Cl^-	40		
Hg^+	0.9		
MnO_2	190		
$Ni_2Fe(CN)_6$	500		
$P_2O_5 \bullet 24WO_2 \bullet 44H_2O$	20		
$ZrO_2 \bullet 2H_2O$	430		
Organic Carbon			200
H_2O	26,000	14,000	4,800
TOTAL	79,000	135,000	12,000

(a) This table taken from Reference [13]

1.3 Experimental Objectives

Although Hanford SST wastes are similar in chemical composition to other nitrate wastes within DOE (e.g., Rocky Flats Plant, Oak Ridge, Savannah River Plant and West Valley) the high concentrations of fission products and resulting high thermal loads (assuming fission products are not separated out of the waste) represent unique conditions that potential final waste forms must meet. Because of these unique properties, the objective of Phase I of this effort is to investigate the potential impacts of residual heat and high radiation doses on key waste form properties including mechanical integrity, strength, and leachability. During FY 1992, studies were completed on the effects of elevated temperature on waste form integrity, strength and leachability. In FY 1993, testing is planned to investigate the effects of elevated temperature on mechanical creep and potential synergistic effects of temperature and radiation doses.

If Phase I testing of simulated waste forms indicates satisfactory performance under anticipated thermal conditions, the second phase will be initiated. This work, will determine pre-treatment requirements, acceptable waste form formulations, and quality assurance/quality control specifications. Phase II development efforts will be conducted using non-radioactive surrogate waste that closely resembles actual SST waste in both chemical and physical characteristics. Surrogate waste and/or recipes for producing surrogates will be coordinated with other UST-ID projects investigating waste characterization. The final phase of this effort (Phase III), will involve confirmation of scale-up feasibility, and completion of a full-scale demonstration of polyethylene encapsulation of surrogate SST nitrate salts.

2. PROCESSING AND SAMPLE PREPARATION

2.1 Extrusion Processing

Samples were prepared using a bench-scale plastics extruder with a 32 mm (1.25 in.) screw diameter and a maximum output rate of about 35 kg/hr (16 lb/hr). The BNL extruder, shown in Figure 2.1, is equipped with two volumetric feeders calibrated to deliver precise quantities of simulated waste and polyethylene binder. The materials are mixed and heated at about 150 °C within the extruder, forming a homogeneous molten mixture. The mixture is then extruded into a suitable mold and forms a monolithic solid waste form on cooling.

Separate feeders for the polyethylene and simulated salt waste were calibrated using the materials that were employed for test specimens. Each feeder was calibrated at five different speeds covering the complete operating range (10, 25, 50 75 and 90% of full speed). Output rate at each speed was measured for at least 10 trials. Mean output rates, associated 2σ error, and linear regression lines were calculated. Calibration results are shown in Figures 2.2 and 2.3 in terms of feeder output (g/min) as a function of percent full speed. Feeder calibration data are included in the Appendix.

2.2 Leach Test Specimen Preparation

The waste forms prepared for leach tests were mixtures of $NaNO_3$ and low-density polyethylene, with nominal salt loadings of 50, 60 and 70 wt%. Mixtures were extruded into polyvinyl chloride (PVC) molds measuring 2.5 cm I.D. x 15 cm in length. After cooling, the extruded rods were cut to form the leaching specimens, measuring 2.5 cm in diameter x 2.5 cm in height, as per Accelerated Leach Test recommendations. Cut surfaces at the tops and bottoms of test specimens exposed unencapsulated salt to leachate and thus were re-sealed by heating to more closely replicate the normally sealed surfaces of cast waste forms.

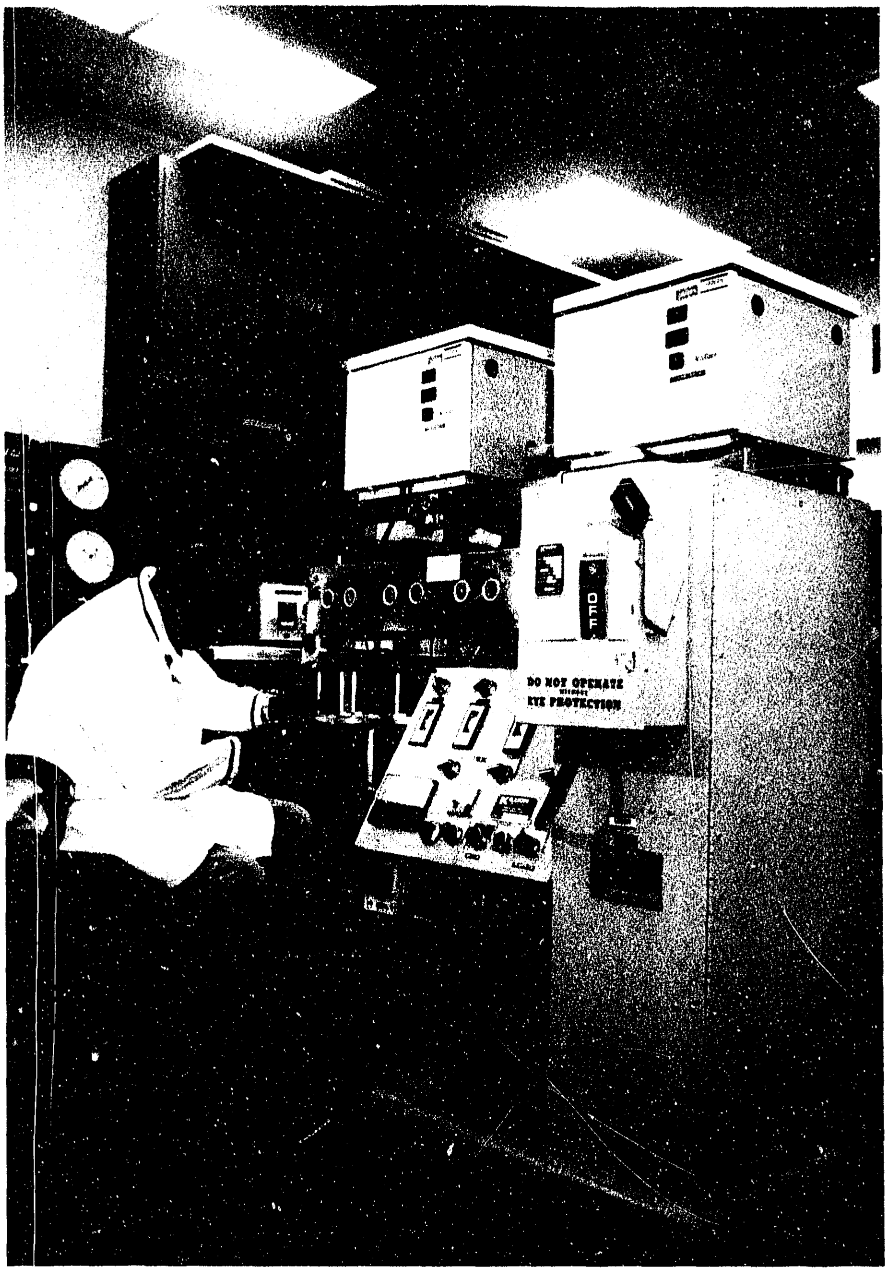

Figure 2.1 The BNL bench-scale extruder, equipped with two volumetric feeders calibrated to deliver precise quantities of simulated waste and polyethylene binder.

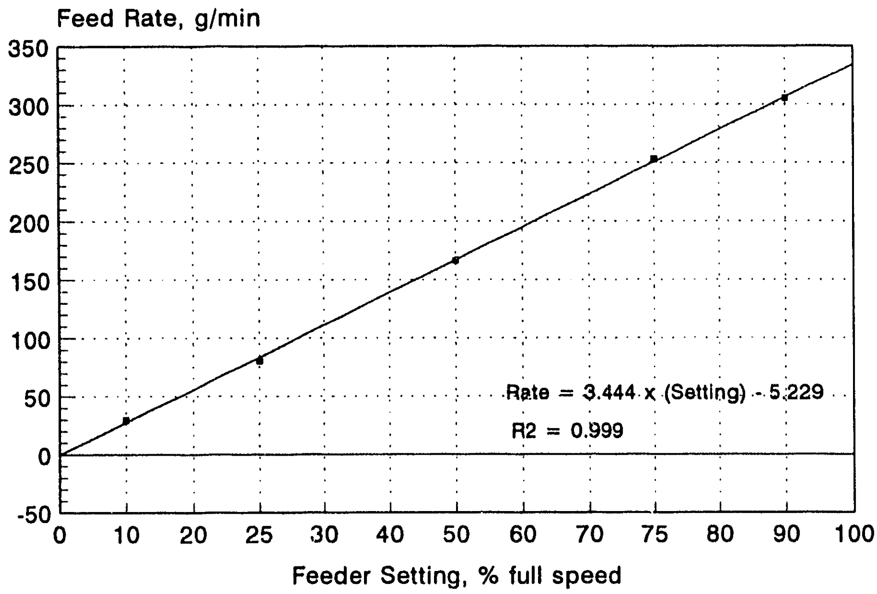

Figure 2.2 Calibration curve for sodium nitrate simulated waste in terms of feeder output (g/min) as a function of percent full speed.

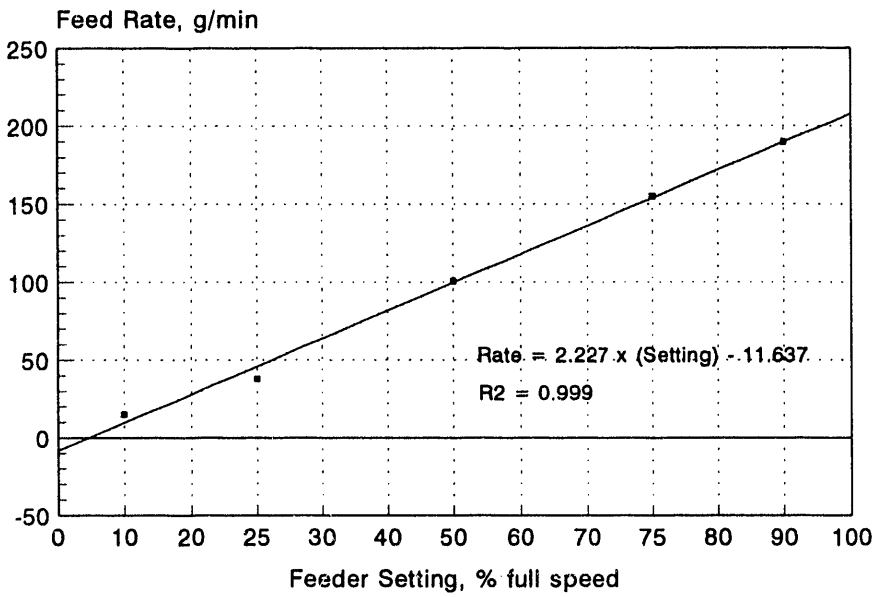

Figure 2.3 Calibration curve for low-denisty polyethylene binder in terms of feeder output (g/min) as a function of percent full speed.

Leach test specimens were then weighed and dimensioned. Densities were calculated in order to compare homogeneity among samples and determine sodium levels for use as the source term in leaching calculations.

2.3 Thermal Effects Specimen Preparation

Simulated waste forms containing 50, 60 and 70 wt% sodium nitrate encapsulated in polyethylene were prepared for examining the effects of elevated temperatures on waste form integrity and mechanical strength. Waste form preparation technique for these specimens was similar to the procedure described above, except that test specimens were extruded into polyethylene molds inserted in copper sleeves which provided a heat sink. Nominal dimensions for these test specimens were 50 mm diameter x 100 mm height. Approximately 40 replicates were made at each waste loading.

In preparation for compressive strength testing, top and bottom surfaces of test specimens were machined to form right cylinders with smooth surfaces. Densities were calculated from dimension and weight data. Average densities were 1.280 $\pm$ .005 (50 wt% salt), 1.371 $\pm$ .005 (60 wt% salt), and 1.544 $\pm$ .011 (70 wt% salt). Data are included in the Appendix.

3. LEACHABILITY AT ELEVATED TEMPERATURES

A critical parameter of waste form performance is the rate at which a contaminant is released under aqueous conditions such as a saturated disposal facility. Release rates are quantified by conducting a leach test in which waste forms, containing a known amount of contaminant, are suspended in an aqueous solution. The concentration of contaminant entering the solution is determined and the fractional quantity of contaminant released over time is calculated in terms of the incremental fraction release (IFL). The sum of the IFLs is the cumulative fraction release (CFL), and the CFL divided by cumulative leach time is the release rate. Under certain test conditions, the mechanism by which leaching occurs also can be determined.

A comprehensive investigation of the leachability of Na from polyethylene waste forms containing $NaNO_3$ was conducted for this study. This salt is used as a simulant for Hanford single-shell tank waste. As described in Section 1.2, actual SST wastes contain a wide range of constituents, but $NaNO_3$ is the predominant component, accounting for about 38 wt% of the sludge, 81 wt% of the saltcake, and 35 wt% of the interstitial liquid. Since the polyethylene process is based on microencapsulation in an inert binder, no chemical reactions take place between the waste and the polyethylene. Thus, releases of sodium will be similar to those of any other highly soluble species such as cesium.

The objectives of the leaching study were to:

(1) determine leach rates of $NaNO_3$/polyethylene waste forms at several waste loadings
(2) determine leach rates at temperatures as high as 70°C which is the maximum projected temperature of this self-heating waste
(3) determine the leaching mechanism of $NaNO_3$/polyethylene waste forms and attempt to predict releases.

The Accelerated Leach Test (ALT) used for this study was recently developed at BNL. It is particularly well suited for this application since it was designed to be run at elevated temperatures.[16] It provides an accelerated determination of the maximum leachability of solidified waste. The ALT method is applicable to any material that does not degrade, deform, or in which there is no change in the mechanism of leaching during the test.

The data obtained with this test can be used to model long-term releases from waste forms, or to extrapolate from laboratory-scale waste forms if diffusion is the dominant leaching mechanism. Diffusion can be confirmed as the leaching mechanism by comparing experimental leach data with predicted releases using a computerized mathematical model for diffusion written to accompany this test. The program, and a User's Guide that gives screen-by-screen instructions on the use of the program, are available.[17] The models used in the program include:

- diffusion from an infinite slab
- diffusion from a finite cylinder
- solubility limited release
- diffusion plus partitioning

The results do not apply to releases in specific disposal environments unless tests are conducted to determine the leaching mechanism under those conditions. Projections of releases assume the long-term stability of the waste form which may not be revealed adequately by short-term tests.

The Accelerated Leach Test is a semi-dynamic leach test, i.e., the leachant is sampled and replaced periodically. Parameters such as temperature, leachant volume, and specimen size are used to obtain releases that are accelerated relative to other standard leach tests and to the leaching of full-scale waste forms.

The results of this accelerated test can be extrapolated to long times if the data from tests run at high temperatures and those run at the reference temperature (20°C) can be modeled by diffusion. A computer program plots the experimental data and a curve calculated from an effective diffusion coefficient for diffusion from a finite cylinder (Figure 3.1). If the data from the accelerated tests, the reference test, and the modeled curve fit within the criteria, diffusion is taken to be the leaching mechanism. In this case, the model can be used to project releases from full-scale waste forms for long times. The accelerated test provides a measure of the maximum fractional release to which the modeled data can be extrapolated. By generating data over a specified temperature range, an Arrhenius plot can be produced, allowing projections at temperatures other than those tested. If the diffusion model does not adequately fit the data, other models (diffusion plus partitioning and solubility limited) can be used to suggest the leaching mechanism that controls releases; no extrapolations are allowed with these models. If no model fits the data, then an alternative graphical comparison of the data is recommended. A linear plot of modeled cumulative fraction leached (CFL) plotted against experimental CFL verifies that the accelerated data is comparable to the reference data, showing that the accelerated test is appropriate. However, no extrapolation of data can be made with this technique.

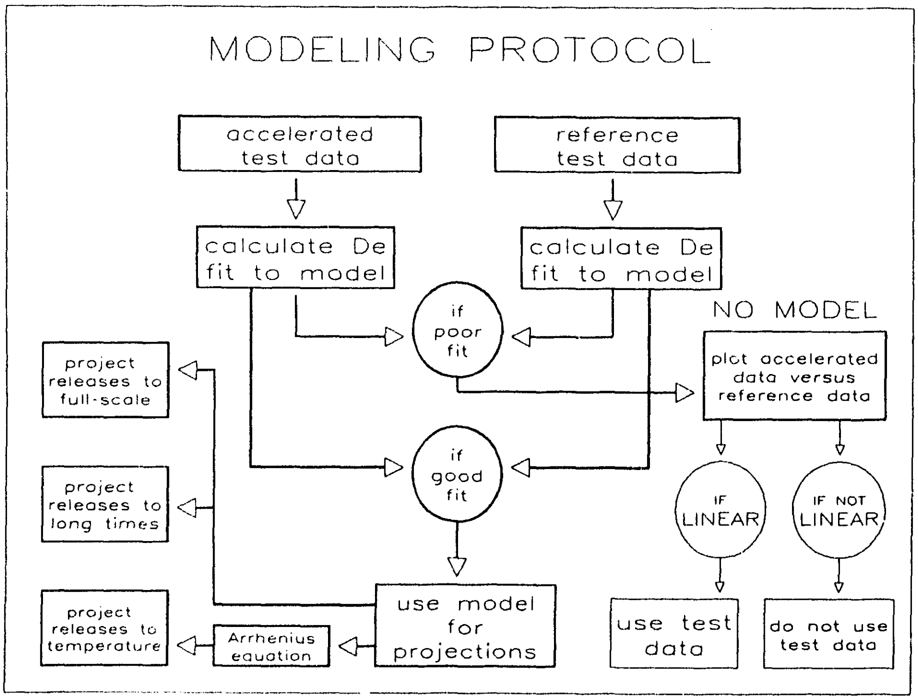

Figure 3.1 A schematic of the concepts used to combine experimental and modeling approaches.

3.1 Leach Test Method

The waste forms tested were mixtures of $NaNO_3$ and polyethylene with nominal salt loadings of 50, 60, and 70 wt%. Test specimens were prepared with right cylinder geometries to a nominal final dimension of 2.5 cm diameter by 2.5 cm in length. Details on sample preparation are described in Section 2.2. The quantity of Na contained in each leach test specimen (source term) was determined by measurement of the sample density. These values were compared to a plot of theoretical density versus salt loading. Although the theoretical plot was a parabolic mixing function the segment of interest was sufficiently small that a linear equation described the segment adequately. The linear equation was then used to calculate the percentage of salt in each sample based on its measured density.

Three liters of distilled water were used for each sampling interval. Leaching tests were conducted at 20°C, 35°C, 50°C, and 70°C. Elevated temperature leaching was conducted in a forced air convection environmental chamber with a temperature control of ± 0.5°C. Fresh leachant was pre-heated in the chamber for 24 hours prior to immersing test specimens. Four replicate samples were tested for each salt loading at each temperature (a total of 48 specimens leached). Sampling times and leachant replacement intervals are specified in Table 3.1. Leachate analysis for Na concentration was done by atomic absorption (AA) spectroscopy.

Table 3.1. Leachant Replacement Intervals for the ALT

Interval	Incremental Time (t)	Cumulative time ($\sum t$)
1	2 hours ± 5%	2 hours
2	5 hours ± 5%	7 hours
3	17 hours ± 2%	1 day
4	1 day ± 2%	2 days
5	1 day ± 2%	3 days
6	1 day ± 2%	4 days
7	1 day ± 2%	5 days
8	1 day ± 2%	6 days
9	1 day ± 2%	7 days
10	1 day ± 2%	8 days
11	1 day ± 2%	9 days
12	1 day ± 2%	10 days
13	1 day ± 2%	11 days

3.2 Leach Test Results

Results of the Na analysis were input to the ALT computer program which performed calculations to determine the Cumulative Fraction Leached (CFL), the Incremental Fraction Leached (IFL), the diffusion coefficient that best fits the leaching data and a value that described the goodness-of-fit between the data and model results. This value is the sum of the differences between the experimental data and the model curve. Goodness-of-fit values that are greater than 100 are excluded from the calculation of average CFLs since these data do not fit the model. Values that are below about 50 are considered to represent a good fit between the data and the model and therefore indicate that diffusion is the leaching mechanism. Those between 50 and 100 represent a lesser, but acceptable fit to the diffusion model. Leaching results for each of the temperatures examined are discussed below.

Samples Tested at 20°C:

The data for samples tested at 20°C are shown in Table 3.2 and Figures 3.2 - 3.4 for waste forms having salt loadings of 50, 60, and 70 wt%. Diffusion coefficients range from 8.84 x 10^{-10} cm^2/s to 6.6 x 10^{-8} cm^2/s and CFLs range from 9.6 to 57.3%. Average CFLs were 15.5%, 32.2%, and 52.4% for 50, 60 and 70 wt% samples, respectively. The goodness-of-fit of the data to the diffusion model samples leached at 20°C was generally good. Only one sample did not meet the goodness-of-fit criteria of less than 100, indicating that diffusion does control releases for most samples.

Samples Tested at 35°C:

Data for samples leached at 35°C are shown in Table 3.3 and Figures 3.5 - 3.7. Diffusion coefficients range from 1.12 x 10^{-9} cm^2/s to 1.33 x 10^{-7} cm^2/s while CFL values range from 10.9% to 75.1%.Average CFLs were 14.4%, 32.2%, and 58.0% for 50, 60, and 70 wt% samples, respectively. The goodness-of-fit for all samples indicates that diffusion is the release mechanism for this group of samples. Samples 60%B and 70%B both have anomalously high CFL values, and sample 60%B is close to the limit for goodness-of-fit.

Samples Leached at 50°C:

Table 3.4 contains results for samples leached at 50°C as do Figures 3.8 - 3.10. This set of data shows more scatter than the samples leached at lower temperatures. Diffusion coefficients range from 1.37 x 10^{-9} cm^2/s to 1.69 x 10^{-7} cm^2/s but both extremes are in the same set of replicates. Values of CFL vary from 12.5% to 90.6%. Average CFLs were 37.5%, 35.8%, and 80.7% for 50, 60, and 70 wt% samples, respectively. Goodness-of-fit generally indicates that diffusion is the release mechanism. Examination of the leaching curves shows that samples 50%C and 70%A are the two that clearly do not fit the model.

Samples Leached at 70°%:

Data for samples leached at 70°C are presented in Table 3.5 and Figures 3.11 - 3.13. The CFL range from 23.4% to 97.7%, with diffusion coefficients ranging from 6.78×10^{-9} to 3.60×10^{-7} cm^2/s. Average CFLs were 26.5%, 66.9%, and 85.2% for 50, 60, and 70 wt% samples, respectively. For most samples, the goodness-of-fit indicates that diffusion is the leaching mechanism with the exception of three samples in the 60 wt% loading set. Anomalies in this data set are probably due to poor sealing of the specimen surfaces after cutting to the proper size.

3.3 Discussion of Leach Test Results

These experiments quantified the effect of two parameters, waste loading and temperature, on leaching. Several topics are of particular interest:

(1) Is diffusion the leaching mechanism for this material at 20°C and if it is, does increasing temperature alter the mechanism?

(2) What is the relationship between salt content and leaching?

(3) Can this information be used to predict releases and to provide information from which a better waste form can be produced?

From the data presented in Tables 3.2 -3.5, the goodness-of-fit of the diffusion model to the experimental data is acceptably close for approximately 85% of the samples tested. The remaining 15% leach in a manner that appears to be controlled more by dissolution than by transport out of the waste form. This is illustrated in Figure 3.3 showing the leaching curve for Sample D for 60 wt% salt leached at 20°C. This set of data is less curved than the model results, crossing the model halfway through the experiment. Comparison of the data to the model indicates that releases of Na were slower than predicted during the beginning of the experiment and faster toward the end.

This is true in both cases; when the leach rate is above the average of other samples in the same set and when it is significantly below the average. For these samples, releases are less controlled by the difference in concentration (which drives diffusion) than they are by other processes that control access of the leachant to the salt grains or by the kinetics of dissolution. In either case, the structure of the sample that typically inhibits dissolution is not effective. As discussed in Section 3.2, improperly sealed surfaces following cutting of specimens could account for this behavior.

Since most samples in this study have been shown to leach by diffusion, the ALT computer model was used to project releases for several conditions. Table 3.6 shows the cumulative fraction release attained by waste forms after 300 years using the average diffusion coefficients shown in Tables 3.2 -3.5. A production-scale waste form measuring 2 meters in diameter by 2 meters in height is assumed for this extrapolation. Projected releases range from 3.6% - 16.8% of the original source term, with samples containing 50 wt% salt releasing Na at approximately one third the rate of the 70 wt% samples. The lowest leaching values are small, and when they are coupled with radioactive decay of Sr-90 and Cs-137, the fraction of the total source term that is released after 300 years is about 0.014%. Based on effective diffusivities derived in previous leaching experiments, conventional cement grout waste forms are projected to leach about 17% of the contaminants after only 11 years.[18] Thus, polyethylene waste forms containing maximum nitrate salt loadings can be expected to leach about 25 times slower than cement grout waste forms, while solidifying between 3.5 and 5 times more nitrate salt waste. Polyethylene waste forms leached at lower temperatures (20 °C to 35 °C) could be expected to leach about 3.5% to 11% of the original contaminants in 300 years. Thus, reduction in the thermal load due to fission products by removal of some of the Cs-137 and Sr-90 from SST wastes could result in lower leachabilities by a factor of about 2 times. Figure 3.14 shows the relationship of leachability (CFL) as a function of waste loading at four temperatures. Examination of leaching data from an earlier study, that extended to lower loadings than the current experiments, indicated that the relationship between salt loading and leaching is an exponential function in which leaching becomes very small as salt loading approaches zero. [5]

The effect of temperature can be seen in Figure 3.15 which is an Arrhenius plot of the natural log of diffusion coefficients plotted as a function of inverse temperature in kelvins. The slopes are quite low and yield activation energies of 2.5, 2.2, and 2.9 Kcal/mole for sample containing 50, 60, and 70 wt% $NaNO_3$ respectively. These values compare quite closely to typical activation energies of 3 - 5 Kcal/mole for diffusion. The Arrhenius plot also indicates that the leaching mechanism does not change between 20°C and 70°C since the slopes of the lines remain unchanged.

3.4 Conclusions Regarding Waste Form Leaching

Based on the data presented in this section several conclusions can be drawn. The leaching of a highly soluble salt contained in polyethylene is diffusion controlled. However, exceptions to this can occur when the surfaces of the waste form are disturbed, creating potential preferential pathways for leaching. Because diffusion was shown to be the operative mechanism, projections were made for cumulative fraction releases out to 300 years using diffusion coefficients measured at 4 temperatures and for 3 waste loadings. Compared with conventional cement grout, polyethylene leach rates are 25 to 75 times lower.

Temperature has a small effect on leaching, increasing diffusion coefficients by a factor of approximately four over a 50 degree temperature range. Salt loading has a greater influence on leaching, as CFLs approximately double for each 10 wt% increase in salt loading. The data in this study indicates that while releases from polyethylene/sodium nitrate waste forms are low even at maximum waste loadings (i.e., 70 wt%), leach rates can be reduced by a factor of 3 to 4 times by reducing nitrate salt loadings to 50 wt%.

Table 3.2. Accelerated Leach Test Results Conducted at 20°C for $NaNO_3$ Encapsulated in Polyethylene

SAMPLE	CUMULATIVE FRACTION LEACHED (%)	DIFFUSION COEFFICIENT (cm^2/sec)	GOODNESS-OF-FIT
50% $NaNO_3$			
A	14.8	2.32×10^{-9}	3.7
B	18.9	4.67×10^{-9}	8.13
C	18.5	4.37×10^{-9}	5.0
D	9.6	8.84×10^{-10}	24.2
AVERAGE	**15.5**	**3.05×10^{-9}**	**10.3**
60% $NaNO_3$			
A	25.3	8.45×10^{-9}	2.02
B	34.0	1.63×10^{-8}	27.5
C	10.7	1.17×10^{-9}	15.7
D	58.8	6.21×10^{-8}	184.0*
AVERAGE	**32.2**	**2.2×10^{-8}**	**15.1**
70% $NaNO_3$			
A	50.2	4.78×10^{-8}	20.6
B	54.4	6.10×10^{-8}	21.2
C	47.6	4.82×10^{-8}	43.8
D	57.3	6.60×10^{-8}	44.1
AVERAGE	**52.4**	**5.58×10^{-8}**	**32.4**

*Not included in average.

Table 3.3 Accelerated Leach Test Results Conducted at 35°C for $NaNO_3$ Encapsulated in Polyethylene

SAMPLE	CUMULATIVE FRACTION LEACHED (%)	DIFFUSION COEFFICIENT (cm^2/sec)	GOODNESS-OF-FIT
50% $NaNO_3$			
A	17.6	3.85×10^{-9}	3.17
B	18.1	4.50×10^{-9}	5.61
C	11.1	1.14×10^{-9}	6.33
D	10.9	1.12×10^{-9}	2.83
AVERAGE	**14.4**	**2.65×10^{-9}**	**4.49**
60% $NaNO_3$			
A	22.3	7.10×10^{-9}	1.56
B	50.5	4.65×10^{-8}	70.70
C	30.0	1.26×10^{-8}	0.60
D	25.1	9.82×10^{-9}	15.10
AVERAGE	**32.0**	**1.90×10^{-8}**	**22.00**
70% $NaNO_3$			
A	53.0	5.67×10^{-8}	3.18
B	75.1	1.33×10^{-7}	19.50
C	57.7	6.75×10^{-8}	26.00
D	46.2	4.79×10^{-8}	43.90
AVERAGE	**58.0**	**7.63×10^{-8}**	**23.10**

Table 3.4. Accelerated Leach Test Results Conducted at 50°C for $NaNO_3$ Encapsulated in Polyethylene

SAMPLE	CUMULATIVE FRACTION LEACHED (%)	DIFFUSION COEFFICIENT (cm^2/sec)	GOODNESS-OF-FIT
50% $NaNO_3$			
A	20.1	4.93×10^{-9}	7.64
B	12.5	1.37×10^{-9}	77.1
C	90.6	1.69×10^{-7}	942*
D	26.7	9.69×10^{-9}	3.20
AVERAGE	**37.5**	$\mathbf{4.62 \times 10^{-8}}$	**29.3**
60% $NaNO_3$			
A	23.8	7.70×10^{-9}	1.19
B	55.4	5.83×10^{-8}	46.0
C	10.4	9.90×10^{-10}	15.3
D	53.5	5.70×10^{-8}	5.35
AVERAGE	**35.8**	$\mathbf{3.10 \times 10^{-8}}$	**17.0**
70% $NANO_3$			
A	90.4	2.47×10^{-7}	136*
B	77.1	1.43×10^{-7}	41.6
C	75.3	1.24×10^{-7}	61.0
D	80.1	1.44×10^{-7}	120*
AVERAGE	**80.7**	$\mathbf{1.64 \times 10^{-7}}$	**51.3**

*Not included in average.

Table 3.5 Accelerated Leach Test Results Conducted at 70°C for $NaNO_3$ Encapsulated in Polyethylene

SAMPLE	CUMULATIVE FRACTION LEACHED (%)	DIFFUSION COEFFICIENT (cm^2/sec)	GOODNESS-OF-FIT
50% $NaNO_3$			
A	27.5	1.06×10^{-8}	10.2
B	25.7	9.10×10^{-9}	4.11
C	29.4	7.23×10^{-8}	0.88
D	23.4	6.78×10^{-9}	1.87
AVERAGE	**26.5**	**9.69×10^{-9}**	**4.26**
60% $NaNO_3$			
A	38.6	2.40×10^{-8}	10.4
B	81.6	1.39×10^{-7}	374*
C	89.7	1.85×10^{-7}	577*
D	57.5	5.77×10^{-8}	148*
AVERAGE	**66.9**	**1.01×10^{-7}**	**—**
70% $NaNO_3$			
A	97.7	3.60×10^{-7}	97.7
B	67.7	8.93×10^{-8}	54.8
C	92.7	2.99×10^{-7}	36.2
D	82.7	1.83×10^{-7}	33.1
AVERAGE	**85.2**	**2.33×10^{-7}**	**55.5**

*Not included in average.

Table 3.6 Projected Cumulative Fractional Releases After 300 Years of Leaching for Full-Scale Polyethylene Waste Forms Containing Nitrate Salt Wastes

Projected Releases After 300 Years[a]						
Temperature °C	50 wt% Salt		60 wt% Salt		70 wt% Salt	
	D_e (cm^2/s)	CFL (%)	D_e (cm^2/s)	CFL (%)	D_e (cm^2/s)	CFL (%)
20	3.05×10^{-9}	3.7	8.6×10^{-9}	5.0	5.58×10^{-8}	9.5
35	2.65×10^{-9}	3.6	1.90×10^{-8}	6.3	7.63×10^{-8}	10.7
50	5.32×10^{-9}	4.3	3.10×10^{-8}	7.6	1.34×10^{-7}	13.4
70	9.69×10^{-9}	5.1	2.40×10^{-8}	6.9	2.33×10^{-7}	16.8

a) Projected releases for 6.3 cubic meter full-scale waste form (2m diameter x 2m in height).

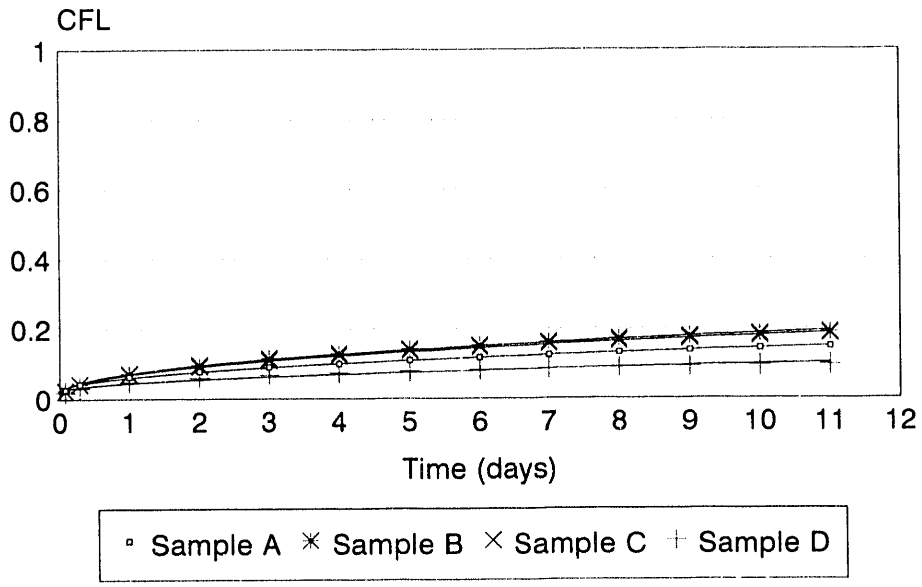

Figure 3.2 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 50 wt% tested at 20°C.

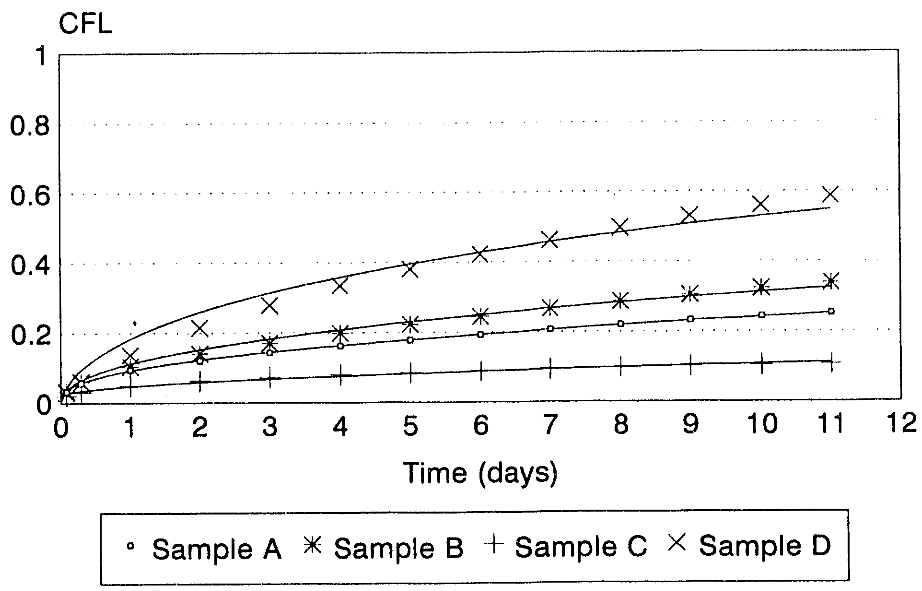

Figure 3.3 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 60 wt% tested at 20°C.

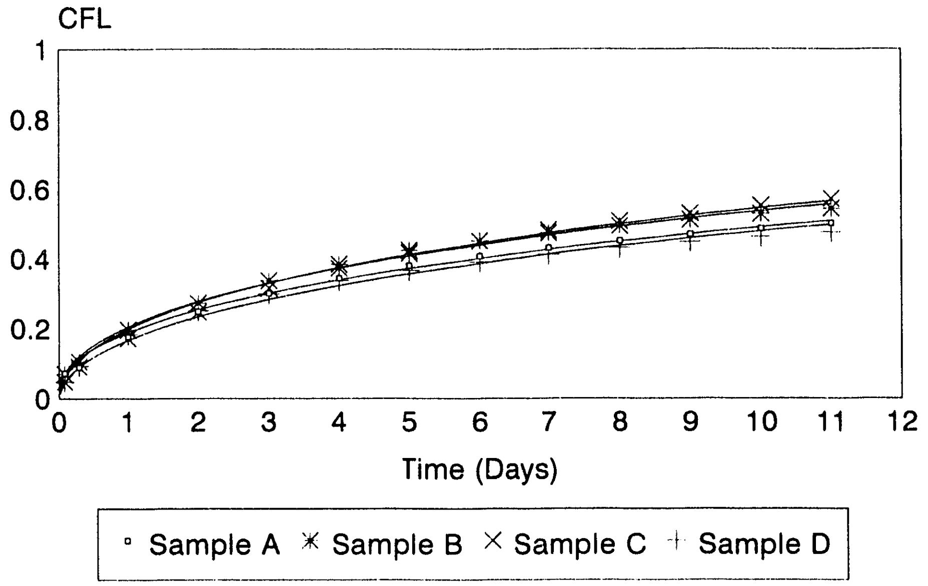

Figure 3.4 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 70 wt% tested at 20°C.

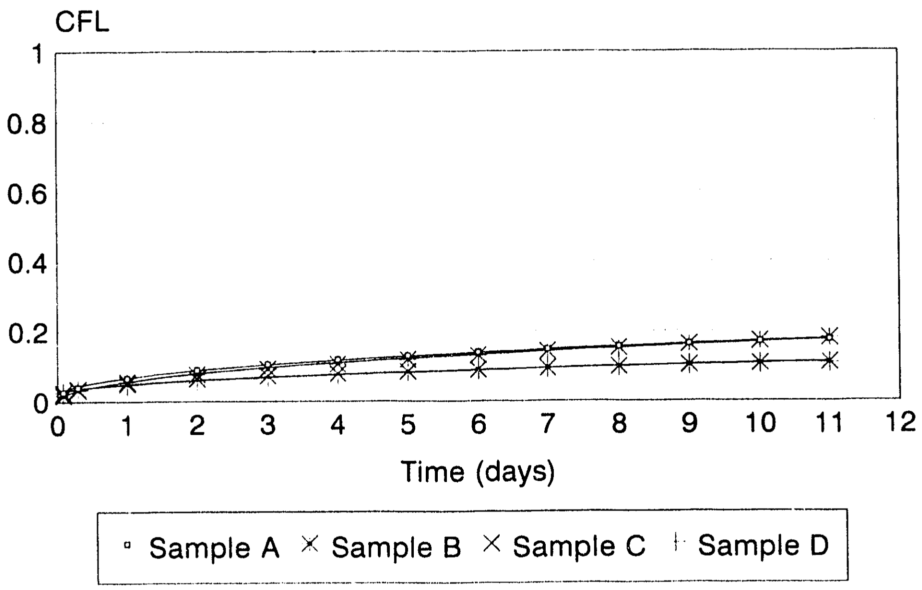

Figure 3.5 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 50 wt% tested at 35°C.

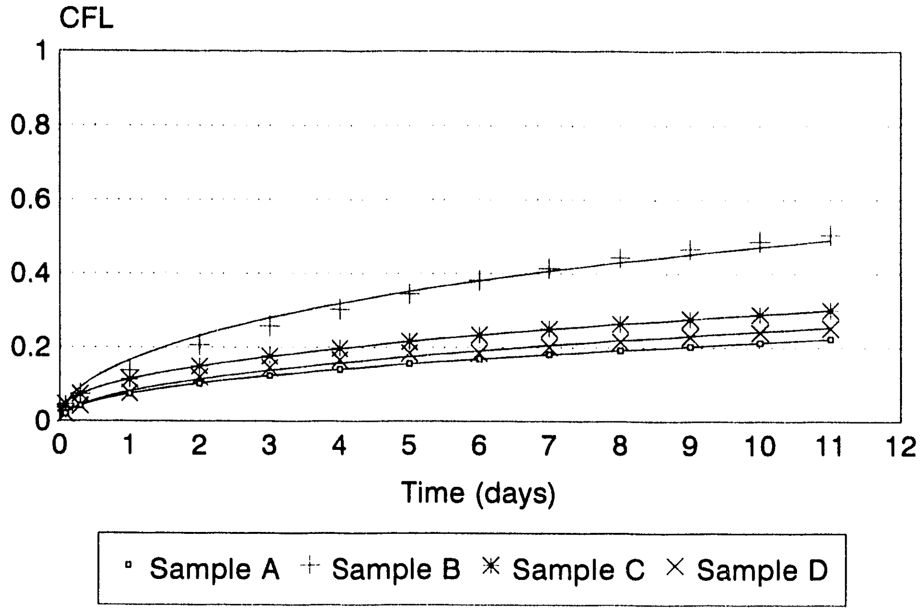

Figure 3.6 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 60 wt% tested at 35°C.

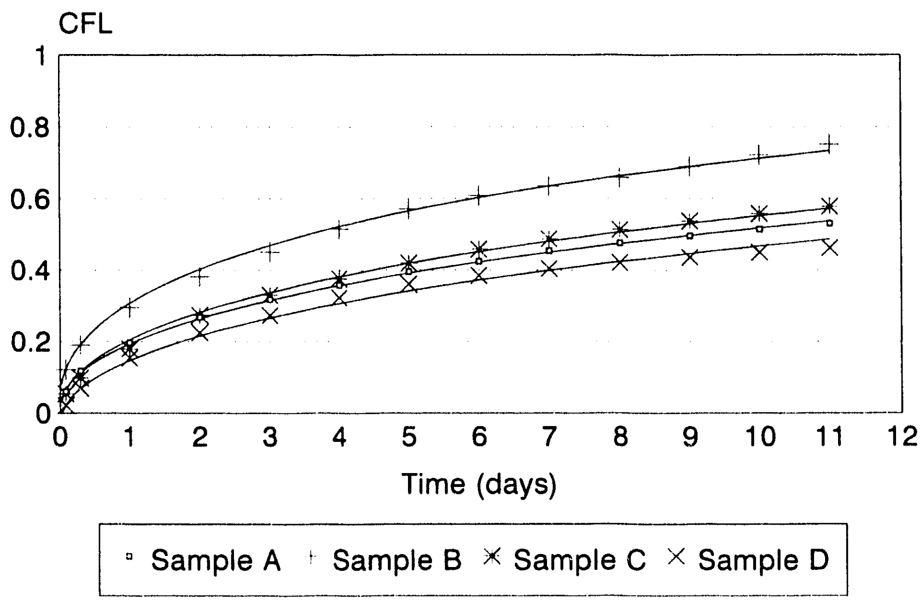

Figure 3.7 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 70 wt% tested at 35°C.

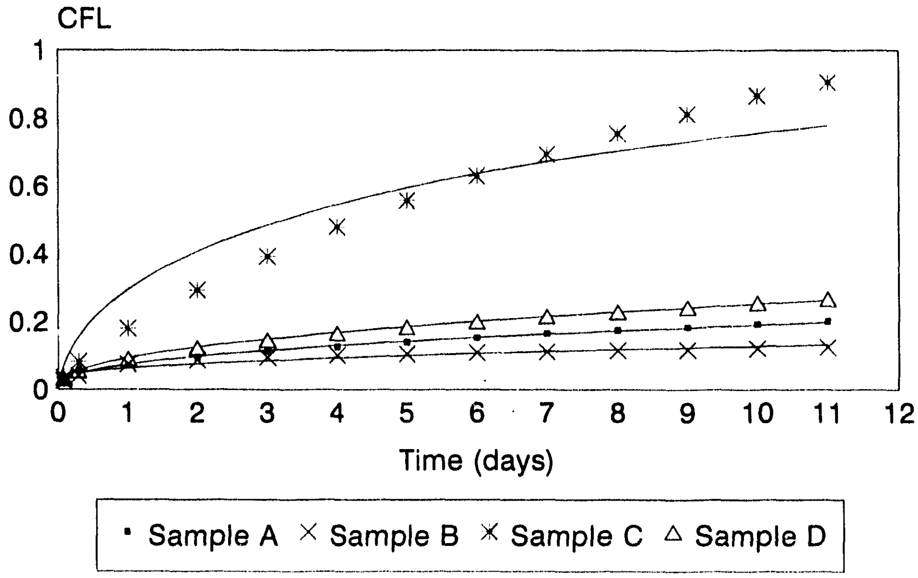

Figure 3.8 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 50 wt% tested at 50°C.

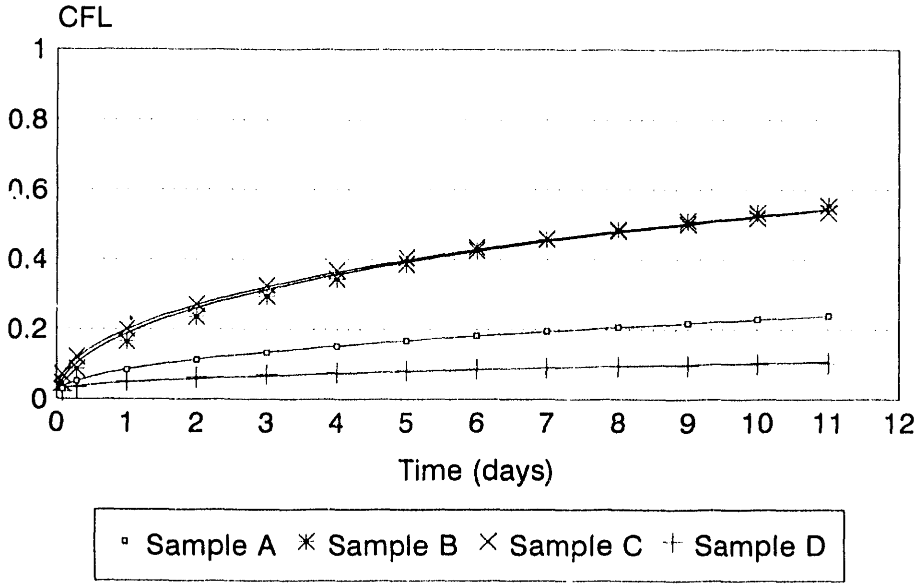

Figure 3.9 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 60 wt% tested at 50°C.

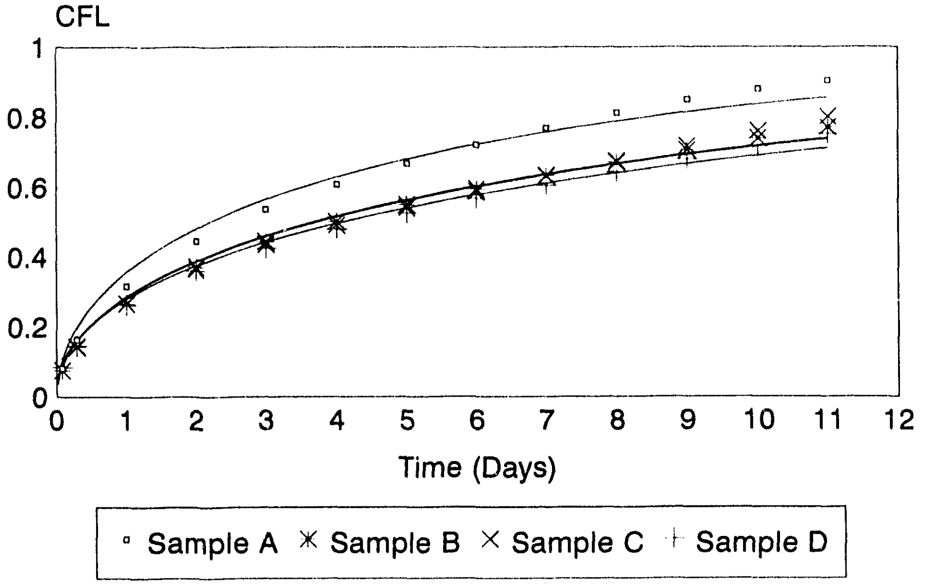

Figure 3.10 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 70 wt% tested at 50°C.

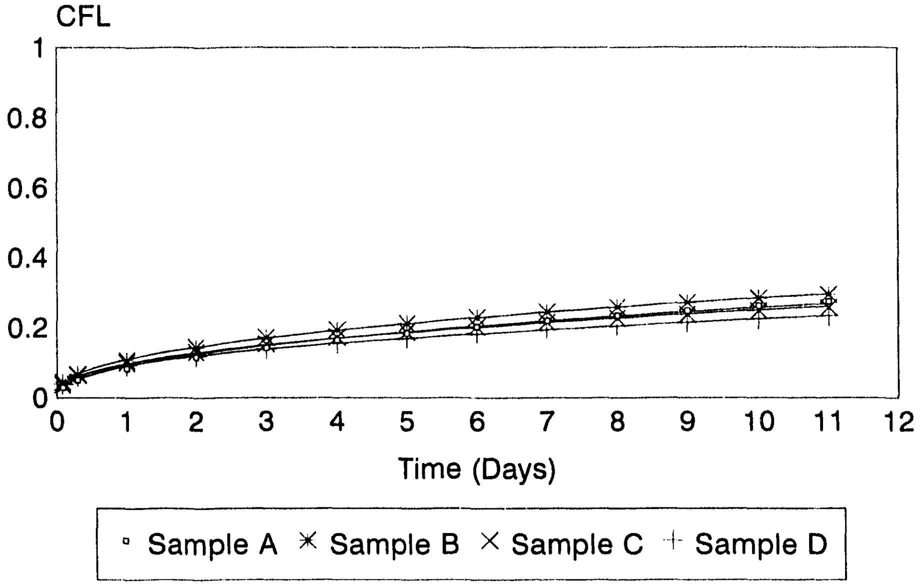

Figure 3.11 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 50 wt% tested at 70°C.

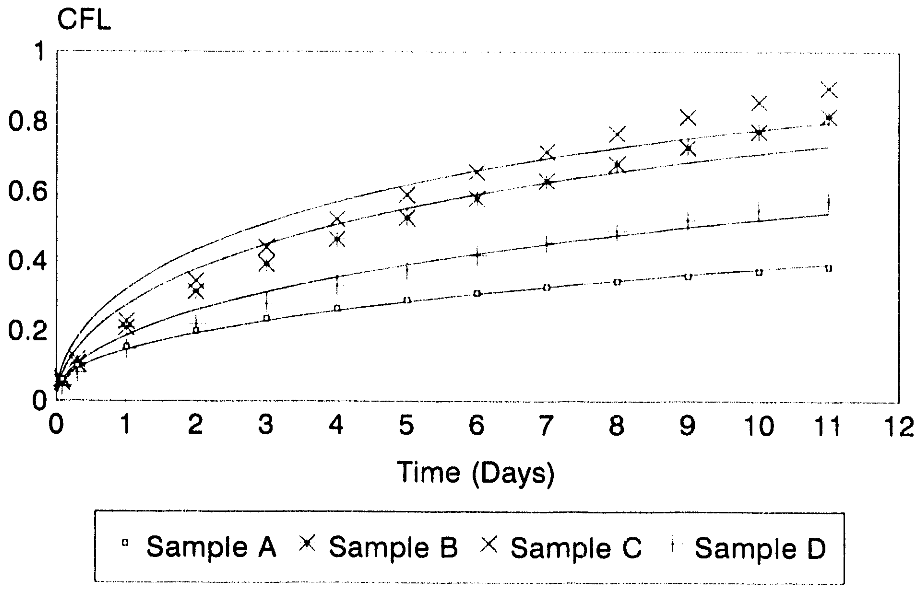

Figure 3.12 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 60 wt% tested at 70°C.

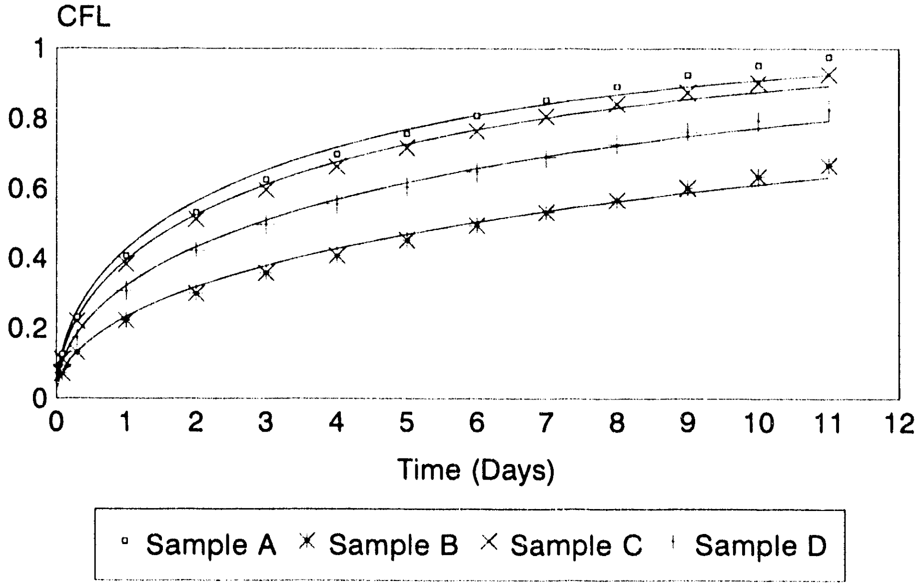

Figure 3.13 Accelerated Leach Test results for polyethylene waste forms with sodium nitrate salt loadings of 70 wt% tested at 70°C.

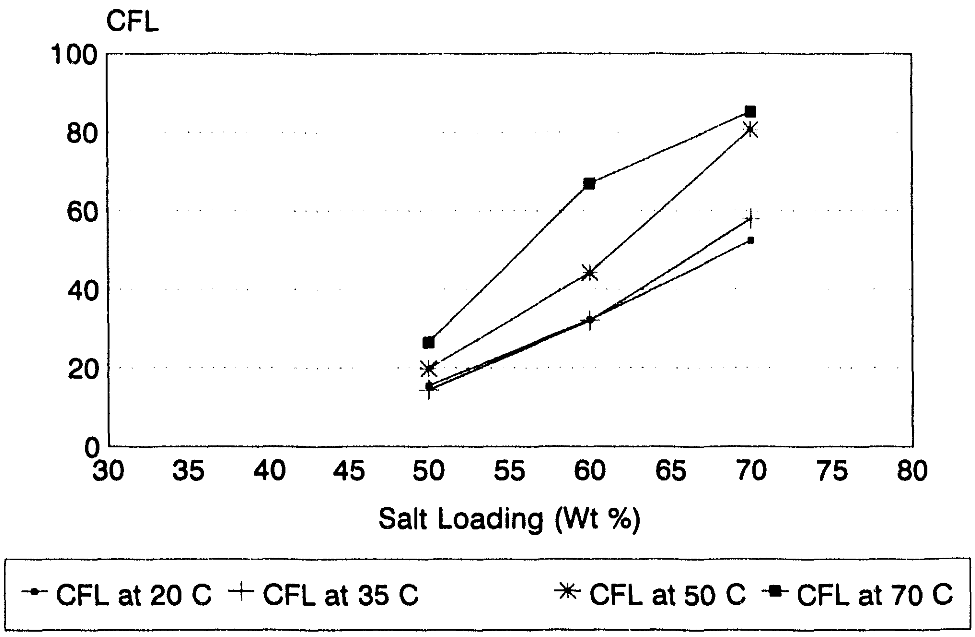

Figure 3.14 Relationship of leachability (CFL) as a function of waste loading at 20°C, 35°C, 50°C, and 70°C.

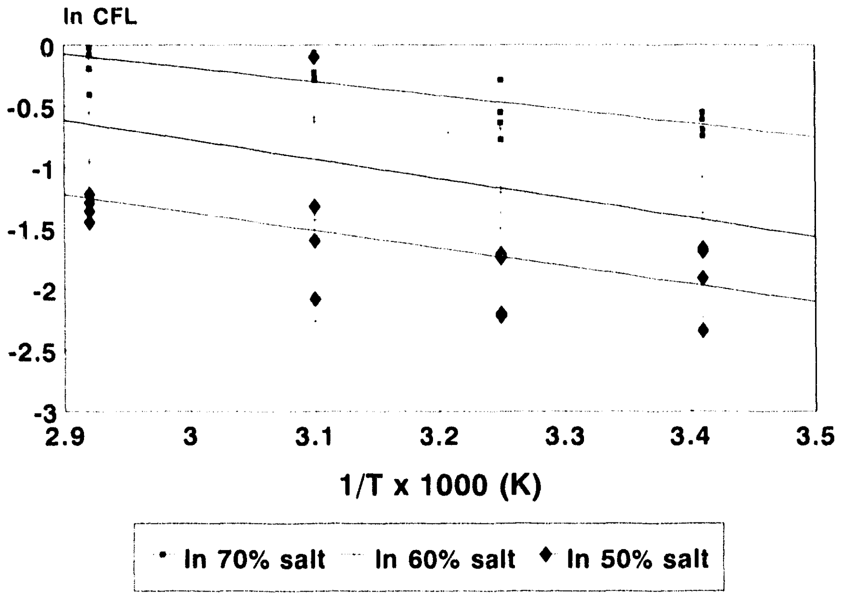

Figure 3.15 Arrhenius plot of the natural log of diffusion coefficients for polyethylene waste forms containing sodium nitrate plotted as a function of inverse leaching temperature in kelvins.

4. THERMAL EFFECTS ON WASTE FORM STRENGTH AND INTEGRITY

Since polyethylene has a melting point of 120°C and the anticipated equilibrium temperature of the SST waste is 50 - 70°C, the stability of polyethylene waste forms under these conditions was an issue raised by the UST-ID. In response, this test was conducted to examine the effects of elevated temperatures on the physical integrity and strength properties of polyethylene waste forms containing simulated sodium nitrate waste.

Simulated waste form specimens containing sodium nitrate at 50, 60, and 70 wt% waste loadings were fabricated using the BNL bench-scale extruder and prepared for testing as described in Section 2.3. 15 replicate specimens at each waste loading were thermally conditioned at each temperature (50 and 70°C) for a total of 90 specimens. Specimens were weighed and measured prior to thermal conditioning.

The two thermal test chambers (Cole Parmer Instruments) are microprocessor controlled with RTD sensors, and digital display of actual and set temperatures. Heat transfer is by convection, regulated by a variable speed air-circulating fan. Temperature stability specifications are $\pm$ 0.5°C at 100°C. Thermocouples were installed inside the chambers and in the center of several waste forms to monitor temperatures over the course of the experiment. A data acquisition system was used to log temperatures.

After three months of conditioning at 50°C and 70°C, 5 replicates of each waste loading (a total of 30 specimens) were removed from the chambers and allowed to equilibrate to ambient temperature. The remaining specimens were left in the chambers to examine the effects of elevated temperatures for longer times. Following thermal conditioning, specimens were weighed and measured again to check for changes in mass or dimensions resulting from storage at elevated temperatures. Data are included in the Appendix. Changes in weight were very slight - the maximum weight gain or loss was 0.05%. Slight changes in physical dimensions were recorded resulting in volume changes up to about 2.5%, but these variations are within the limits of normal measurement error.

Thermally conditioned specimens were then tested for changes in mechanical strength according to ASTM Method D-695, "Standard Method of Test for Compressive Properties of Rigid Plastics." Since polyethylene specimens do not always fail catastrophically, stress was plotted as a function of time. Compressive yield strength was determined at the point where the slope decreased to zero. A typical plot of compressive stress vs. time is shown in Figure 4.1. The remaining plots are included in the Appendix. Compressive yield strength for UST-ID polyethylene waste forms containing sodium nitrate stored at elevated and ambient temperatures is presented in Table 4.1 and Figures 4.2 and 4.3. These data represent the average of 5 replicates with the associated error reported at the 95% confidence limit. Although the percent of original strength ranged from 94% to 111%, no statistically significant changes in compressive yield strength were observed as a result of thermal conditioning at these anticipated temperatures for periods of 3 months.

Table 4.1 Compressive Yield Strength for UST-ID Polyethylene Waste Forms Containing Sodium Nitrate Stored at Elevated and Ambient Temperatures[a]

	Control (ambient temperature)	Stored at 50°C, 3 months		Stored at 70 °C, 3 months	
Waste Loading, wt%	Yield Strength, psi	Yield Strength, psi	% of Original Strength	Yield Strength, psi	% of Original Strength
50	2080 ± 260	2010 ± 280	96.6	1960 ± 130	94.2
60	1600 ± 140	1730 ± 150	108.1	1780 ± 200	111.3
70	1500 ± 200	1570 ± 200	104.7	1580 ± 200	105.3

a) Average of 5 replicates. Error calculated at 95% confidence limit.

Preliminary results after 3 months of storage at 50°C and 70°C indicate that the mechanical integrity and strength of polyethylene waste forms containing sodium nitrate would not be affected by anticipated thermal loads associated with SST wastes. Further work planned for FY 1993 will examine potential effects at longer times, elevated temperature creep behavior, and possible synergistic effects of high radiation dose and temperature.

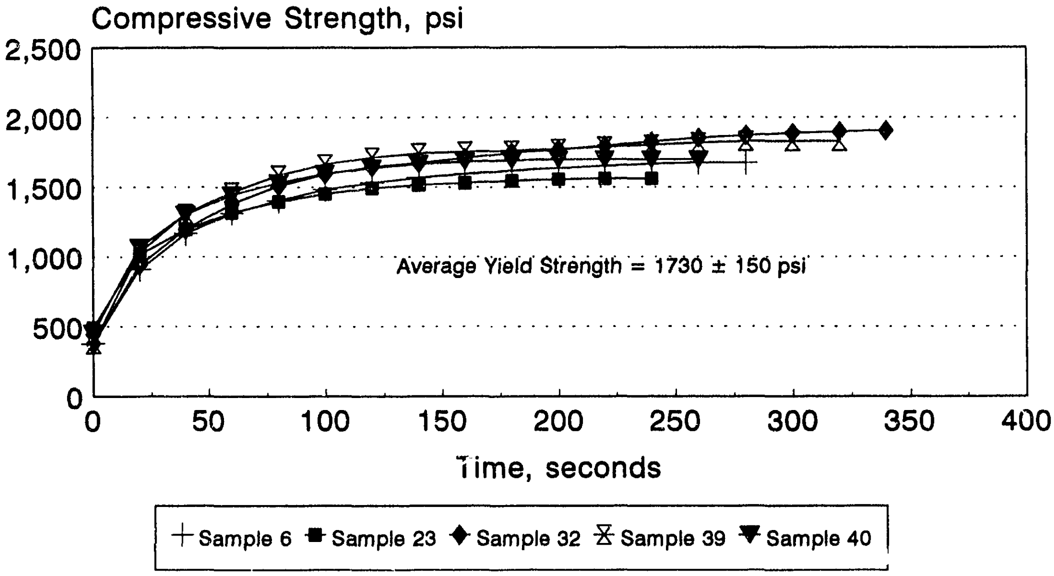

Figure 4.1 Typical compressive yield stress data plotted as a function of time for 5 replicate polyethylene waste form specimens containing sodium nitrate (60 wt% $NaNO_3$, stored at 50°C for 3 months).

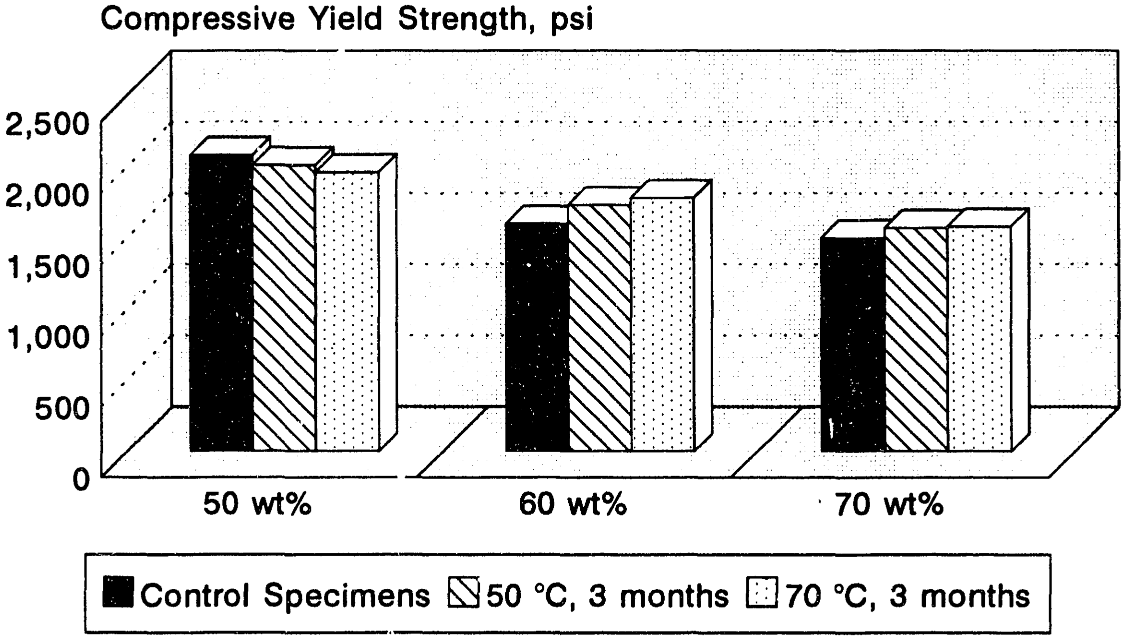

Figure 4.2 Compressive yield strength for UST-ID polyethylene waste forms containing sodium nitrate stored at elevated and ambient temperatures.

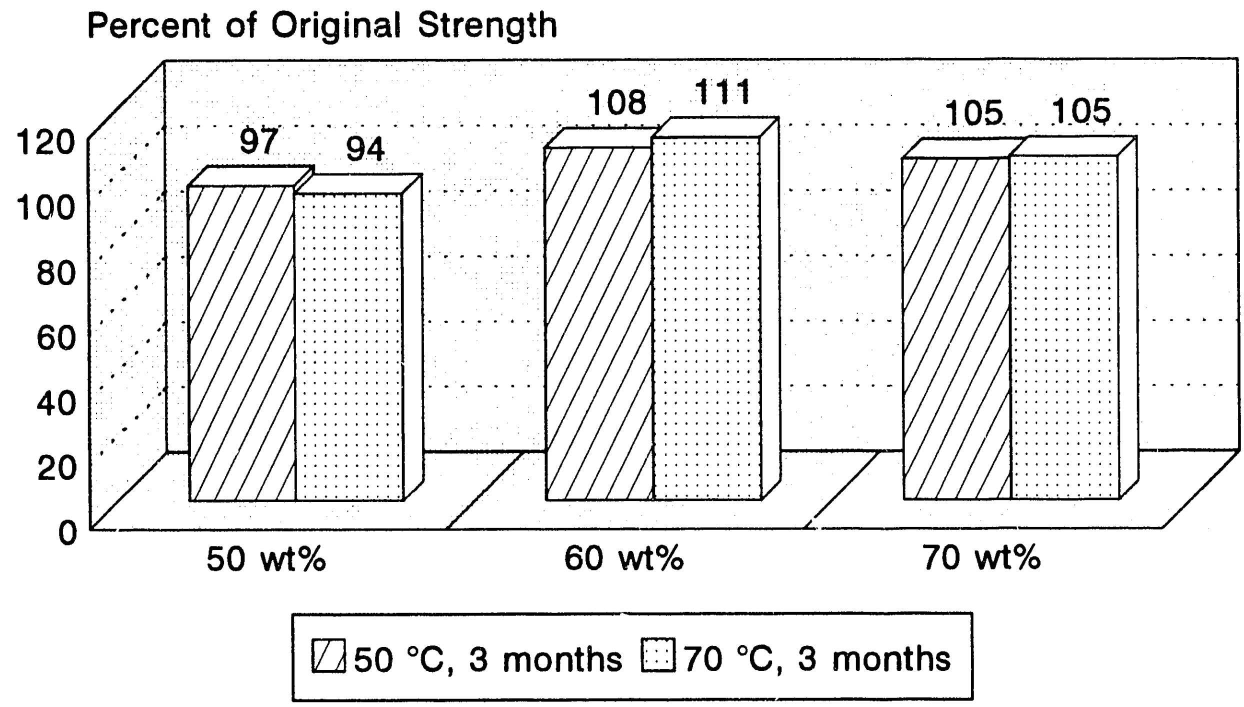

Figure 4.3 Percent of original compressive strength for polyehtylene waste forms containing sodium nitrate.

5. SUMMARY AND CONCLUSIONS

Testing completed in FY 1992 represents an important step toward determining the performance of polyethylene waste forms for SST LLW under anticipated conditions. The information generated as a result of this activity will assist Westinghouse Hanford Co. and the Underground Storage Tank Integrated Demonstration in assessing potential alternatives for improved final waste forms needed to stabilize tank wastes.

Although Phase I of this effort is not yet completed, several significant findings and conclusions can be drawn as a result of the work completed to date:

- The leaching of nitrates and other soluble salts from polyethylene waste forms is diffusion controlled, enabling prediction of releases for full-scale waste forms over long time intervals.

- Full-scale polyethylene waste forms can be expected to leach a total of 5% to 17% of the original contaminant source term (for waste forms containing 50 wt% and 70 wt% nitrate salts, respectively) after 300 years of leaching under worst-case (70°C, fully saturated) conditions.

- Elevated temperatures up to 70°C have a negligible impact on polyethylene leachability. Compared with leaching at ambient temperature, projected cumulative fraction releases for full-scale polyethylene waste forms increase by factors of 1.4 to 1.8 for waste forms containing 50 wt% to 70 wt% nitrate salt, respectively.

- Compared with conventional cement grout waste forms, polyethylene encapsulation of SST nitrate salt wastes can reduce long-term leachability by 25 to 75 times.

- Elevated temperatures appear to have negligible impact on polyethylene waste form mechanical properties and durability.

- Waste form test specimens stored at temperatures of 70°C for up to 3 months showed no significant change in weight or dimensions.

- Compressive yield strength for polyethylene waste forms containing sodium nitrate waste was unaffected by thermal conditioning of 70°C for up to 3 months.

Additional testing for Phase I of this effort is scheduled to be completed in FY 1993. This work will focus on examination of the effects of elevated temperature at longer time intervals, potential impacts on waste form properties due to elevated temperature creep, and possible synergistic effects of irradiation at elevated temperatures. Upon successful completion of Phase I, waste form development and testing using SST LLW surrogates will be initiated, leading to scale-up feasibility and full-scale demonstration of the polyethylene encapsulation process for SST LLW surrogates.

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APPENDIX

Feeder Calibration Data:

Date: 10/28/91 **Material:** LDPE
Feeder: B **Helix:** 0.5"
Tube: 0.75"

	Feed Rate, g/min				
Speed: / Trial No.	**100**	**250**	**500**	**750**	**900**
1	14.99	36.6	101	154.7	187.91
2	15.51	37.74	100.5	155.33	188.86
3	14.85	37.74	99.7	153.97	187.69
4	14.88	38.32	102.1	154.1	189.62
5	15.89	37.82	100.8	154.02	189.29
6	15.61	37.82	100.5	156.46	189.91
7	14.81	38.58	99.85	155.6	191
8	15.34	38.16	100.41	154.47	190.92
9	14.86	37.8	101.72	156.91	190.95
10	15.28	38.44	100.31	154.98	191.36
Total	152.02	379.02	1006.89	1550.54	1897.51
Mean	15.20	37.90	100.69	155.05	189.75
Std. Dev.	0.361	0.526	0.717	0.971	1.251
Absolute Error	0.258	0.376	0.513	0.694	0.895
Relative Error, %	1.70	0.99	0.51	0.45	0.47

Feeder B, Linear Regression Analysis:

Speed	Output, g/min
100	15.20
250	37.90
500	100.69
750	155.97
900	189.75

Regression Output:

Constant		-11.7114
Std Err of Y Est		4.488169
R Squared		0.997282
No. of Observations		5
Degrees of Freedom		3
X Coefficient(s)	0.223228	
Std Err of Coef.	0.006728	

Density Data for UST-ID Thermal Test Specimens

file dpe50ust
Density of Polyethylene/ 50 wt% $NaNO_3$
UST-ID TTP# CH321201
Thermal Conditioning Specimens

Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
1	195.03	90.79	45.80	45.97	45.60	22.99	150.69	1.294
2	186.78	88.39	46.06	45.83	45.69	22.92	145.81	1.281
3	192.81	90.20	46.25	46.05	45.87	23.03	150.23	1.283
4	194.16	90.27	46.07	45.99	46.26	23.00	149.95	1.295
5	196.77	91.27	46.81	46.32	46.04	23.16	153.80	1.279
6	195.28	89.97	46.25	46.42	46.55	23.21	152.26	1.283
7	196.35	90.99	46.15	46.06	46.37	23.03	151.61	1.295
8	198.78	92.16	46.62	46.46	46.12	23.23	156.24	1.272
9	199.96	92.06	46.61	46.52	46.36	23.26	156.47	1.278
10	195.90	90.52	46.60	46.46	46.37	23.23	153.46	1.277
11	195.07	91.78	46.45	46.24	46.02	23.12	154.13	1.266
12	196.48	90.67	46.44	46.45	46.21	23.23	153.65	1.279
13	196.58	92.22	46.19	46.17	46.54	23.09	154.40	1.273
14	197.94	91.44	46.61	46.51	46.10	23.26	155.35	1.274
15	198.35	91.50	46.01	46.01	46.68	23.01	152.13	1.304
16	198.78	92.21	46.49	46.30	46.22	23.15	155.25	1.280
17	198.35	91.92	46.46	46.35	46.40	23.18	155.10	1.279
18	197.52	91.02	46.56	46.23	46.00	23.12	152.78	1.293
19	198.03	91.51	46.55	46.67	46.09	23.34	156.54	1.265
20	192.78	91.17	45.70	46.27	46.22	23.14	153.30	1.258
21	195.37	91.04	46.23	46.27	46.45	23.14	153.08	1.276
22	193.73	89.38	46.46	46.60	46.02	23.30	152.44	1.271
23	195.84	90.22	46.72	46.55	46.23	23.28	153.54	1.275
24	198.25	91.69	46.78	46.52	46.15	23.26	155.84	1.272
25	193.46	90.91	46.11	45.95	45.97	22.98	150.76	1.283
26	197.10	90.90	46.72	46.51	46.18	23.26	154.44	1.276
27	196.68	90.84	46.68	46.53	46.33	23.27	154.47	1.273
28	193.41	89.33	46.46	45.69	46.35	22.85	146.46	1.321
29	193.56	91.21	46.61	46.45	46.22	23.23	154.56	1.252
30	194.48	88.83	46.42	46.36	46.40	23.18	149.95	1.297
31	187.20	87.18	46.17	46.15	45.98	23.08	145.83	1.284
32	189.65	87.93	46.20	46.02	45.92	23.01	146.26	1.297
33	200.69	92.10	46.23	46.12	46.32	23.06	153.86	1.304
34	196.88	89.92	46.24	46.16	45.97	23.08	150.48	1.308
35	184.42	88.92	46.23	46.14	46.14	23.07	148.68	1.240
36	185.82	87.41	45.90	46.07	46.31	23.0[illegible]	145.71	1.275
37	192.15	89.57	46.21	46.01	46.21	23.01	148.92	1.290
38	189.62	89.02	46.35	46.02	45.98	23.[illegible]	148.07	1.281
39	189.55	88.46	46.04	45.97	45.86	22.9[illegible]	146.82	1.291
40	167.07	81.28	46.22	46.00	45.88	23.0[illegible]	135.08	1.237
					avg radius	23.11713		
					avg area,in	2.602256		

Sum	51.212
Average	1.280
Standard Deviation	0.0164
Error	0.0053
% Error	0.0041

file dpe60ust
Density of Polyethylene/ 60 wt% $NaNO_3$
UST-ID TTP# CH321202
Thermal Conditioning Specimens

Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
1	222.00	93.68	46.40	46.60	46.50	23.30	159.77	1.389
2	211.50	91.40	46.85	46.75	46.70	23.38	156.89	1.348
3	218.42	91.25	46.45	46.60	46.80	23.30	155.63	1.403
4	225.18	93.60	46.75	46.50	45.90	23.25	158.95	1.417
5	211.91	91.69	46.70	46.55	46.35	23.28	156.05	1.358
6	209.89	89.97	46.60	46.65	46.65	23.33	153.78	1.365
7	215.65	91.64	46.35	46.47	46.60	23.24	155.42	1.387
8	213.31	91.60	46.75	46.80	46.50	23.40	157.57	1.354
9	212.37	91.00	46.55	46.55	46.75	23.28	154.87	1.371
10	213.18	92.20	46.35	46.40	46.80	23.20	155.90	1.367
11	215.15	92.02	46.65	46.55	46.40	23.28	156.61	1.374
12	216.68	92.95	46.76	46.67	46.30	23.34	159.01	1.363
13	211.63	91.42	46.40	46.45	46.47	23.23	154.92	1.366
14	214.62	92.05	46.80	46.66	46.45	23.33	157.40	1.364
15	212.37	91.12	46.40	46.62	46.86	23.31	155.54	1.365
16	212.45	91.54	46.52	46.76	46.71	23.38	157.20	1.351
17	213.61	90.99	46.53	46.51	46.40	23.26	154.59	1.382
18	214.92	91.87	46.43	46.70	46.82	23.35	157.36	1.366
19	214.89	91.78	46.80	46.69	46.67	23.35	157.14	1.368
20	212.00	90.86	46.56	46.70	46.50	23.35	155.63	1.362
21	210.67	90.77	46.57	46.36	46.59	23.18	153.22	1.375
22	214.76	91.60	46.67	46.63	46.60	23.32	156.43	1.373
23	216.59	92.32	46.55	46.60	46.57	23.30	157.46	1.376
24	212.38	90.30	46.46	46.40	46.50	23.20	152.69	1.391
25	217.61	91.99	46.52	46.60	46.65	23.30	156.89	1.387
26	211.74	90.69	46.51	46.58	46.56	23.29	154.54	1.370
27	214.89	91.23	46.67	46.71	46.87	23.36	156.33	1.375
28	214.05	91.77	46.28	46.33	46.58	23.17	154.71	1.384
29	216.09	92.34	46.45	46.30	46.20	23.15	155.47	1.390
30	213.26	92.18	46.84	46.63	46.30	23.32	157.42	1.355
31	212.63	91.74	46.36	46.40	46.43	23.20	155.13	1.371
32	212.20	90.85	46.63	46.52	46.75	23.26	154.42	1.374
33	217.13	93.07	46.68	46.51	46.48	23.26	158.12	1.373
34	213.57	91.88	46.68	46.52	46.47	23.26	156.17	1.368
35	206.18	90.30	46.56	46.55	46.58	23.28	153.68	1.342
36	212.45	90.90	46.65	46.77	46.83	23.39	156.17	1.360
37	214.10	91.89	46.40	46.58	46.69	23.29	156.59	1.367
38	204.26	90.72	46.20	46.33	46.40	23.17	152.94	1.336
39	214.84	91.35	46.52	46.59	46.66	23.30	155.73	1.380
40	218.89	93.15	46.58	46.63	46.59	23.32	159.08	1.376
					avg radius	23.284		
					avg area,in	2.639962		

Sum	54.841
Average	1.371
Standard Deviation	0.0154
Error	0.0049
% Error	0.0036

Density Data for UST-ID Thermal Test Specimens

file dpe70ust
Density of Polyethylene/ 70 wt% NaNO3
UST-ID TTP# CH321202
Thermal Conditioning Specimens

Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
1	248.60	91.99	46.85	46.75	46.62	23.38	157.90	1.574
2	235.75	92.57	46.70	46.65	46.52	23.33	158.22	1.490
3	248.12	92.25	47.10	46.73	46.55	23.37	158.22	1.568
4	235.73	91.92	46.60	46.70	46.60	23.35	157.45	1.497
5	252.30	93.04	46.85	46.90	46.75	23.45	160.73	1.570
6	250.33	91.88	46.80	46.85	46.65	23.43	158.39	1.580
7	245.30	90.47	47.15	47.05	46.90	23.53	157.29	1.559
8	241.10	92.03	46.55	46.50	46.60	23.25	156.29	1.543
9	250.43	92.50	46.15	46.50	46.66	23.25	157.09	1.594
10	251.04	92.25	47.15	47.00	46.59	23.50	160.05	1.569
11	247.12	91.33	47.00	46.90	46.75	23.45	157.78	1.566
12	246.57	90.97	46.95	47.00	46.70	23.50	157.83	1.562
13	250.32	92.06	46.90	46.55	46.75	23.28	156.68	1.598
14	248.25	91.59	46.75	46.80	46.85	23.40	157.55	1.576
15	239.69	92.37	46.88	46.85	46.77	23.43	159.24	1.505
16	247.41	90.98	47.15	46.78	46.67	23.39	156.37	1.582
17	248.29	91.35	46.90	46.96	46.87	23.48	158.22	1.569
18	246.56	91.26	46.80	46.70	46.66	23.35	156.32	1.577
19	241.92	92.30	46.86	46.68	46.20	23.34	157.96	1.532
20	247.80	90.62	47.00	47.11	46.95	23.56	157.96	1.569
21	247.46	92.31	46.99	46.85	46.75	23.43	159.13	1.555
22	250.93	92.68	47.05	46.90	46.60	23.45	160.11	1.567
23	249.49	92.07	47.00	46.87	46.70	23.44	158.85	1.571
24	239.84	92.62	46.95	47.00	46.50	23.50	160.69	1.493
25	245.46	91.02	47.02	46.91	46.75	23.46	157.31	1.560
26	237.52	92.11	46.75	46.65	46.50	23.33	157.43	1.509
27	248.70	91.92	47.10	46.80	46.68	23.40	158.12	1.573
28	238.74	92.27	46.50	46.85	46.50	23.43	159.06	1.501
29	235.76	92.91	46.75	46.60	46.50	23.30	158.46	1.488
30	235.06	92.20	46.65	46.58	46.40	23.29	157.12	1.496
31	235.89	91.97	46.70	46.75	46.62	23.38	157.87	1.494
32	248.85	92.06	46.90	46.80	46.70	23.40	158.36	1.571
33	236.49	92.30	46.70	46.72	46.60	23.36	158.23	1.495
34	239.35	93.01	46.40	46.52	46.65	23.26	158.09	1.514
35	248.32	91.49	46.95	46.80	46.80	23.40	157.38	1.578
36	241.76	93.95	46.77	46.70	46.65	23.35	160.92	1.502
37	238.15	91.42	46.85	46.80	46.70	23.40	157.26	1.514
38	246.42	91.87	46.88	46.75	46.65	23.38	157.70	1.563
39	237.73	92.82	46.70	46.70	46.45	23.35	158.99	1.495
					avg radius	23.39115		
					avg area,in	2.664316		

Sum	60.220
Average	1.544
Standard Deviation	0.0354
Error	0.0113
% Error	0.0073

file: ust50%50.wk3
Density of Polyethylene/ 70 wt% NaNO3
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 50 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	2	186.78	88.39	46.06	45.83	45.69	22.92	145.81	1.281
After		186.68	88.4936		46.3804		23.19	149.51	1.249
Change		-0.1	0.1036		0.5504		0.2752	3.698346	-0.03236
% Change		-0.05354	0.117208		1.20096		1.20096	2.536383	-2.52586
Before	24	198.25	91.69	46.78	46.52	46.15	23.26	155.84	1.272
After		198.24	91.694		46.4312		23.22	155.26	1.277
Change		-0.01	0.004		-0.0888		-0.0444	-0.58763	0.00475
% Change		-0.00504	0.004363		-0.19089		-0.19089	-0.37706	0.373425
Before	29	193.56	91.21	46.61	46.45	46.22	23.23	154.56	1.252
After		193.51	91.1606		46.1264		23.06	152.33	1.270
Change		-0.05	-0.0494		-0.3236		-0.1618	-2.22861	0.017993
% Change		-0.02583	-0.05416		-0.69666		-0.69666	-1.44188	1.436766
Before	34	196.88	89.92	46.24	46.16	45.97	23.08	150.48	1.308
After		196.88	89.8144		46.5836		23.29	153.07	1.286
Change		0	-0.1056		0.4236		0.2118	2.59453	-0.02218
% Change		0	-0.11744		0.917678		0.917678	1.724174	-1.69495
Before	39	189.55	88.46	46.04	45.97	45.86	22.99	146.82	1.291
After		189.49	88.4682		46.228		23.11	148.49	1.276
Change		-0.06	0.0082		0.258		0.129	1.666402	-0.01489
% Change		-0.03165	0.00927		0.561236		0.561236	1.134995	-1.15356

file: ust60%50.wk3
Density of Polyethylene/ 60 wt% NaNO3
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 50 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	6	209.89	89.97	46.60	46.65	46.65	23.33	153.78	1.365
After		209.87	89.8906		46.355		23.18	151.70	1.383
Change		-0.02	-0.0794		-0.295		-0.1475	-2.07272	0.018517
% Change		-0.00953	-0.08825		-0.63237		-0.63237	-1.34788	1.356634
Before	23	216.59	92.32	46.55	46.60	46.57	23.30	157.46	1.376
After		216.48	91.9988		46.5836		23.29	156.80	1.381
Change		-0.11	-0.3212		-0.0164		-0.0082	-0.65824	0.005073
% Change		-0.05079	-0.34792		-0.03519		-0.03519	-0.41805	0.368804
Before	32	212.20	90.85	46.63	46.52	46.75	23.26	154.42	1.374
After		212.23	90.7288		46.7614		23.38	155.82	1.362
Change		0.03	-0.1212		0.2414		0.1207	1.3986	-0.01214
% Change		0.014138	-0.13341		0.518917		0.518917	0.905731	-0.88359
Before	39	214.84	91.35	46.52	46.59	46.66	23.30	155.73	1.380
After		214.82	91.313		46.7106		23.36	156.48	1.373
Change		-0.02	-0.037		0.1206		0.0603	0.743886	-0.00669
% Change		-0.00931	-0.0405		0.258854		0.258854	0.477664	-0.48466
Before	40	218.89	93.15	46.58	46.63	46.59	23.32	159.08	1.376
After		218.79	93.0148		46.5836		23.29	158.53	1.380
Change		-0.1	-0.1352		-0.0464		-0.0232	-0.54685	0.004116
% Change		-0.04569	-0.14514		-0.09951		-0.09951	-0.34377	0.299111

file: ust70%50.wk3
Density of Polyethylene/ 70 wt% $NaNO_3$
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 50 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	3	248.12	92.25	47.10	46.73	46.55	23.37	158.22	1.568
After		248.24	92.1766		46.9392		23.47	159.51	1.556
Change		0.12	-0.0734		0.2092		0.1046	1.292744	-0.01196
% Change		0.048364	-0.07957		0.447678		0.447678	0.81708	-0.76249
Before	15	239.69	92.37	46.88	46.85	46.77	23.43	159.24	1.505
After		239.61	92.3544		46.9646		23.48	159.99	1.498
Change		-0.08	-0.0156		0.1146		0.0573	0.752942	-0.00758
% Change		-0.03338	-0.01689		0.24461		0.24461	0.472848	-0.50384
Before	30	235.06	92.20	46.65	46.58	46.40	23.29	157.12	1.496
After		235.03	92.1512		46.4312		23.22	156.03	1.506
Change		-0.03	-0.0488		-0.1488		-0.0744	-1.08484	0.01021
% Change		-0.01276	-0.05293		-0.31945		-0.31945	-0.69047	0.68242
Before	35	248.32	91.49	46.95	46.80	46.80	23.40	157.38	1.578
After		248.38	91.5416		46.863		23.43	157.90	1.573
Change		0.06	0.0516		0.063		0.0315	0.513008	-0.00475
% Change		0.024162	0.0564		0.134615		0.134615	0.325964	-0.30082
Before	37	238.15	91.42	46.85	46.80	46.70	23.40	157.26	1.514
After		238.1	91.4146		46.1772		23.09	153.09	1.555
Change		-0.05	-0.0054		-0.6228		-0.3114	-4.16677	0.04089
% Change		-0.021	-0.00591		-1.33077		-1.33077	-2.64958	2.700126

file: ust50%70.wk3
Density of Polyethylene/ 50 wt% NaNO3
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 70 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	9	199.96	92.06	46.61	46.52	46.36	23.26	156.47	1.278
After		200.06	92.075		46.2534		23.13	154.71	1.293
Change		0.1	0.015		-0.2666		-0.1333	-1.76311	0.01521
% Change		0.05001	0.016294		-0.57309		-0.57309	-1.12678	1.190203
Before	21	195.37	91.04	46.23	46.27	46.45	23.14	153.08	1.276
After		195.47	91.1352		46.5074		23.25	154.82	1.263
Change		0.1	0.0952		0.2374		0.1187	1.736594	-0.01367
% Change		0.051185	0.104569		0.513075		0.513075	1.134429	-1.07109
Before	27	196.68	90.84	46.68	46.53	46.33	23.27	154.47	1.273
After		196.77	90.8812		46.6598		23.33	155.40	1.266
Change		0.09	0.0412		0.1298		0.0649	0.933447	-0.00707
% Change		0.04576	0.045354		0.27896		0.27896	0.604306	-0.55519
Before	32	189.65	87.93	46.20	46.02	45.92	23.01	146.26	1.297
After		189.73	87.8586		45.5168		22.76	142.96	1.327
Change		0.08	-0.0714		-0.5032		-0.2516	-3.29718	0.030466
% Change		0.042183	-0.0812		-1.09344		-1.09344	-2.25435	2.349503
Before	36	185.82	87.41	45.90	46.07	46.31	23.04	145.71	1.275
After		185.89	87.1982		46.5836		23.29	148.62	1.251
Change		0.07	-0.2118		0.5136		0.2568	2.90594	-0.02447
% Change		0.037671	-0.24231		1.114825		1.114825	1.99434	-1.91841

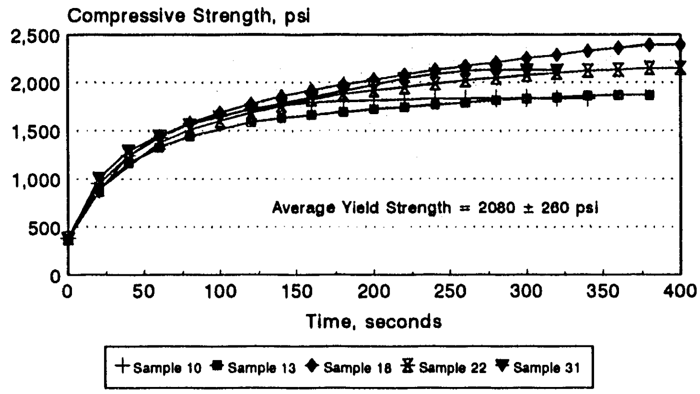
file: ust60%70.wk3
Density of Polyethylene/ 60 wt% NaNO3
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 70 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	7	215.65	91.64	46.35	46.47	46.60	23.24	155.42	1.387
After		215.69	91.6432		46.0502		23.03	152.63	1.413
Change		0.04	0.0032		-0.4198		-0.2099	-2.79013	0.025625
% Change		0.018549	0.003492		-0.90338		-0.90338	-1.79517	1.84687
Before	14	214.62	92.05	46.80	46.66	46.45	23.33	157.40	1.364
After		214.64	92.0242		46.7106		23.36	157.70	1.361
Change		0.02	-0.0258		0.0506		0.0253	0.297354	-0.00244
% Change		0.009319	-0.02803		0.108444		0.108444	0.188917	-0.17926
Before	19	214.89	91.78	46.80	46.69	46.67	23.35	157.14	1.368
After		214.95	91.8464		46.8122		23.41	158.08	1.360
Change		0.06	0.0664		0.1222		0.0611	0.937909	-0.00773
% Change		0.027921	0.072347		0.261726		0.261726	0.596864	-0.56557
Before	22	214.76	91.60	46.67	46.63	46.60	23.32	156.43	1.373
After		214.78	91.7448		46.6344		23.32	156.71	1.371
Change		0.02	0.1448		0.0044		0.0022	0.276849	-0.0023
% Change		0.009313	0.158079		0.009436		0.009436	0.176981	-0.16737
Before	31	212.63	91.74	46.36	46.40	46.43	23.20	155.13	1.371
After		212.67	91.5924		46.6852		23.34	156.79	1.356
Change		0.04	-0.1476		0.2852		0.1426	1.660182	-0.01426
% Change		0.018812	-0.16089		0.614655		0.614655	1.070215	-1.04027

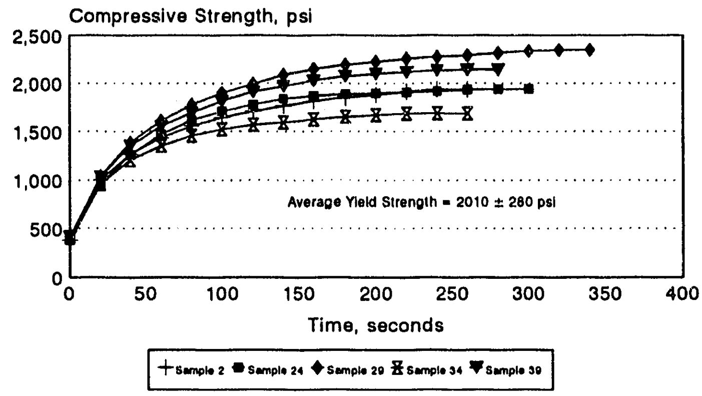
file: ust70%70.wk3
Density of Polyethylene/ 70 wt% NaNO3
UST-ID TTP# CH321201
Thermal Conditioning Specimens
Weights and Dimensions following 3 month thermal conditioning at 70 degrees C

	Sample No	Weight (gm)	Height (mm)	Top Dia. (mm)	Mid Dia. (mm)	Bot Dia. (mm)	Radius (mm)	Volume (mL)	Density (gm/cm3)
Before	19	241.92	92.30	46.86	46.68	46.20	23.34	157.96	1.532
After		242.02	92.202		46.2788		23.14	155.09	1.560
Change		0.1	-0.098		-0.4012		-0.2006	-2.86845	0.02897
% Change		0.041336	-0.10618		-0.85947		-0.85947	-1.81591	1.891594
Before	20	247.80	90.62	47.00	47.11	46.95	23.56	157.96	1.569
After		247.91	90.6272		47.2948		23.65	159.21	1.557
Change		0.11	0.0072		0.1848		0.0924	1.25433	-0.01167
% Change		0.044391	0.007945		0.392273		0.392273	0.794093	-0.7438
Before	28	238.74	92.27	46.50	46.85	46.50	23.43	159.06	1.501
After		238.76	92.2528		46.7868		23.39	158.60	1.505
Change		0.02	-0.0172		-0.0632		-0.0316	-0.45843	0.004464
% Change		0.008377	-0.01864		-0.1349		-0.1349	-0.28821	0.29744
Before	29	235.76	92.91	46.75	46.60	46.50	23.30	158.46	1.488
After		235.79	92.9132		46.5328		23.27	158.01	1.492
Change		0.03	0.0032		-0.0672		-0.0336	-0.45125	0.004439
% Change		0.012725	0.003444		-0.14421		-0.14421	-0.28477	0.298344
Before	36	241.76	93.95	46.77	46.70	46.65	23.35	160.92	1.502
After		241.74	93.9038		46.9646		23.48	162.67	1.486
Change		-0.02	-0.0462		0.2646		0.1323	1.748706	-0.01627
% Change		-0.00827	-0.04918		0.566595		0.566595	1.086667	-1.08317

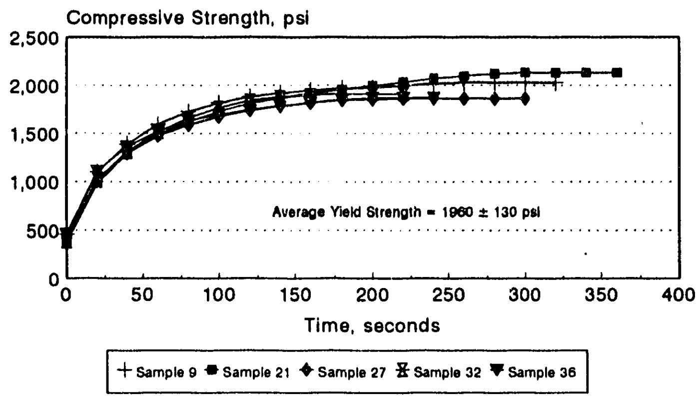
Polyethylene Waste Form Compressive Strength
50 wt% Sodium Nitrate
Control Specimens (Stored at Ambient Temp)



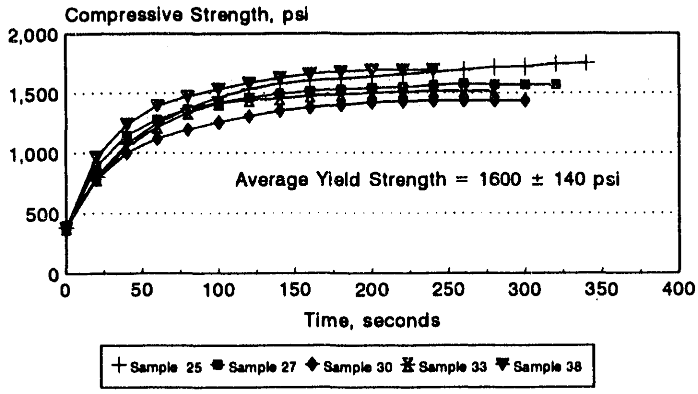
Polyethylene Waste Form Compressive Strength
50 wt% Sodium Nitrate
Conditioned at 50 °C, 3 months



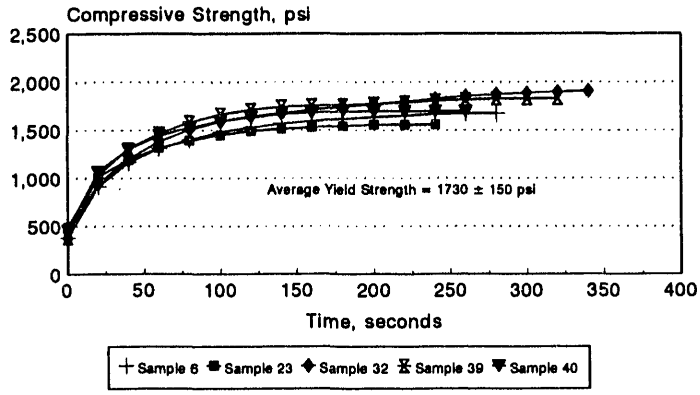
Polyethylene Waste Form Compressive Strength
50 wt% Sodium Nitrate
Conditioned at 70 °C, 3 months



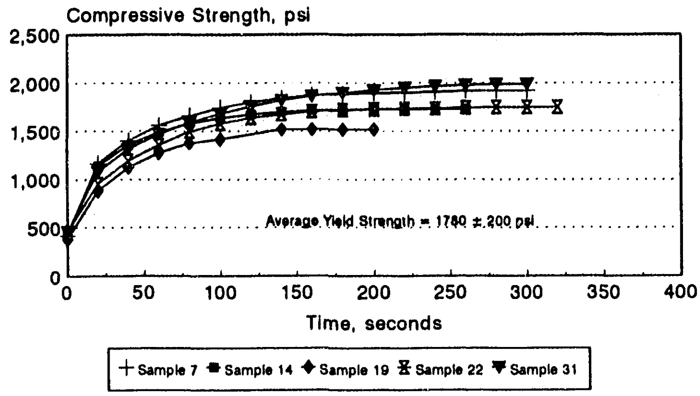
Polyethylene Waste Form Compressive Strength
60 wt% Sodium Nitrate
Control Specimens (Stored at Ambient Temp)



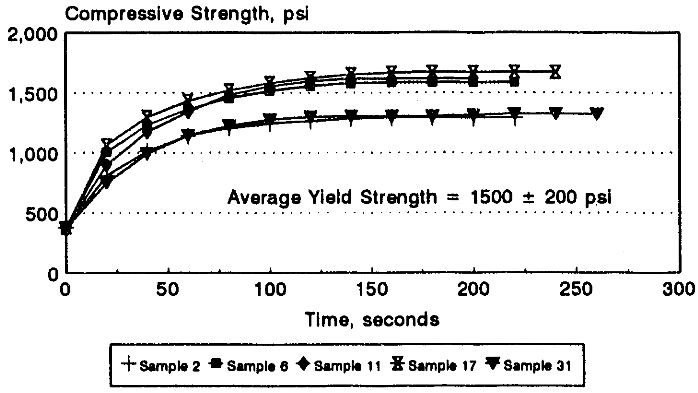
Polyethylene Waste Form Compressive Strength
60 wt% Sodium Nitrate
Conditioned at 50 °C, 3 months



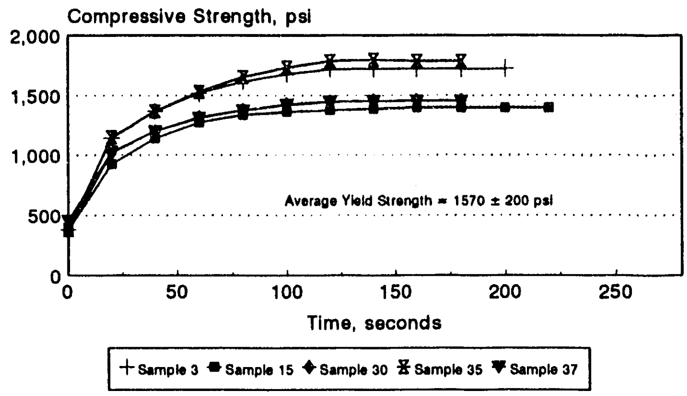
Polyethylene Waste Form Compressive Strength
60 wt% Sodium Nitrate
Conditioned at 70 °C, 3 months



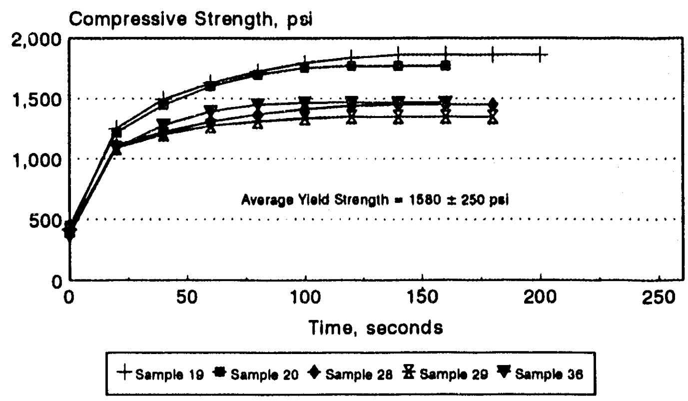
Polyethylene Waste Form Compressive Strength
70 wt% Sodium Nitrate
Control Specimens (Stored at Ambient Temp)



Polyethylene Waste Form Compressive Strength
70 wt% Sodium Nitrate
Conditioned at 50 °C, 3 months



Polyethylene Waste Form Compressive Strength
70 wt% Sodium Nitrate
Conditioned at 70 °C, 3 months



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