Solidification Testing for a High Activity Wastestream from the Savannah River Site using Grout and Gamma Radiation Shielding Materials - 10017

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ABSTRACT

The U.S. Department of Energy (DOE) tasked MSE Technology Applications, Inc. (MSE) with evaluating grouts that include gamma radiation shielding materials to solidify surrogates of liquid aqueous radioactive wastes from across the DOE Complex. The Savannah River Site (SRS) identified a High Activity Waste (HAW) that will be treated and solidified at the Waste Solidification Building (WSB) for surrogate grout testing. The HAW, which is produced at the Mixed Oxide Fuel Fabrication Facility (MFFF), is an acidic aqueous wastestream generated by the alkaline treatment process and the aqueous purification process. The HAW surrogate was solidified using Portland cement with and without the inclusion of different gamma radiation shielding materials to determine the shielding material that is the most effective to attenuate gamma radiation for this application.

INTRODUCTION

The U.S. Department of Energy (DOE) has tasked MSE Technology Applications, Inc. (MSE) with evaluating grouts using various mixing and addition methods to solidify radioactive aqueous liquid wastestreams from across the DOE Complex using surrogate wastestreams. The Nuclear Nonproliferation Design Authority (NNP-DA) at the Savannah River Site (SRS) is in the design stage for the Waste Solidification Building (WSB). The WSB is slated to treat and solidify three different SRS wastestreams: one high activity waste (HAW) and two low activity wastestreams. The liquid HAW stream is a moderately acidic aqueous wastestream that is generated by the alkaline treatment process and the aqueous purification process at the Mixed Oxide Fuel Fabrication Facility (MFFF). NNP-DA has selected in-drum cementation as the solidification method for the HAW stream, and that wastestream will be the focus of this testing sequence.

SRS has also identified the need to test different gamma radiation shielding materials that will be included in the grouted HAW wasteforms for radiation attenuation. In 2006 and 2007, SRS previously tested HAW grout formulations that included magnetite, iron oxide, and zirconium oxide as the shielding materials. Several different SRS grout formulations were tested to develop grout mixtures that produced no bleed water after 3 days. The sample densities were also measured; however, the samples were not subjected to radiation bombardment to determine how effective the shielding materials were to attenuate gamma radiation.

SRS provided MSE with the surrogate recipe for the HAW stream identified for grout testing. Surrogate and grout formulations both with and without radiation shielding materials were tested at bench scale and column scale for the SRS HAW surrogate. The grout and surrogate combinations should be capable of withstanding conditions similar to those experienced during sample generation, shipping, and storage and be compatible with solidification processing equipment.

TEST OBJECTIVES

The first objective of this work was to identify the SRS surrogate and initial grouting formulations for the HAW stream that was grout tested using Portland cement grout mixtures. The second project objective was to develop several grout combinations with the SRS HAW surrogate and Portland cement both with and without the incorporation of the five different radiation-shielding materials. The HAW wasteforms were then sent to Oak Ridge National Laboratory (ORNL) for gamma bombardment to determine the most effective shielding materials to attenuate gamma radiation.

Specific objectives for the SRS grout and surrogate testing and evaluation were:

- identify the SRS surrogate formulations that would be used for testing;
- identify initial SRS grout formulations for bench-scale testing;
- determine the best addition order for each grout/surrogate combination at bench scale;
- determine the mixing requirements for each grout/surrogate combination at bench scale and column scale;
- identify several grout and surrogate combinations both with and without the inclusion of radiation shielding materials for the SRS HAW surrogate;
- verify the absence/presence of free liquid by observing the solidified grout wasteforms at bench scale and column scale after a 3-day curing period;
- determine the density distribution of the wasteforms both with and without radiation shielding materials at bench scale and column scale;
- determine the effectiveness of the radiation shielding materials to attenuate radiation by bombarding the bench-scale and column samples with gamma radiation at ORNL; and
- perform a cost evaluation to determine the cost to solidify a 208-liter (L) [55-gallon (gal)] drum of the HAW at the selected grout formulation with the incorporation of the shielding materials.

MATERIAL DESCRIPTIONS

Surrogate Waste Descriptions

The recipe for the aqueous surrogate HAW wastestream was developed by SRS for previously performed grout tests in 2006 and 2007. Note that the mixing of surrogate ingredients was conducted within laboratory hoods.

Grout Descriptions

In support of the procurement specifications in the request for proposals to provide a mixing system for the WSB, Savannah River National Laboratory (SRNL) prepared a series of grout samples with surrogate waste for the HAW stream. The baseline grout formulation was provided to MSE by SRNL to use as the initial grout testing formulation and was referred to as Formulation 1 (F1). SRS also provided two different formulations that varied the initial grouting formulation, which were referred to as Formulation 2 (F2) and Formulation 3 (F3). Portland cement Type I/II was used as the cement in the grouting formulations.

Radiation Shielding Materials

The SRS HAW stream was tested by incorporating gamma radiation shielding materials in the grout matrix during earlier SRS test work. Magnetite was tested as well as zirconium oxide and iron oxide for samples generated by SRS in 2006 and 2007. Several different formulations were tested at that time using cement and several radiation shielding materials to develop mixtures that produced no bleed water after 3 days. The sample densities were also measured; however, the samples were not subjected to radiation bombardment to determine how effective the shielding materials were at attenuating gamma radiation.

Five different radioactive shielding materials were tested at MSE using the three grouting formulations for the SRS HAW surrogate. SRS identified three radiation shielding materials for testing including iron oxide, zirconium oxide, and zirconium silicate. MSE identified two newly patented proprietary radiation shielding materials called Gamma Guard II (GG II) and Gamma Guard III (GG III) that were provided by Science and Technology Applications, LLC.

EXPERIMENTAL ACTIVITIES

The first objective of the experimental work was to determine if different addition methods would affect the mixing process. The second objective of this work was to identify the most effective radiation shielding material for attenuating gamma radioactivity within the HAW stream. The HAW surrogate and grout samples both with and without radiation shielding materials were sent to ORNL for radioactive bombardment to determine the most effective radiation shielding material to attenuate gamma radiation.

A cost analysis was also performed for the HAW stream to solidify a 208-L (55-gal) drum using the selected grouting formulation for each of the different radiation shielding materials.

Bench-Scale Grout Testing with Gamma Radiation Shielding

As previously mentioned, three different grout formulations were used during this test sequence: F1 (SRS baseline), F2, and F3. Each grout formulation was generated at two different water-to-cement (W/C) ratios of 0.35 and 0.30. The criterion for successful grout mixtures was the lack of freestanding liquid on the samples after 3 days of curing at ambient laboratory temperature. MSE discovered during previous testing that by adding the grout and radiation shielding materials in a different order or different combinations that the solidified wasteforms would vary in uniformity and consistency. Therefore, a duplicate sample was generated for each radiation shielding material that used the alternative addition method. The alternative addition method added the liquid waste to the solid with mixing while the traditional addition method adds the dry cement mixture to the liquid waste with mixing.

Small-scale laboratory samples were generated in plastic containers and checked daily for 3 days for freestanding liquid and to determine surrogate compatibility with each of the five different shielding materials when combined with Portland cement. After compatibility was confirmed, bench-scale samples were generated in 3.8-L (1-gal) plastic containers. The samples were checked daily for the presence of free liquid and were allowed to cure for at least 1 week before being removed from the sample containers. The samples were cut from the sample containers and visually inspected to determine if the different mixing processes produced uniform wasteforms and if the radiation shielding materials were evenly incorporated in the samples. The bench-scale samples were then trimmed into 10.16- by 10.16- by 2.54-centimeter (cm) [4- by 4- by 1-inch (in.)] samples and measured for density. The sample test matrix, mixing observations, and densities for the 10.16- by 10.16- by 2.54-cm [4- by 4- by 1-in.] attenuation samples are presented in Table I.

All of the samples generated passed the bleed water criteria of no bleed water after 3 days. The samples generated using the alternative mixing technique were not quite as dense as the samples generated using the traditional mixing methodology. More air was entrained in the samples resulting in slightly larger sample volumes and slightly lower sample densities with the exception of the GG II samples, which had the same density values.

Table I. HAW Sample Test Matrix, Mixing Observations and Density Data.

Grout Formulation	Water-to-Cement Ratio	Shielding Material	Bleed Water after 3 Days (mL)	Mixing Observations	Sample Density (g/cc)
F1	0.35	Zirconium Oxide	0	Easy Mixing	2.14
F1[a]	0.35	Zirconium Oxide	0	Easy Mixing	1.96
F2	0.35	Zirconium Oxide	0	Moderate Mixing	2.14
F3	0.35	Zirconium Oxide	0	Difficult Mixing	2.23
F1	0.30	Zirconium Oxide	0	Moderate Mixing	2.11
F2	0.30	Zirconium Oxide	0	Moderate Mixing	2.15
F3	0.30	Zirconium Oxide	0	Difficult Mixing	2.33
F1	0.35	Zirconium Silicate	0	Easy Mixing	2.08
F2	0.35	Zirconium Silicate	0	Moderate Mixing	2.10
F3	0.35	Zirconium Silicate	0	Difficult Mixing	2.30
F1	0.30	Zirconium Silicate	0	Easy Mixing	2.08
F1[a]	0.30	Zirconium Silicate	0	Moderate Mixing	2.05
F2	0.30	Zirconium Silicate	0	Moderate Mixing	2.21
F3	0.30	Zirconium Silicate	0	Difficult Mixing	2.31
F1	0.35	Iron Oxide	0	Easy Mixing	2.08
F2	0.35	Iron Oxide	0	Moderate Mixing	2.18
F3	0.35	Iron Oxide	0	Difficult Mixing	2.20
F1	0.30	Iron Oxide	0	Moderate Mixing	2.07
F2[a]	0.30	Iron Oxide	0	Difficult Mixing	2.22
F2	0.30	Iron Oxide	0	Difficult Mixing	2.20
F3	0.30	Iron Oxide	0	Very Difficult Mixing	2.27
F1	0.35	Gamma Guard II	0	Easy Mixing	2.09
F2	0.35	Gamma Guard II	0	Easy Mixing	2.22
F3	0.35	Gamma Guard II	0	Easy Mixing	2.36
F3[a]	0.35	Gamma Guard II	0	Easy Mixing	2.36
F1	0.30	Gamma Guard II	0	Easy Mixing	2.17
F2	0.30	Gamma Guard II	0	Moderate Mixing	2.25
F3	0.30	Gamma Guard II	0	Moderate Mixing	2.41
F1	0.35	Gamma Guard III	0	Easy Mixing	2.01
F2	0.35	Gamma Guard III	0	Easy Mixing	2.24
F2[a]	0.35	Gamma Guard III	0	Easy Mixing	2.20
F3	0.35	Gamma Guard III	0	Moderate Mixing	2.22
F1	0.30	Gamma Guard III	0	Moderate Mixing	2.11
F2	0.30	Gamma Guard III	0	Moderate Mixing	2.17
F3	0.30	Gamma Guard III	0	Difficult Mixing	2.22
Neat	0.35	No Shielding	0	Easy Mixing	1.87
Neat	0.30	No Shielding	0	Easy Mixing	2.13

[a] Duplicate sample generated using alternative mixing method.

The 0.35 W/C ratio samples were much easier to mix for all of the sample sets since there were less solids and more surrogate liquid waste than in the 0.30 W/C ratio mixtures. The GG II samples were the easiest to mix because the GG II shielding material was easily wetted and did not seem to sorb any liquid during the mixing process. The GG III samples were only slightly harder to mix than the GG II samples since the shielding material was easily wetted but tended to sorb only minor amounts of the surrogate waste during the mixing process. Both the GG II and GG III sample sets had the consistency of a moderate slurry that compares to cake batter. The zirconium oxides samples were harder to mix since the zirconium oxide material was a very fine-grained powder and not as wettable as the Gamma Guard materials and tended to sorb more of the surrogate waste, producing drier samples especially at the 0.30 W/C ratio. The consistency of the zirconium oxide samples was that of a thick slurry that compares to thick cake batter. The zirconium silicate samples were slightly more difficult to mix than the zirconium oxide samples and seemed to sorb more of the liquid surrogate waste than the zirconium oxide samples did, producing an even drier mixture. The zirconium silicate samples had the consistency of a very thick slurry and were comparable to brownie batter. The iron oxide samples were the most difficult to mix of all the samples sets. The iron oxide shielding material seemed to be wettable but sorbed the surrogate liquid waste quickly and seemed to set up quicker than the samples generated using the other shielding materials. The samples had the consistency of a thick paste resembling cool peanut butter. After mixing the samples and removing the mixer from the mixture, a void space was left where the mixing blade was located, and the grout mixture would not flow into the void space. The iron oxide samples also had the most entrained air because of the thick sample consistency during the mixing process. Fig. 1 shows a picture of the 0.30 W/C at the F3 grout formulation iron oxide bench-scale sample after the cutting process and the associated bombardment sample that was sent to ORNL for attenuation testing. Notice the number and size of the voids in both the large and sub-sample pieces.

Fig. 1. Iron oxide bench-scale sample and the associated bombardment sample.

After the density values were determined for the 10.16- by 10.16- by 2.54-cm [4- by 4- by 1-in.] samples, they were sent to ORNL and placed in front of a collimated cesium-137 (Cs-137) source, and the degree of gamma attenuation was measured. For comparative studies, an empty sample box was also bombarded with the selected radiation source of 171 roentgens per hour (R/hr) to determine the baseline radiation reading provided by the selected source strength through the empty box; that value was 166.3 R/hr. The percent radiation attenuation for each sample was calculated using the baseline radiation source strength of 166.3 R/hr. Fig. 2 shows the zirconium silicate sample set prior to gamma bombardment at ORNL. The picture shows the F1 grout formulation on the left, F2 formulation in the middle, and F3 grout formulation on the right.

Fig. 2. Zirconium silicate samples at the W/C ratio of 0.35.

Table II presents the percent gamma attenuation for each sample and the percent attenuation for each sample compared to the neat cement sample with the same corresponding W/C ratio. After observing the data presented in Table II, the general trend for the attenuation data is that the 0.35 W/C ratio samples seem to attenuate gamma radiation better than the 0.30 W/C ratio samples. This was not the trend expected for this test sequence since less liquid surrogate waste and more solids were incorporated in the 0.30 W/C ratio samples. This trend may be a function of mixing; however, that cannot be confirmed with this data set.

The bench-scale attenuation results indicated that the GG II shielding material provided the best gamma attenuation results for all of the shielding materials tested at both W/C ratios and the best attenuation data trend for the specific grouting formulations (F1, F2, and F3). The F1 formulation had the least amount of shielding material while the F3 grouting formulation had the largest amount of shielding material, which correlates well for the GG II density and attenuation data sets.

It is hard to determine if GG III or iron oxide produced the second best attenuation results based on the bench-scale data. The F1 – 0.35 W/C iron oxide sample attenuation value seems artificially low compared to the other 0.35 W/C ratio samples in that sample set. In addition, the F3 – 0.30 W/C iron oxide sample attenuation value also seems low; however, that can be explained by the large air holes in the sample due to difficult mixing at that F3 grout formulation and 0.30 W/C ratio as shown in Fig. 1.

The zirconium oxide and the zirconium silicate sample sets produced gamma attenuation results that were very comparable to one another. Again, the 0.30 W/C ratio sample attenuation data does not trend well, and it is suspected that it is because these shielding materials do not wet easily and because mixing was difficult.

Table II. Bench-Scale Gamma Attenuation Results for the SRS HAW Samples.

Grout Formulation	Water-to-Cement Ratio	Shielding Material	Radiation Reading (R/hr)	Percent Attenuation for each Sample	Percent Attenuation, Shielded Sample to Neat Sample
F1	0.35	Zirconium Oxide	122.4	26.4	2.9
F1[a]	0.35	Zirconium Oxide	121.3	27.1	3.8
F2	0.35	Zirconium Oxide	119.4	28.2	5.3
F3	0.35	Zirconium Oxide	116.5	29.9	7.6
F1	0.30	Zirconium Oxide	120.7	27.4	2.7
F2	0.30	Zirconium Oxide	120.5	27.5	2.8
F3	0.30	Zirconium Oxide	118	29.0	4.8
F1	0.35	Zirconium Silicate	123.2	25.9	2.3
F2	0.35	Zirconium Silicate	120.5	27.5	4.4
F3	0.35	Zirconium Silicate	116	30.2	8.0
F1	0.30	Zirconium Silicate	123.3	25.9	0.6
F1[a]	0.30	Zirconium Silicate	121.1	27.2	2.3
F2	0.30	Zirconium Silicate	116.3	30.1	6.2
F3	0.30	Zirconium Silicate	118.0	29.0	4.8
F1	0.35	Iron Oxide	122.7	26.2	2.7
F2	0.35	Iron Oxide	117.3	29.5	7.0
F3	0.35	Iron Oxide	116.7	29.8	7.5
F1	0.30	Iron Oxide	120.0	27.8	3.2
F2	0.30	Iron Oxide	118.5	28.7	4.4
F2[a]	0.30	Iron Oxide	118.3	28.9	4.6
F3	0.30	Iron Oxide	120.3	27.7	3.0
F1	0.35	Gamma Guard II	117.3	29.5	7.0
F2	0.35	Gamma Guard II	113.3	31.9	10.2
F3	0.35	Gamma Guard II	109.0	34.5	13.6
F3[a]	0.35	Gamma Guard II	110.5	33.6	12.4
F1	0.30	Gamma Guard II	117.3	29.5	5.4
F2	0.30	Gamma Guard II	112.6	32.3	9.2
F3	0.30	Gamma Guard II	108.8	34.6	12.3
F1	0.35	Gamma Guard III	118.7	28.6	5.9
F2	0.35	Gamma Guard III	119.6	28.1	5.2
F2[a]	0.35	Gamma Guard III	119.6	28.1	5.2
F3	0.35	Gamma Guard III	118.3	28.9	6.2
F1	0.30	Gamma Guard III	119.3	28.3	3.8
F2	0.30	Gamma Guard III	117.9	29.1	4.9
F3	0.30	Gamma Guard III	119.3	28.3	3.8
Neat	0.35	No Shielding	126.1	24.2	0
Neat	0.30	No Shielding	124	25.4	0

[a] Duplicate sample generated using alternative mixing method.

After discussions with SRS personnel, F1 was selected for the grout formulation, and 0.30 was selected as the W/C ratio for the column testing to mimic the SRS baseline grout formulation even though the 0.35 W/C ratio samples generated at the F3 grout formulation produced superior attenuation results.

Column Grout Testing with Radiation Shielding Materials

The column samples, which were approximately the height of a 208-L (55-gal) drum, were prepared using the F1 (SRS baseline) grouting formulation and 0.30 W/C ratio for each of the radioactive shielding materials to determine if the mixtures would separate or the shielding materials settle at the larger scale represented by the column. The samples were mixed in a 19-L (5-gal) bucket and poured into the columns to cure for 1 week. The samples were all easy to mix in the 19-L (5-gal) buckets. The GG II and GG III samples were the least viscous grout mixtures and were self-leveling in the 19-L (5-gal) buckets after mixing. A picture of the GG II sample during the mixing process is shown in Fig. 3. The zirconium oxide and the zirconium silicate samples were thicker than the Gamma Guard samples and produced small indentations when the mixing blades were removed from the bucket. However, the grout mixtures did level in the buckets after gently shaking the buckets. The iron oxide sample also mixed easily but produced high ridges during mixing, and when the mixing blades were removed from the bucket, void spaces were left. Fig. 4 shows the iron oxide samples after the mixing process. Notice how much thicker the iron oxide sample is compared to the GG II sample.

Fig. 3. GG II sample during mixing.

Fig. 4. Iron oxide sample after mixing.

Sample flowability was observed when the grout mixtures were poured from the 19-L (5-gal) buckets into the columns. The initial sample temperatures were taken after the samples were poured from the buckets into the columns, and the temperature was monitored until the maximum temperature was reached. The time to reach the maximum temperature and the temperature value was noted during testing. The samples were monitored daily for 3 days to check for the presence of freestanding liquid on top of the samples and visual inspection to detect sample settling or separation. None of the samples had any free liquid after mixing or during the 3-day inspection period. The volumetric expansion was calculated for each of the samples during the 1-week curing period. Fig. 5 is a photograph of the five column samples.

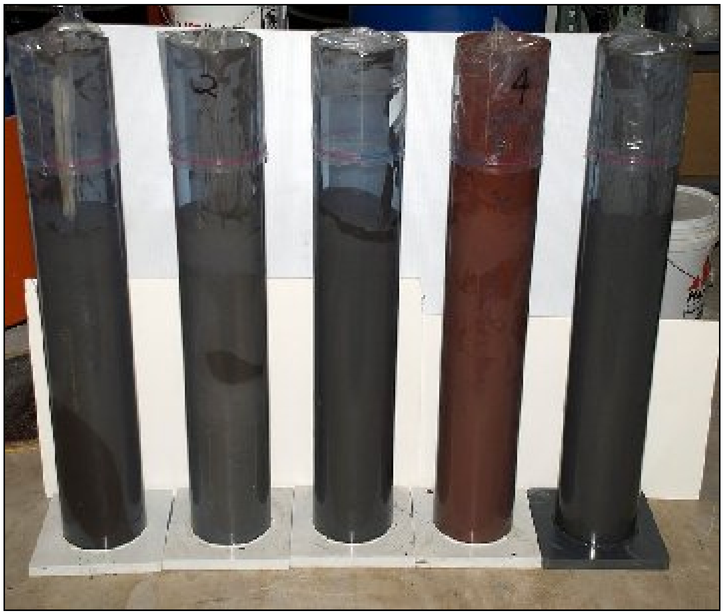

Fig. 5. Column samples that simulate the height of a 208-L (55-gal) drum.

After approximately 1 week, the samples were removed from the columns, weighed, and measured to determine the bulk density values for each of the column samples. The samples were then cut into three sections: top, middle, and bottom. Each sample section was weighed and measured to determine the sectional sample density. Table III presents the observation data, density data, and volumetric expansion data for the column samples.

Table III. Column Sample Observational Data and Density Data.

Shielding Material	Flowability	Volumetric Expansion (% Increase)	Maximum Temperature (°C)	Column Bulk Density (g/mL)	Column Section	Column Sectional Density (g/cc)
Zirconium Oxide	Moderately Flowable	30.7%	24	2.21	Top	2.22
					Middle	2.25
					Bottom	2.20
Zirconium Silicate	Difficult Flowability	30.6%	25	2.21	Top	2.22
					Middle	2.22
					Bottom	2.23
Iron Oxide	No Flowability	34.0%	25	2.12	Top	2.08
					Middle	2.20
					Bottom	2.22
Gamma Guard II	Easily Flowable	30.0%	23	2.24	Top	2.23
					Middle	2.24
					Bottom	2.25
Gamma Guard III	Easily Flowable	30.0%	25	2.22	Top	2.23
					Middle	2.22
					Bottom	2.23

The GG II and GG III shielding materials produced the most flowable grouts while the zirconium oxide sample was moderately flowable, and the zirconium silicate sample flowed slowly. The iron oxide sample produced the most viscous grout mixture, and the mixture would not physically pour out of the bucket into the column. The volumetric expansion for the all samples was approximately 30% except the iron oxide sample, which had a value of 34%. This sample contained large voids, which increased the volume and decreased the bulk density for the sample. The samples all were slightly exothermic, and the maximum temperatures ranged from 23 °C to 25 °C.

The bulk density values are consistent with the sectional density values for each of the column samples except the iron oxide sample. The sample consistency was so thick that the grout mixture could not be poured into the column and was scooped out of the bucket into the column, which resulted in large void spaces within the grouted surrogate wasteform. Fig. 6 is a photograph showing the large void spaces in the iron oxide column sample due to sample consistency.

The column sample sections were then cut into 10.16- by 10.16- by 2.54-cm [4- by 4- by 1-in.] attenuation samples, which were shipped to ORNL, placed in front of a collimated Cs-137 source, and the degree of radiation reduction was measured. For comparative studies, an empty sample box was also bombarded with the selected radiation source of 171 R/hr to determine the baseline radiation reading provided by the selected source strength through the empty box; that value was 168.2 R/hr. The percent radiation attenuation for each sample was calculated using the baseline radiation source strength of 168.2 R/hr. ORNL provided these test results to MSE. The column gamma attenuation results are presented in Table IV.

Fig. 6. Voids in iron oxide column sample.

Table IV. Gamma Attenuation Data for the SRS HAW Column Samples.

Grout Formulation	Water-to-Cement Ratio	Shielding Material	Sample Section	Radiation Reading (R/hr)	Percent Attenuation for each Sample	Percent Attenuation, Shielded Sample to Neat Sample	Average Percent Attenuation for Shielded to Neat Sample
F1	0.30	Zirconium Oxide	Top	116.6	30.7	7.1	6.9
			Middle	117.7	30.0	6.2	
			Bottom	116.2	30.9	7.4	
F1	0.30	Zirconium Silicate	Top	118.5	29.5	5.6	5.8
			Middle	118.4	29.6	5.7	
			Bottom	117.9	29.9	6.1	
F1	0.30	Iron Oxide	Top	116.9	30.5	6.9	6.9
			Middle	116.6	30.7	7.1	
			Bottom	117.0	30.4	6.8	
F1	0.30	Gamma Guard II	Top	115.7	31.2	7.8	8.2
			Middle	115.4	31.4	8.0	
			Bottom	114.4	32.0	8.8	
F1	0.30	Gamma Guard III	Top	116.8	30.6	6.9	6.1
			Middle	118.8	29.4	5.3	
			Bottom	117.9	29.9	6.1	
F1	0.30	Neat[a]	NA[b]	125.5	25.4	--	--

[a] Neat sample – does not include shielding material.

[b] NA – sample taken from the middle of the bench-scale sample.

The gamma attenuation data for the column samples is consistent within each of the column sample sets. The GG II radiation material samples produced superior attenuation results when compared to the rest of the radiation shielding materials tested with percent attenuation data ranging from 31.2% to 32%, which resulted in an average percent attenuation for the shielded to neat sample of 8.2%. The zirconium oxide and iron oxide samples produced percent attenuation values that ranged from 30.0% to 30.9% and 30.4% to 30.7%, respectively, which resulted in average values of 6.9% for both samples sets. The GG III samples produced percent attenuation values that ranged from 30.0% to 31.4%, resulting in an average value of 6.1% while the zirconium silicate samples had percent attenuation values that ranged from 29.5% to 29.9% with average value of 5.8%.

COST ANALYSIS

Table V presents the cost to solidify a 208-L (55-gal) drum of waste using the 0.30 W/C ratio, the F1 grout formulation and assuming 132.5-L (35 gal) of waste per 208-L (55-gal) drum. The costs were calculated assuming the cost for Portland cement was \$0.43/kg [\$0.94/pound (lb)]; the cost for zirconium oxide was \$2.49/kg (\$5.48/lb), the cost for zirconium silicate was \$0.53/kg (\$1.17/lb); the cost for iron oxide was \$0.24/kg (\$0.545/lb), the cost for GG II was \$2.27/kg (\$5.00/lb), and the cost for GG III was \$0.45/kg (\$1.00/lb).

Table V. Costs to Solidify a 208-L (55-Gal) Drum of HAW.

Shielding Material	Grout Formulation	Water-to-Cement Ratio	Waste Volume (L) (gal)	Cost Evaluation
Zirconium Oxide	F1	0.30	132.5 (35)	\$397.30
Zirconium Silicate	F1	0.30	132.5 (35)	\$141.80
Iron Oxide	F1	0.30	132.5 (35)	\$104.75
Gamma Guard II	F1	0.30	132.5 (35)	\$368.85
Gamma Guard III	F1	0.30	132.5 (35)	\$131.72

After reviewing Table V, it is apparent that the iron oxide radiation material provides the least expensive option of \$104.75 to solidify 132.5 L (35 gal) of SRS HAW. The listing of the other radiation shielding materials (when rated from least expensive to most expensive) are GG III, zirconium silicate, GG II, and zirconium oxide.

CONCLUSIONS

When gamma attenuation data and cost data are compared, the iron oxide provides the least expensive radiation shielding material option while providing the second best attenuation results. However, the iron oxide samples produced the most viscous grout mixtures. The Gamma Guard II radiation shielding material provided the best gamma attenuation results but was the second most expensive shielding material tested. Depending on the application and the required shielding, the data generated provides several options.

RECOMMENDATIONS

Although the iron oxide grout samples were very viscous, the samples did mix easily in the 19-L (5-gal) buckets that were used for mixing the column samples. Since SRS selected in-drum cementation as the solidification technique, MSE recommends that follow on scale-up testing at the 208-L (55-gal) drum scale to investigate any scale-up mixing issues that may arise.

If any additional testing is performed, MSE also recommends that the 0.35 W/C ratio should be tested at a larger scale based on the bench-scale testing that showed better attenuation results for the 0.35 W/C ratio samples than for the 0.30 W/C ratio samples. If this data can be confirmed at a larger scale, more waste could be solidified per drum, the grouted wastes would be easier to mix since more liquid would be solidified per drum, and costs would be lower per drum since less cement and shielding materials would be required for solidification.

If the attenuation results are not sufficient for the desired application, MSE recommends that other grout formulations (that include larger amounts of the radiation shielding material) be tested at a larger scale.

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