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Formulation and Analysis of Compliant Grouted Waste Forms for SHINE Waste Streams

Chemical Sciences and Engineering Division

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FORMULATION AND ANALYSIS OF COMPLIANT GROUTED WASTE FORMS FOR SHINE WASTE STREAMS

ABSTRACT

Optional grouted waste forms were formulated for waste streams generated during the production of ^{99}Mo to be compliant with regulations for low-level radioactive waste. The amounts and dose rates of the various waste form materials that would be generated annually were estimated and used to determine the effects of various waste processing options, such as the of number irradiation cycles between uranium recovery operations, different combinations of waste streams, removal of Pu, Cs, and Sr from waste streams for separate disposition (which is not evaluated in this report), and use of some or all of the process water to produce the waste forms. These calculations indicate that Class C-compliant grouted waste forms can be produced for all waste streams. More frequent uranium recovery results in the generation of more chemical waste, but this is balanced by the fact that waste forms for those waste streams can accommodate higher waste loadings, such that similar amounts of grouted waste forms are required regardless of the recovery schedule. Similar amounts of grouted waste form are likewise needed whether waste streams are grouted individually or in combination. Class B waste forms can be made by removing 90% of the Pu from the waste streams for separate disposition. Waste loadings can be increased by also removing Cs and Sr. Removing Cs from waste streams for separate disposition lowers the waste-form dose rate significantly at times beyond about 1 year after irradiation, which may benefit handling and transport. Although these calculations should be revised after experimentally optimizing the grout formulations and waste loadings, they provide initial guidance for process development.

1 INTRODUCTION

Work is in progress to evaluate the SHINE Medical Technologies process for producing ^{99}Mo for medical use by the fission of dissolved low-enriched uranium (LEU). This report addresses waste stream characterization, mass balances, and preliminary formulations of waste forms from the SHINE process that are used to assess the compliance of the waste streams with disposal regulations and the impacts of various processing options. For this purpose, the waste forms are made by immobilizing individual and combined waste streams in ordinary portland cement-based grout. The proposed flowsheet for the SHINE process was used to estimate the chemical compositions of the waste streams generated by the various separation processes. To that end, we used mass balances based on the expected partition factors for separation and washing operations.

Figure 1 shows a simple schematic of the target solution treatment process. There are two legs to the process. In the first leg, the irradiated target solution is passed from the target solution vessel (TSV) through a titania column to recover Mo. The majority of fission products and actinides are not sorbed and are recycled to the TSV for the next irradiation recycle. The Mo-recovery column is washed to remove residual uranium and fission products,[1] and Mo is then stripped from the column. The eluted Mo is then acidified and concentrated by sorption on a second titania column. The column is then washed, and Mo is stripped from the column and then purified by the LEU-Modified Cintichem process [Conner et al. 2000]. The column washes and spent eluates are combined with the uranium extraction (UREX) raffinate generated in the second leg of the treatment process prior to waste form production.

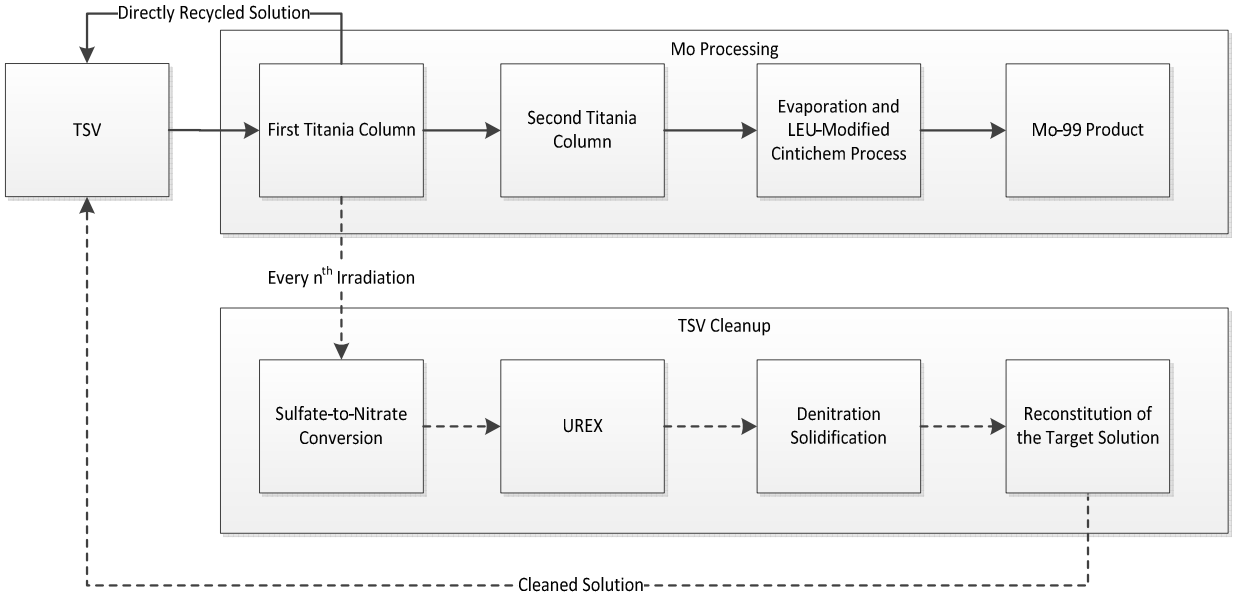

FIGURE 1 Schematic of the Overall Process

[1] The acid wash from this column is likely to contain enough uranium that it will be saved and added to the feed to the spent target-target-solution cleanup leg to recover the uranium.

The solution leaving the first titania column is treated periodically to remove fission products and actinides. This solution is first treated by the addition of strontium nitrate and then barium nitrate to precipitate a mixed barium-strontium sulfate solid. The other components remain in a nitrate solution that, after acidification to 1 M nitric acid, serves as the feed to the UREX process. The UREX raffinate is combined with the column washes and spent eluate, and then mixed with cement, fly ash, and slag to produce a grouted waste form for disposal. The UREX uranium product is first passed through an anion-exchange column to remove technetium and iodine and then denitrated and solidified to produce UO_3. This solid is dissolved in sulfuric acid and irradiated to begin the next TSV solution cycle. The frequency of cleanup cycles relative to the direct recycle will depend on many factors, including nuclear poisoning effects of the fission products and the purity requirements for the Mo product.

The chemical compositions of the waste streams generated from the Mo recovery and purification operation and uranium purification were combined with the results from Origen calculations[2] of radionuclide generation for various irradiation schedules and times after irradiation to determine waste-form formulations that would meet requirements for permanent land disposal. These waste forms were designed to comply with regulations promulgated by the Nuclear Regulatory Commission [NRC 2014], which identifies maximum acceptable curie contents for specific long- and short-lived radionuclides based on the mass and volume of the final waste form, regardless of the matrix composition. For this analysis, the waste forms made with each waste stream were assumed to have the same densities as portland-cement-based grouts, which are expected to be suitable encapsulating media. (This remains to be verified.) Calculations were performed to (1) estimate the maximum loadings of waste solids in grouted waste forms made with these waste streams that will meet regulatory requirements for radioactivity, (2) estimate the number of 55-gal drums of grouted waste forms that would be generated annually and the benefits of combining compatible waste streams in the same waste form, and (3) evaluate the potential benefits of enhanced separation and removal of Pu, Cs, and Sr from each waste stream for immobilization in separate waste forms. The present study included initial dose rate calculations for these waste-form formulations. Compliance with transport and disposal criteria will be addressed in a follow-on study when the grout formulations and waste loadings are more mature.

The calculations described in this report provide the minimum amount of matrix material required to immobilize the liquid and solid waste streams generated annually from each TSV with UREX treatments on a 4-, 8-, or 50-cycle cleanup schedule, such that the waste forms meet curie limits for NRC-regulated isotopes. The total curie contents of the regulated radionuclides used in these calculations are from the Origen results provided by SHINE Medical Technologies for the 4- and 50-cycle cleanup schedules. These provided curie values at 7, 14, 30, 180, and 365 days after irradiation. The decay of isotopes for the 8-cycle schedule was estimated by applying the time dependence in the results for the 4-cycle schedule to the inventory after 8 cycles that was determined for the 50-cycle cleanup schedule. The masses and compositions of the individual waste streams are based on the element-partitioning behavior of the chemical separation processes developed at Argonne. The distribution of the regulated isotopes between the various waste streams was assumed to be the same as the element distributions that were

[2] Origen calculations were provided by SHINE Medical Technologies.

determined on a chemical basis. That is, the same fraction of the total element mass accumulated annually in an individual waste stream was used as the fraction of the total isotopic curie content that accumulated in that waste stream. This imposes the conservative assumption that all regulated radionuclides that were generated during the irradiation operations are present in the waste streams to be immobilized for disposal.

Regulatory dose limits are summarized in two tables within 10 CFR 61.55 [NRC 2014], which indicate the maximum curie contents for specific long- and short-lived radionuclides for Class C, B, and A wastes. Rules are provided to identify the radionuclide determining the appropriate waste class. Some isotopes are regulated on a mass basis and others are regulated on a volume basis. The curie limits provided in the two tables are referred to herein as "NRC Tables 1 and 2" to distinguish them from the tables that are part of this report. NRC guidance for waste streams containing both long- and short-lived regulated radionuclides is, "If the concentration of a nuclide listed in Table 1 [for long-lived radionuclides] does not exceed 0.1 times the value listed in Table 1, the class shall be that determined by the concentration of nuclides listed in Table 2 [for short-lived radionuclides]" [NRC 2014]. Because some limits are regulated on a Ci per mass basis and others are regulated on a Ci per volume basis, both the required mass and required volume of the grouted waste form were estimated. The maximum waste loading was first determined from the mass-based limits for the long-lived alpha-emitting transuranic nuclides having a half-life greater than 5 years, Pu-241, and Cm-242 (NRC Table 1). The sum of fractions (SOF) rule[3] is used to evaluate the compliance of waste forms containing more than one regulated long-lived nuclide. The volume of a waste form made with that maximum waste loading compliant with the SOF limit was then estimated to determine if the other regulated radionuclides (i.e., those listed in NRC Tables 1 and 2) met the volume-based limits.

Nominal values for grout mixtures and densities were used to provide an initial assessment of production parameters and estimate the waste form volumes required to produce compliant waste forms with individual and combined waste streams, for different cleanup schedules, with the removal of particular radionuclides, and by using different amounts of processing water. Characteristics of portland-cement-based grouts relevant to this application are summarized in the following section.

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[3] From 10 CFR 61.55 [NRC 2014]:

> (7) The sum of the fractions rule for mixtures of radionuclides. For determining classification for waste that contains a mixture of radionuclides, it is necessary to determine the sum of fractions by dividing each nuclide's concentration by the appropriate limit and adding the resulting values. The appropriate limits must all be taken from the same column of the same table. The sum of the fractions for the column must be less than 1.0 if the waste class is to be determined by that column. Example: A waste contains Sr-90 in a concentration of 50 Ci/m^3 and Cs-137 in a concentration of 22 Ci/m^3. Since the concentrations both exceed the values in Column 1, Table 2, they must be compared to Column 2 values. For Sr-90 fraction 50/150=0.33; for Cs-137 fraction, 22/44=0.5; the sum of the fractions=0.83. Since the sum is less than 1.0, the waste is Class B.

2 PORTLAND CEMENT-BASED GROUT

Grout, mortar, and concrete are trade terms for materials that contain the same ingredients (cement, water, sand, and aggregate) but have different stiffnesses and plasticities due to different water contents. They differ as follows:

- Concretes are made with tightly controlled water/cement ratios to provide slight plasticity and the desired fluidity. Low fluidity can result in undesirable voids, so poured concrete must be mechanically settled to fill space and remove voids.

- Grouts are made with a higher water/cement ratio to provide greater fluidity and plasticity than normal concrete that allows it to flow into narrow spaces.

- Mortars are made with a lower water/cement ratio and higher cement content than normal concrete to be stiff and not flow.

Freshly prepared waste forms should be sufficiently fluid to fill the drums with a minor void content, but sufficiently stiff to avoid separation of the aggregates (or encapsulated wastes) and, most important, avoid excess water. The water used to make the waste form is intended to stay within the grout when placed in a drum, with very little residual free water. The water content of the waste form must be adjusted to maintain the free-liquid content within the waste acceptance criterion of 1 vol%. Although the expected waste-form matrix would be considered a concrete in the construction trade, similar materials are commonly referred to as "grouted" waste forms in the waste-management community. The appropriate composition of grouted waste forms for SHINE waste streams will require testing to evaluate the effects of the chemicals in the wastes (primarily pH and sulfate content) and optimize the relative amounts of water, ordinary portland cement (OPC), and additives such as blast furnace slag (BFS) and fly ash for processing, performance, and regulatory compliance. For example, ASTM Type V cements have high sulfate resistance (due to low $CaOAl_2O_3$ content and the generation of ettringite and calcium sulfoaluminate hydrates), which will be important for some waste streams.

The key aspect of grout formulation relevant to the current assessments is the relative amounts of waste, solid matrix constituents, and water used to generate the grout. Insight regarding grout formulation is provided by the study of waste-form grouts made with a waste solution similar to the aqueous SHINE waste streams using OPC:fly ash:BFS mass ratios of 8:45:47 [Westsik et al. 2013]. The fly ash and BFS are pozzolans, which have hydraulic properties similar to those of cement and consume the $Ca(OH)_2$ that is released as OPC reacts with water. These materials are less expensive than OPC and often used to replace a portion of the OPC in the grout mixture. As mentioned above, the relative amount of water used to make the waste form is a crucial parameter affecting the performance of the grout: too little water will result in a mixture that is too stiff to settle and will not efficiently fill the drum or encapsulate other aggregate wastes, whereas too much water will generate a mixture that is too fluid and allows separation of the aggregates in the drum, forms a weak matrix, and yields unacceptably high amounts of free water after the grout has cured. The water/cement mix mass ratio of

workable concrete is between about 0.38 and 0.65. The study of Westsik et al. [2013] confirmed the importance of the mix ratio on the production and performance of grouted waste forms; grouts made with a water/total dry mass ratio of 0.4 set too quickly, and those made with a water/total dry mass ratio of 0.6 had unacceptably poor durability. A water/dry mix mass ratio of 0.5 was used as a logical initial target in the present analysis, where the dry mix may include OPC, BFS, finely crushed glass, and other additives. We expect that additional waste materials can serve as aggregates in the grout or become macro-encapsulated within the grout, but those are not included explicitly in the present calculations. Instead, the minimum total mass and volume of the waste form matrix required to meet regulatory Class C, B, or A limits are determined without regard to the individual materials that are used. For example, the titania particles will contribute to the required mass and volume of the grout matrix, but are not considered explicitly for the present purpose. We note that titanium dioxide is often added to concretes as a pigment. The compatibility of other waste constituents remains to be determined.

The densities of concretes made with OPC range from 85 to 140 pounds per cubic foot (1360 to 2240 kg/m^3). Light-weight concretes are made with expanded shale, clay, slate, and slag, whereas the heavier concretes are made with sand, gravel, crushed stone, and air-cooled blast furnace slag. The corresponding range of specific volumes is $7.34 \times 10^{-4} - 4.46 \times 10^{-4}$ m^3/kg. A specific volume of 5.41×10^{-4} m^3/kg is used to represent grouted waste forms made with moderately dense aggregates such as TiO_2 (4 g/cm^3) and crushed glass (2.5 g/cm^3). Using a moderate grout density qualitatively accounts for the volume of additives to estimate the final volumes of waste forms for individual and combined waste streams. For example, the volume occupied by a 500-kg grouted waste form is 0.27 m^3, and is estimated to fill one and one-half 55-gal drums to 90% capacity (55 gal = 0.208 m^3). This calculation is based on conservative estimates of the waste form properties. The actual volume will depend on the water/OPC mix ratio and chemical reactions that occur between the waste constituents and the grout that will impact the amount of additives required.

3 WASTE FORM FORMULATION METHOD

The maximum amount of a waste stream that can be immobilized in a compliant grouted waste form was determined on the basis of the mass or volume of a grout containing the amounts of regulated radionuclides generated annually (on a per TVS basis) that are required to meet compliance limits. The mass of the grouted waste form is the sum of the masses of fission products and chemical processing components in the waste stream and additives to make the grout. These may include portland cement, blast furnace slag, fly ash, and water, plus other processing wastes that are encapsulated in the waste form, such as crushed glassware. For the purpose of formulating the grouted waste forms, we do not distinguish between the masses contributed by the waste stream constituents from those contributed by the additives used to make the grout. In particular, the titania and resin sorbents and glassware contribute to the total mass of the grouted waste form, but were not considered separately from the grout-forming additives. It is possible that the masses of the waste streams alone are sufficient to meet regulatory limits without the additional mass of the grout matrix, especially in waste streams from which Pu, Cs, and Sr have been removed. The role of grout in these cases is to consolidate the waste in a non-dispersible form.

The mass of water in the waste streams was considered separately to determine the amount of waste water required to produce the grout and the amount of excess water to be removed. Although the amount of water required to make an acceptable grout must be determined experimentally, a water/cement mix mass ratio of 0.5 was assumed for the present calculations. The mass of water available in the individual or combined waste streams was not considered in the calculations. Instead, the mass of water required to produce the grout was included in the total mass of grout required to produce a compliant waste form—one-third of the total mass of the grout matrix is water and two-thirds is dry mix. Some waste streams contain more water than needed to produce grout, and other waste streams have less than what is needed. The water mass will be an important issue in producing grouts (and in the plant's water balance), but does not impact formulations of compliant waste forms. Accommodating the waste water in the waste forms is considered separately.

The total mass of each waste stream to be grouted annually was calculated by using the masses of the chemical components and fission products predicted to be in each waste stream after each irradiation based on process knowledge and partitioning estimated by Argonne. The estimates of mass balance distinguish the compositions of batches that went through uranium cleanup and the batches that were re-irradiated without treatment and include calculations for elemental concentrations for any number of cycles. Three cleanup schedules were evaluated with uranium cleanup being performed after different numbers of irradiations: the 4th, 8th, and 50th cycle. The amounts and compositions of waste generated annually were calculated as the sums of the following:

- 39 recycled batches and 13 uranium-cleanup batches for the 4-cycle cleanup schedule,

- 45 recycled batches and 7 UREX-treated batches for the 8-cycle cleanup schedule, and

- 50 recycled batches and 1 uranium-cleanup batch for the 50-cycle cleanup schedule.

The mass-balance calculations for the 39/13, 45/7, and 50/1 schedules were performed in separate EXCEL workbooks. These are referred to as the 4-, 8-, and 50-cycle cleanup schedules.

The mass distributions of elements among the waste streams to be grouted were used to calculate the fraction of the total curies of each regulated isotope present in each waste stream. For example, if 40% of the mass of Cs is in Stream A, then 40% of the total inventory of Cs-137 that is generated per year was assigned to Stream A. The accumulations of chemical components and fission products were totaled separately, as was the accumulated amounts of uranium and water.

Separate worksheets were used to calculate the radionuclide inventories and compliant waste-form formulations for each individual waste stream and for various combinations of waste streams. These include worksheets for the following waste streams:

- Ti column (for the spent titania sorbent),

- Tc column (the spent anion column resin),

- glassware (from the LEU-Modified Cintichem processing),

- combined columns (sum of the spent sorbent from Ti column, spent resin from Tc column, and glassware),

- Ba/$SrSO_4$ (mixture of precipitated $BaSO_4$ and $SrSO_4$),

- spent wash,

- rotovap (for the condensate),

- spent eluate,

- LMC (LEU-Modified Cintichem),

- raffinate (from UREX),

- combined aqueous waste (sum of the spent wash, rotovap, spent eluate, LMC, and raffinate), and

- combined all-waste streams (sum of combined columns, combined aqueous, and Ba/$SrSO_4$ waste streams).

(Note that the glassware is considered as a separate waste stream, whereas the columns containing the titania sorbent and anion resin materials are considered additives to the grout mass with no additional contamination.)

Compliance with the limit for long-lived transuranic isotopes was calculated first by using the regulatory SOF rule. This provided the minimum mass of grouted waste form required to meet regulatory limits based on mass. The inventory of each regulated isotope that was generated in the cycle of irradiations (as provided by the Origen calculations) was multiplied by the number of cycles performed in a year to calculate the total Ci on a per year basis and by the fraction of that isotope in the waste stream of interest (based on the elemental fraction). This inventory was divided by the total mass of chemicals and radionuclides calculated to accumulate in that waste stream annually (excluding water). The resulting value (units of nCi/g) of the waste stream was used to determine the maximum waste loading (grams waste stream/ grams waste form)[4] giving an SOF value meeting the Class C limit of 1.00. The maximum waste loading determines the minimum mass of grout required to meet the mass-based curie limit. The volume of grouted waste form having the required mass was estimated by using a typical value for the density of grouts made with light aggregates. This value was used to calculate the curie contents on a volume basis for comparisons with volume-based regulatory limits. The annual inventory of each regulated isotope was divided by the trial value of the waste form volume for comparison with the appropriate regulatory limits for Classes C, B, or A. (The initial trial value was that for a waste form compliant with the mass-based regulations.) The calculated value (units of Ci/m^3) for the trial waste form was divided by the compliance limit. The waste loading was adjusted until that ratio was less than 1, meaning that all isotopes met the mass- or volume-based compliance limit for the waste classification being evaluated. The trial waste forms were compared with compliance limits in the following order:

- sum of fractions Class C limits for long-lived alpha-emitting isotopes,
- NRC Table 1 Class C limits for long-lived isotopes,
- NRC Table 2 Class C limits for short-lived isotopes,
- NRC Table 2 Class B limits for short-lived isotopes, and
- NRC Table 2 Class A limits for short-lived isotopes.

This follows the guidance in 10 CFR 61.55 [NRC 2014].

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[4] The concept of waste loading depends on how the waste stream is defined. Whereas in practice the waste stream will be well-defined by the masses being treated, the possible evaporation of some waste streams and slurries of others prevent using that approach at this time. These calculations use waste loadings based on the combined masses of chemicals and fission products (excluding the water). This facilitates evaluating the benefits of changes to processing parameters to the amounts and classifications of optional waste forms. An alternative approach would have been to use only the masses of the regulated isotopes to define waste loading. Only the curie content and mass of the waste form, not the waste loading, are pertinent to compliance.

The number of 55-gal drums required to contain the volume of each compliant waste form was then calculated by dividing the waste form volume by 0.187 m^3/drum to represent 90 vol% filling. This addresses requirement 10 CFR 61.56 (b) (3) that "void spaces within the waste and between the waste and its package must be reduced to the extent practical" [NRC 2014]. The mass of grout was used to determine the required masses of dry mix and water, which were added in a 2:1 mass ratio for all waste forms. The separate amounts of OPC and additives that comprise the dry mix and the mass of water used to make the grout were not considered when determining the mass of waste form matrix material required to meet the Class C waste regulations; only the total mass of the matrix was used. The mass of the drum (and possible overpack materials) was excluded from these compliance calculations. Compliant formulations were determined for the individual and combined waste streams by using inventories based on the partitioning factors and the assumption of the total separation of Pu; Pu and Cs; Pu and Sr; and Pu, Cs, and Sr from all waste streams. This was done to evaluate the benefit of modifying the separation efficiencies on the amounts and classifications of waste forms to be sent to a low-level radioactive waste disposal site. Other disposition options are required for the Pu, Cs, and Sr recovered from the waste streams, but these were not addressed in this study.

4 CALCULATIONS FOR COMPLIANT WASTE FORMS

4.1 RADIOACTIVITY AND NRC CLASSIFICATION FOR DIFFERENT CASES

As an example of the approach outlined in the preceding section, Table 1 provides the calculated radioactivity values (nCi/g and Ci/m^3) for 1,562 kg of a grouted waste form[5] made with the combined-aqueous streams generated per TSV-yr for a 4-cycle cleanup schedule. The mass-based values are below the NRC Class C limits based on the SOF rule applied to all times after irradiation. The volume-based values are also below the NRC Class C limits. This formulation meets NRC criteria for Class C wastes. However, as shown in Table 2, the concentrations of several isotopes exceed the Waste Control Specialist[6] (WCS) administrative values provided to SHINE (Havlicak, 2014). For the example of the combined-aqueous waste streams provided in Table 1, Table 3 shows comparisons of formulated waste forms with the mass-based limits in NRC Table 1 and the volume-based limits in NRC Table 2 for four cases: the original waste- stream composition, the waste stream with Pu-239 (and Pu-241) removed, the waste stream with Pu-239 and Cs-137 removed, and the waste stream with Pu-239, Cs-137, and Sr-90 removed. All values are for irradiations per TSV-yr for a 4-cycle cleanup schedule. For the 1,492 kg of grouted waste form (GWF) having the maximum waste loading meeting the SOF limit as shown in Table 1, the top section of Table 3 shows the waste loading is limited by Pu-239 (indicated by the bold font) and the contents of all other isotopes are compliant with the Class C limits (i.e., all ratios are <1.00). If all Pu is removed from the waste stream and excluded from the waste form, 5,714 kg of a grouted waste form made without Pu-239 is compliant with SOF limits for long-lived alpha emitters regulated by NRC Table 1 and with Class B limits for short-lived isotopes regulated by NRC Table 2. As shown in the second part of Table 3, the waste loading is limited by the Cs-137 content (shown in bold font). The Cs-137 content will limit the waste loading if 90% or more of the Pu is removed from the waste stream. If the Pu-239 and Cs-137 are both removed from the waste stream, 212 kg of a grouted waste form is compliant with Class B limits, as summarized in the third section of Table 3. The waste loading in this waste form is limited by Sr-90. If the Sr-90 is also removed from the waste stream, 63.4 g of waste form can be made that is compliant with the Class A limits of all regulated isotopes that remain. These amounts of GWF would fill 4.3, 16, 0.61, and 0.87 55-gal drums to 90% capacity per TSV-yr. Note that the numbers of drums are calculated for comparative purposes and may not represent practical waste-form materials.

The inventories used to formulate the compliant waste forms for the individual waste streams are provided in Appendix A, Tables A.1, A.2, and A.3 for the 4-cycle, 8-cycle, and 50-cycle cleanup schedules, respectively. Table 4 compares the amounts of regulated isotopes generated annually for the three cleanup schedules (after 180-day decay). This provides

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[5] Note that the numbers of significant figures reported herein are used to track calculations and distinguish the impacts of processing options at intermediate stages, but do not represent the accuracy of actual measurements.

[6] The Waste Control Specialists (Andrews, Texas) operate a possible disposal site for radioactive wastes from the SHINE process.

TABLE 1 Radioactivity of Grouted Waste Form for Combined-Aqueous Wastes for 4-Cycle Cleanup Schedule and Class C Limit

	Time after Irradiation, days					Class C Limit[a]	
Isotope	7	14	30	180	365	Table 1	Table 2
	Ci/m^3 waste form						
H-3	7.4E-01	7.4E-01	7.3E-01	7.2E-01	7.0E-01	—	none
C-14	8.6E-04	8.6E-04	8.6E-04	8.6E-04	8.6E-04	8	
Co-60	1.4E-02	1.4E-02	1.4E-02	1.3E-02	1.2E-02	—	none
Ni-63	3.4E-04	3.4E-04	3.4E-04	3.4E-04	3.4E-04	—	700
Sr-90	2.0E+01	2.0E+01	2.0E+01	2.0E+01	2.0E+01	—	7000
Tc-99	1.4E-03	1.4E-03	1.4E-03	1.4E-03	1.4E-03	3	—
I-129	7.2E-06	7.2E-06	7.2E-06	7.2E-06	7.2E-06	0.08	—
Cs-137	1.5E+02	1.5E+02	1.5E+02	1.5E+02	1.5E+02	—	4600
	nCi/g waste form						
Np-237	6.6E-03	7.4E-03	8.0E-03	8.1E-03	8.1E-03	100	—
Pu-238	trace	trace	trace	trace	trace	100	—
Pu-239	9.8E+01	1.0E+02	1.0E+02	1.0E+02	1.0E+02	100	—
Pu-240	5.2E-02	5.2E-02	5.2E-02	5.2E-02	5.2E-02	100	—
Pu-241	trace	trace	trace	trace	trace	100	—
Cm-242	trace	trace	trace	trace	trace	100	—
SOF[b]	*0.9797*	*0.9963*	*0.9988*	*0.9988*	*0.9988*	1	—

[a] From 10 CFR 61.55 [NRC 2014].
[b] Sum of fractions.

TABLE 2 Radioactivity of Grouted Waste Form for Combined-Aqueous Wastes for 4-Cycle Cleanup Schedule and WCS Limit (units of nCi/g)

	Time after Irradiation, days					WCS Administrative Limit[a]
Isotope	7	14	30	180	365	
H-3	4.0E+02	4.0E+02	4.0E+02	3.9E+02	3.8E+02	2.5
C-14	4.6E-01	4.6E-01	4.6E-01	4.6E-01	4.6E-01	50
Co-60	7.7E+00	7.6E+00	7.6E+00	7.2E+00	6.7E+00	174
Ni-63	1.9E-01	1.8E-01	1.8E-01	1.8E-01	1.8E-01	219
Sr-90	1.1E+04	1.1E+04	1.1E+04	1.1E+04	1.1E+04	2.5
Tc-99	7.4E-01	7.4E-01	7.4E-01	7.4E-01	7.4E-01	0.188
I-129	3.9E-03	3.9E-03	3.9E-03	3.9E-03	3.9E-03	0.0788
Cs-137	8.3E+04	8.3E+04	8.3E+04	8.2E+04	8.1E+04	62.5
Pu-239	9.8E+01	1.0E+02	1.0E+02	1.0E+02	1.0E+02	1

[a] From Havlicak [2014].

TABLE 3 Ratios of Annual Generation of Combined-Aqueous Waste Stream per TSV to NRC limits for Four Cases: with No Isotopes Removed, with Pu-239 Removed, with Pu-239 and Cs-137 Removed, and with Pu-239, Cs-137, and Sr-90 Removed

Isotope	NRC Table Regulating Compliance	Time after Irradiation, days 7	14	30	180	365
1562 kg GWF/TSV-yr No isotopes removed		Fraction of NRC 10 CFR 61 Class C limit				
C-14	1	1.07E-04	1.07E-04	1.07E-04	1.07E-04	1.07E-04
Ni-59	1	1.66E-13	1.66E-13	1.66E-13	1.66E-13	1.66E-13
Ni-63	2	4.89E-07	4.89E-07	4.89E-07	4.87E-07	4.86E-07
Sr-90	2	2.90E-03	2.90E-03	2.90E-03	2.87E-03	2.84E-03
Nb-94	1	6.55E-07	6.55E-07	6.55E-07	6.55E-07	6.55E-07
Tc-99	1	4.59E-04	4.59E-04	4.59E-04	4.59E-04	4.59E-04
I-129	1	8.97E-05	8.97E-05	8.98E-05	9.01E-05	9.01E-05
Cs-137	2	3.35E-02	3.35E-02	3.35E-02	3.32E-02	3.28E-02
Pu-239	1	**9.79E+01**	**9.96E+01**	**9.98E+01**	**9.98E+01**	**9.98E+01**
SOF		*0.9804*	*0.9970*	*0.9995*	*0.9995*	*0.9995*
5714 kg GWF/TSV-yr ^{239}Pu removed		Fraction of NRC 10CFR61 Class B limit				
C-14	1	2.93E-05	2.93E-05	2.93E-05	2.93E-05	2.93E-05
Ni-59	1	3.40E-09	3.40E-09	3.40E-09	3.40E-09	3.40E-09
Ni-63	2	1.34E-06	1.34E-06	1.34E-06	1.33E-06	1.33E-06
Sr-90	2	3.71E-02	3.70E-02	3.70E-02	3.66E-02	3.62E-02
Nb-94	1	1.79E-07	1.79E-07	1.79E-07	1.79E-07	1.79E-07
Tc-99	1	1.25E-04	1.26E-04	1.26E-04	1.26E-04	1.26E-04
I-129	1	2.45E-05	2.45E-05	2.46E-05	2.46E-05	2.46E-05
Cs-137	2	**9.58E-01**	**9.58E-01**	**9.57E-01**	**9.48E-01**	**9.37E-01**
Pu-239	1			ignored		
SOF		*0.9951*	*0.9947*	*0.9938*	*0.9844*	*0.9729*
212 kg GWF/TSV-yr ^{239}Pu, ^{137}Cs removed		Fraction of NRC 10CFR61 Class B limit				
C-14	1	7.89E-04	7.89E-04	7.89E-04	7.89E-04	7.89E-04
Ni-59	1	9.15E-08	9.15E-08	9.15E-08	9.15E-08	9.15E-08
Ni-63	2	3.60E-05	3.59E-05	3.59E-05	3.58E-05	3.57E-05
Sr-90	2	**9.98E-01**	**9.98E-01**	**9.97E-01**	**9.87E-01**	**9.75E-01**
Nb-94	1	4.82E-06	4.82E-06	4.82E-06	4.82E-06	4.82E-06
Tc-99	1	3.45E-03	3.46E-03	3.46E-03	3.46E-03	3.46E-03
I-129	1	6.58E-04	6.59E-04	6.59E-04	6.61E-04	6.61E-04
Cs-137	2			ignored		
Pu-239	1			ignored		
SOF		*0.9982*	*0.9978*	*0.9968*	*0.9870*	*0.9750*

TABLE 3 (Cont.)

Isotope	NRC Table Regulating Compliance	Time after Irradiation, days				
		7	14	30	180	365
63.4 kg GWF/TSV-yr ^{239}Pu, ^{137}Cs, ^{90}Sr removed		Fraction of NRC 10CFR61 Class A limit				
C-14	1	2.64E-03	2.64E-03	2.64E-03	2.64E-03	2.64E-03
Ni-59	1	3.06E-07	3.06E-07	3.06E-07	3.06E-07	3.06E-07
Ni-63	2	2.41E-03	2.41E-03	2.41E-03	2.40E-03	2.39E-03
Sr-90	2			ignored		
Nb-94	1	1.61E-05	1.61E-05	1.61E-05	1.61E-05	1.61E-05
Tc-99	1	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02
I-129	1	2.21E-03	2.21E-03	2.21E-03	2.22E-03	2.22E-03
Cs-137	2			ignored		
Pu-239	1			ignored		
SOF		*0.0024*	*0.0024*	*0.0024*	*0.0024*	*0.0024*

TABLE 4 Annual Operations and Accumulations of Regulated Isotopes (units of Ci/year per TSV for each isotope listed--after 180-day decay)

	Cleanup Schedule		
	4-cycle	8-cycle	50-cycle
Irradiations:	52	52	50
Recycles:	39	45	49
Cleanups:	13	7	1
H-3	6.09E-01	6.63E-01	5.73E-01
C-14	1.15E-03	1.25E-03	1.11E-03
Co-60	1.16E-02	1.29E-02	1.07E-02
Ni-59	2.38E-06	2.57E-06	2.29E-06
Ni-63	2.97E-04	3.21E-04	2.85E-04
Sr-90	1.29E+02	1.40E+02	1.23E+02
Nb-94	1.15E-07	1.24E-07	1.11E-07
Tc-99	9.57E-03	1.02E-02	9.16E-03
I-129	2.05E-05	2.19E-05	1.95E-05
Cs-137	1.31E+02	1.42E+02	1.25E+02
Np-237	1.31E-05	1.13E-05	1.32E-05
Pu-238	9.13E-07	5.83E-06	3.70E-04
Pu-239	2.38E-01	2.39E-01	2.27E-01
Pu-240	1.25E-04	2.97E-04	1.80E-03

estimates of the total amounts of Pu, Cs, and Sr recovered from the various waste streams that would require separate disposition if completely removed from the waste streams. Note that removing either Sr-90 or Cs-137 (and Pu-239) has a greater effect on the compliance of some waste streams.

The elemental distributions for the 4-, 8-, and 50-cycle cleanup schedules are provided in Appendix B, Tables B.1, B.2, and B.3, respectively. These values were used to calculate the relative masses of each waste stream that could be immobilized in a grouted waste form such that the curie contents of the regulated isotopes present in the waste streams were compliant with NRC regulations on the curie per mass or curie per volume limit. Appendices C, D, and E summarize the results for solid waste materials, aqueous waste streams, and combined waste streams from the 4-, 8-, and 50-cycle cleanup schedules, respectively. Data are given for the waste streams with and without Pu, Cs, and Sr. Given in these tables is the following:

- the mass of the total waste solids used to represent the waste stream in the calculation (with the separate masses of uranium, fission products excluding U, and chemical wastes),
- the waste loading based on the mass that meets the radionuclide compliance limits for the identified waste form classification,
- the mass of GWF that would be made with that waste loading based on a water/cement mix ratio of 0.5 and a GWF density of 1850 kg/m^3, and
- the number of 55-gal drums that this volume of GWF would fill to 90% capacity.

Calculations were made using a 90% fill level to allow for up to 10% void volume due to pouring and the efficiency of macro-encapsulating other waste components.

The impact of the number of cycles between cleanup operations was evaluated by using the data for combined solids, aqueous waste streams, and all waste streams in Table 5. More frequent cleanups result in greater amounts of chemical waste but not greater amounts of regulated isotopes. Because the compliance is based only on the isotope content and total mass (and volume) of the waste form, similar amounts of these waste forms are predicted for each cleanup cycle; all are compliant with Class C requirements. The difference will be the relative amounts of wastes (other than the regulated isotopes) and grout components present in the different waste forms. Although the effect of cleanup frequency must be evaluated after actual grout compositions have been formulated, these estimated waste loadings provide some insight into the likely effect. The relatively low waste loadings of waste streams from the 50-cycle cleanup schedule provide more flexibility in grout formation and will be more easily achieved than the relatively high waste loadings of waste streams from the 4-cycle cleanup schedule.

TABLE 5 Comparison of Annual Generations per TSV Class C and Class B Waste Forms for Pu Removal Options and Different Numbers of Irradiations between Cleanup

		Number of Irradiations between Cleanup								
Waste Stream	Characteristic	4			8			50		
Combined-Column Waste Streams[a]	Recovered Uranium, kg		11.5			11.5			11.0	
	Fission Products, g		15.8			19.6			57.5	
	Chemical Waste, kg		6.43			3.43			0.49	
	Total Waste Solids, kg		6.44			3.45			0.55	
	Amount Pu removed	0%	90%	100%	0%	90%	100%	0%	90%	100%
	Minimum Mass GWF, kg	825	8250	183	776	7760	267	709	7080	418
	Number of Drums & Class	2.4 C	23.8 B	0.5 B	2.2 C	22.4 B	0.77 B	2.1 C	20.5 B	1.2 B
Combined-Aqueous Waste Streams[b]	Recovered Uranium, kg		39.5			45.5			49.5	
	Fission Products, kg		90.1			85.4			195.6	
	Chemical Waste, kg		63.3			37.0			10.2	
	Total Waste Solids, kg		63.4			37.0			10.4	
	Amount Pu removed	0%	90%	100%	0%	90%	100%	0%	90%	100%
	Minimum Mass GWF, kg	1560	15600	5710	1630	16300	6220	1600	15956	5810
	Number of Drums	4.5 C	45.1 B	16.5 B	4.7 C	47.1 B	18.0 B	4.9 C	46.07 B	16.8 B
Combined All- Waste Streams[c]	Recovered Uranium, kg		51.0			57.0			60.6	
	Fission Products, kg		111			111			264	
	Chemical Waste, kg		122			70.5			19.0	
	Total Waste Solids, kg		122			70.6			19.3	
	Amount Pu removed	0%	90%	100%	0%	90%	100%	0%	90%	100%
	Minimum Mass GWF, kg	2390	23900	7240	2410	24100	7740	2300	23000	6860
	Number of Drums	6.9 C	69.0 B	20.9 B	7.0 C	69.6 B	22.4 B	6.6 C	66.3 B	19.8 B

[a] Combination of Ti-column sorbent + anion resin + LMC glassware.

[b] Combination of spent wash + spent eluate + rotovap concentrate + LMC + UREX raffinate.

[c] Combination of combined columns + combined aqueous + Ba/$SrSO_4$ waste streams.

4.2 EFFECTS OF REMOVING PLUTONIUM, CESIUM, AND STRONTIUM

The benefits of removing Pu, Cs, and Sr from the waste streams to the regulatory classifications and minimum required amounts of grouted waste form are summarized in Table 6 for the individual and combined waste streams generated by the 4-, 8-, and 50-cycle cleanup schedules. Removal of Pu changes the classifications of most individual and combined waste streams from Class C to Class B with less than a 2.5-fold increase in the number of drums for the combined waste streams. The separate removal of either Cs or Sr (without removing Pu) does not affect the classification of the combined wastes or most of the individual waste streams, but reduces the mass of waste form that is required for some waste streams. Many waste streams from which both Cs and Sr are removed (in addition to the removal of Pu) become compliant with Class A. Note that the complete removal of Pu, Cs, and Sr results in several waste streams with low contaminant levels that do not require the additional mass (or volume) provided by grout to be compliant. In those cases, the grout serves as a binder. The anion-exchange resin and LMC waste streams are regulated by Tc-99, and the Ba/$SrSO_4$ waste stream is regulated by Sr-90, so the removal of Pu and Cs does not lower the classifications of those waste streams.

For waste forms to be compliant with Class B or Class A limits, the SOF for the long-lived nuclides regulated by NRC Table 1 must be less than 0.1. Since Pu-239 dominates the SOF and is the limiting nuclide for Class C compliance of most waste streams, the Pu-239 content must be decreased by at least 90% to achieve an SOF less than 0.1. The removal of Pu, Cs, and Sr will increase the waste loading and lower the number of drums required for most waste streams, and lowers the classification of some waste streams. Waste loadings for some waste streams become limited by Tc-99 or I-129 contents after Pu, Cs, and Sr are removed. For example, the spent wash solution for the 4-cycle cleanup schedule is regulated as Class C and the waste loading is limited by the Pu-239 content. That waste form will fill about 0.7 drums. If 90% of the Pu-239 is removed for separate disposition, the waste becomes Class B. The waste loading is still limited by the Pu-239 content and will generate about 7 drums of that waste form. If all the Pu is removed, the modified solution is still Class B, but the maximum waste loading is higher and limited by the Cs-137 content (primarily). This would generate about 1.4 drums of that waste form. If all the Pu and all the Cs are removed, the solution becomes regulated by the Sr-90 content and generates 0.2 drums of Class B waste. If all the Pu, Cs, and Sr are removed, the waste loading will be regulated by the Tc-99 content and generate 0.01 drums of that Class A waste form.

The primary benefit is gained by removing 90% of the Pu to change from Class C to Class B. The added benefit of removing more than 90% up to 100% of the Pu in terms of the number of drums generated is limited for most waste streams because compliance becomes determined by another nuclide.

TABLE 6 Impacts of Removing Pu, Cs, and Sr from Waste Streams on Classification, Limiting Isotope, and Number of Drums of Waste Form Generated Annually per TSV for Different Numbers of Irradiations between Cleanup

	4-Cycle Cleanup Schedule				8-Cycles Cleanup Schedule				50-Cycles Cleanup Schedule			
Waste Stream	Class & Rules		Limiting Isotope	Drums per year	Class & Rules		Limiting Isotope	Drums per year	Class & Rules		Limiting Isotope	Drums per year
Ti-column sorbent	C	5(ii)	Pu-239	2.37	C	5(ii)	Pu-239	2.23	C	5(ii)	Pu-239	2.56
Without Pu	B	5(i);4(ii)	Cs-137	0.53	B	5(i);4(ii)	Cs-137	0.77	B	5(i);4(ii)	Cs-137	15.41
Without Pu and Cs	B	5(i);4(ii)	Sr-90	0.22	B	5(i);4(ii)	Sr-90	0.29	B	5(i);4(ii)	Sr-90	11.26
Without Pu and Sr	B	5(i);4(ii)	Cs-137	0.33	B	5(i);4(ii)	Cs-137	0.48	B	5(i);4(ii)	Cs-137	10.54
Without Pu, Sr, and Cs	A	5(i);4(i)	Tc-99	0.02	A	5(i);4(i)	I-129	0.01	A	5(i);4(i)	I-129	3.67
$Ba/SrSO_4$	C	4(iii)	Sr-90	0.18	C	4(iii)	Sr-90	0.09	C	4(iii)	Sr-90	0.04
$Ba/SrSO_4$	B	4(ii)	Sr-90	3.85	B	4(ii)	Sr-90	3.61	B	4(ii)	Sr-90	1.83
Anion resin	A	3(i)	Tc-99	0.15	A	3(i)	Tc-99	0.14	A	3(i)	Tc-99	0.07
Glassware	A	5(i);4(i)	Sr-90	<0.01	A	5(i);4(i)	Sr-90	<0.01	A	5(i);4(i)	Sr-90	<0.01
Spent Wash	C	5(ii)	Pu-239	0.70	C	5(ii)	Pu-239	0.80	C	5(ii)	Pu-239	0.89
Without Pu	B	5(i);4(ii)	Cs-137	1.38	B	5(i);4(ii)	Cs-137	2.55	B	5(i);4(ii)	Cs-137	4.97
Without Pu and Cs	B	5(i);4(ii)	Sr-90	0.24	B	5(i);4(ii)	Sr-90	0.44	B	5(i);4(ii)	Sr-90	0.84
Without Pu and Sr	B	5(i);4(ii)	Cs-137	1.15	B	5(i);4(ii)	Cs-137	2.11	B	5(i);4(ii)	Cs-137	4.15
Without Pu, Cs, and Sr	A	5(i);4(i)	Tc-99	0.01	A	5(i);4(i)	Tc-99	0.02	A	5(i);4(i)	Tc-99	0.04
Spent Eluate	C	5(ii)	Pu-239	1.76	C	5(ii)	Pu-239	2.13	C	5(ii)	Pu-239	2.44
Without Pu	B	5(i);4(ii)	Cs-137	1.85	B	5(i);4(ii)	Cs-137	3.47	B	5(i);4(ii)	Cs-137	6.86
Without Pu and Cs	B	5(i);4(ii)	Sr-90	0.37	B	5(i);4(ii)	Sr-90	0.69	B	5(i);4(ii)	Sr-90	1.32
Without Pu and Sr	B	5(i);4(ii)	Cs-137	1.48	B	5(i);4(ii)	Cs-137	2.79	B	5(i);4(ii)	Cs-137	5.56
Without Pu, Cs, and Sr	A	5(i);4(i)	none	<0.01	A	5(i);4(i)	none	<0.01	A	5(i);4(i)	none	<0.01
Rotovap Concentrate	A	5(i);4(i)	none	<0.01	A	5(i);4(i)	none	<0.01	A	5(i);4(i)	none	<0.01
LMC	C	5(ii)	Tc-99	<0.01	C	5(ii)	Tc-99	<0.01	C	5(ii)	Tc-99	<0.01
LMC	B	5(i);4(ii)	Tc-99	0.01	B	5(i);4(ii)	Tc-99	0.02	B	5(i);4(ii)	Tc-99	0.05
LMC	A	5(i);4(i)	Sr-90	0.14	A	5(i);4(i)	Sr-90	0.26	A	5(i);4(i)	Sr-90	0.51
Without Cs	A	5(i);4(i)	Sr-90	0.14	A	5(i);4(i)	Sr-90	0.25	A	5(i);4(i)	Sr-90	0.49
Without Sr	A	5(i);4(i)	Tc-99	<0.01	A	5(i);4(i)	Tc-99	0.02	A	5(i);4(i)	Tc-99	0.05
Without Cs and Sr	A	5(i);4(i)	Tc-99	<0.01	A	5(i);4(i)	Tc-99	0.02	A	5(i);4(i)	Tc-99	0.05
UREX Raffinate	C	5(ii)	Pu-239	2.05	C	5(ii)	Pu-239	1.77	C	5(ii)	Pu-239	1.27
Without Pu	B	5(i);4(ii)	Cs-137	13.23	B	5(i);4(ii)	Cs-137	11.98	B	5(i);4(ii)	Cs-137	4.91
Without Pu and Cs	A	5(i);4(i)	none	0.17	A	5(i);4(i)	none	0.09	A	5(i);4(i)	none	0.02

TABLE 6 (Cont).

Waste Stream	4-Cycle Cleanup Schedule			8-Cycle Cleanup Schedule			50-Cycle Cleanup Schedule		
	Class & Rules	Limiting Isotope	Drums per year	Class & Rules	Limiting Isotope	Drums per year	Class & Rules	Limiting Isotope	Drums per year
Combined Columns	C 5(ii)	Pu-239	2.38	C 5(ii)	Pu-239	2.23	C 5(ii)	Pu-239	2.05
Without Pu	B 5(i);4(ii)	Cs-137	0.53	B 5(i);4(ii)	Cs-137	0.77	B 5(i);4(ii)	Cs-137	1.21
Without Pu and Cs	B 5(i);4(ii)	Sr-90	0.20	B 5(i);4(ii)	Sr-90	0.29	B 5(i);4(ii)	Sr-90	0.44
Without Pu and Sr	B 5(i);4(ii)	Cs-137	0.33	B 5(i);4(ii)	Cs-137	0.51	B 5(i);4(ii)	Cs-137	0.77
Without Pu, Cs, and Sr	A 5(i);4(i)	Tc-99	0.16	A 5(i);4(i)	Tc-99	0.16	A 5(i);4(i)	Tc-99	0.09
Combined Aqueous	C 5(ii)	Pu-239	4.51	C 5(ii)	Pu-239	4.71	C 5(ii)	Pu-239	4.91
Without Pu	B 5(i);4(ii)	Cs-137	16.50	B 5(i);4(ii)	Cs-137	17.98	B 5(i);4(ii)	Cs-137	16.78
Without Pu and Cs	B 5(i);4(ii)	Sr-90	0.61	B 5(i);4(ii)	Sr-90	1.12	B 5(i);4(ii)	Sr-90	2.16
Without Pu and Sr	B 5(i);4(ii)	Cs-137	15.92	B 5(i);4(ii)	Cs-137	16.87	B 5(i);4(ii)	Cs-137	14.58
Without Pu, Sr, and Cs	A 5(i);4(i)	none	0.18	A 5(i);4(i)	none	0.11	A 5(i);4(i)	Tc-99	0.10
Combined All Wastes	C 5(ii)	Pu-239	6.90	C 5(ii)	Pu-239	6.96	C 5(ii)	Pu-239	6.63
Without Pu	B 5(i);4(ii)	Cs-137	20.90	B 5(i);4(ii)	Cs-137	22.36	B 5(i);4(ii)	Cs-137	19.80
Without Pu and Cs	B 5(i);4(ii)	Sr-90	4.66	B 5(i);4(ii)	Sr-90	5.01	B 5(i);4(ii)	Sr-90	4.45
Without Pu and Sr	B 5(i);4(ii)	Cs-137	16.18	B 5(i);4(ii)	Cs-137	17.43	B 5(i);4(ii)	Cs-137	15.37
Without Pu, Sr, and Cs	A 5(i);4(i)	none	0.35	A 5(i);4(i)	Tc-99	0.21	A 5(i);4(i)	Tc-99	0.18

4.3 USE OF WATER TO MAKE GROUTED WASTE FORMS

We calculated the amounts of grout that would be made and number of drums filled for waste forms (1) filling the minimum number of drums, (2) meeting Class B requirements, and (3) using the total amount of water present in the waste streams. Waste forms were formulated for the Combined All-waste streams generated by the 4-, 8-, and 50-cycle cleanup schedules. The results are summarized in Table 7. Compared with the minimum numbers of drums, the numbers of drums of Class B waste forms increase 10-fold due to the different Pu-239 limits for Class C and Class B wastes. The Class B limit for Pu-239 is met due to the lower waste loading rather than by removing Pu from the waste streams. Note that the 50-cycle cleanup schedule does not generate enough waste water to make Class B waste form with all the waste and water must be added. The number of drums of waste form increases by factors of 17, 13, and 8.5 for the 4-, 8-, and 50-cycle cleanup schedules, respectively, if all the processing water is used. The waste forms for the 4- and 8-cycle cleanup schedules are Class B, but the waste form for the 50-cycle waste is Class C. It is expected that the cleanup schedule could be optimized to make about 70 drums of a Class B waste form using all the waste water. That would eliminate the needs to (1) treat the large volumes of waste water in excess of the small amount needed to make compliant waste forms and (2) remove Pu and Cs for separate disposition to avoid Class C waste forms.

TABLE 7 Calculated Numbers of Drums per TSV-Year Generated Annually with Combined Waste Streams[a] to use All Process Water and Minimum Number of Drums

	4-Cycle	8-Cycle	50-Cycle
Total mass water, kg	13,100	10,700	6470
Minimum number of drums	6.9 Class C	7.0 Class C	6.6 Class C
Mass excess water for minimum drums, kg	12,300	9880	4960
Number of drums Class B[a]	69 Class B	70 Class B	66 Class B
Mass excess water for Class B, kg	5160	2650	-1180
Number of drums if all water grouted	114 Class B	92 Class B	56 Class C

[a]With no radionuclides removed.

4.4 DOSE RATES FOR WASTE STREAMS FROM 4-CYCLE CLEANUP SCHEDULE

The dose rates for grouted waste forms made with the maximum waste loadings were calculated by using MicroShield 9.05 software. Whereas the waste form compliance calculations only included the 13 regulated isotopes, the compositions used for these dose calculations included the 272 isotopes contributing the highest doses. The isotope contents in each waste stream were calculated from the elemental distributions in an EXCEL workbook for the 4-cycle UREX cleanup schedule and the total curies of each isotope generated per TSV at 7 days after irradiation. These values were multiplied by 13 TSV/year to calculate the annual generation. The

values of Ci isotope/year were then divided by the number of drums of each waste stream (or combination of waste streams) required to meet Class C, Class B, or Class A regulations for the conditions provided in Table 6.

The geometry was modeled as a cylindrical grouted waste form contained in a 55-gal drum having a diameter of 57.15 cm (22.5 in.), a height of 85.09 cm (33.5 in.), and wall thickness of 0.15 cm (1/16 in.). The density of the grout was assumed to be 1850 kg m^{-3}, and it was assumed that the grout would fill the drum to 90% capacity, which is a waste form volume of 0.18 m^3. The dose rates were calculated at distances of 2 cm (0.8 in.), 30 cm (12 in.), and 100 cm (39 in.) from the outer surface of the drum with no additional shielding. Note that the maximum waste loadings that were calculated using the Origen software met the waste classification limits for regulated isotopes in waste streams predicted at 7, 14, 30, 180, and 365 days after irradiation. The dose calculations used the isotope contents of waste streams 7 days after irradiation; these were aged over time by the MicroShield 9.05 software. "Time zero" on the dose plot corresponds to 7 days after irradiation. Dose rates were calculated for 0.019, 0.25, 0.50, 1, 2, 4, and 10 years. Decay occurring as waste is stored prior to grouting and as grouted waste forms are stored prior to shipping can be estimated from these dose rate curves. The dose rates were calculated for maximum waste loading in a drum and can be scaled to represent lower loadings of the same waste streams. The present calculations are evaluated to assess the benefits of removing radionuclides from the waste streams and combining waste streams in a common waste form.

Figure 2 shows the results of dose calculations made for one drum of grouted waste form made with the maximum loadings meeting Class C limits for the separate $BaSrSO_4$ waste stream and various combined waste streams. The contribution of $Ba/SrSO_4$ waste to the dose rate becomes insignificant within about 6 months. The combined aqueous waste streams account for about 72% of the total dose from all wastes initially and for about 98% after 10 years.

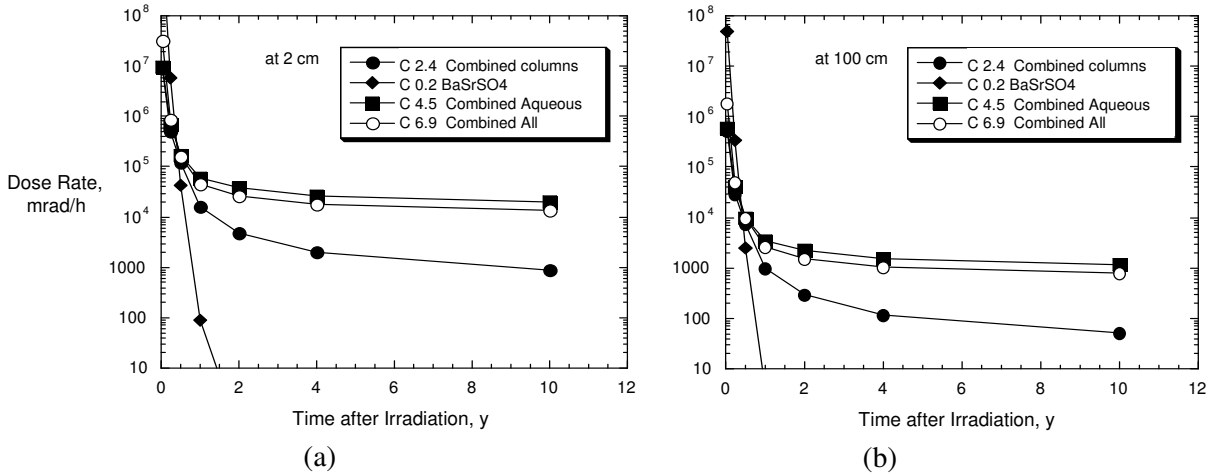

FIGURE 2 Dose Rate Calculations for One Drum Filled with Various Waste Streams at (a) 2 cm and (b) 100 cm from Drum Surface. The legend provides the waste classification and number of drums generated for each waste stream.

The benefits of removing various radionuclides on the dose rates at 2 and 100 cm away from the waste package are indicated in Figure 3. Removing Cs from the aqueous waste streams has a significant benefit to the dose rate beyond about one-half year (due mainly to Cs-137) and decreases the amount of waste form (number of drums) generated annually. Removing Pu lowers the waste classification, but does not lower the dose rate significantly. Removing Sr without removing Cs likewise provides no benefit to the dose rate. This comparison shows the benefits of removing Pu and Cs from the combined-aqueous wastes to lowering the dose rate and the trade-off between dose rate, storage time, and the number of drums generated. The effects of removing Cs but not removing Pu were not evaluated.

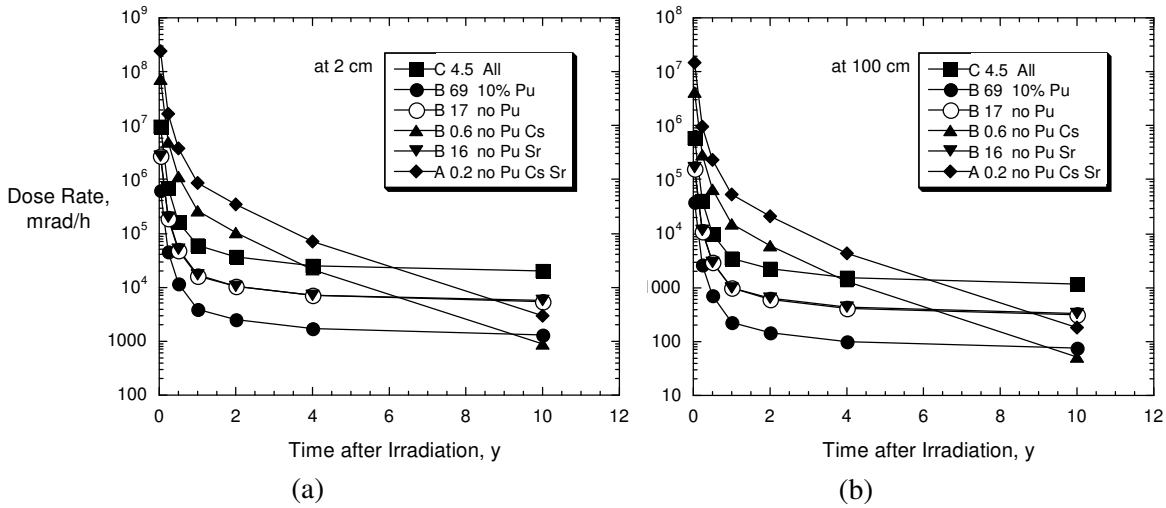

FIGURE 3 Dose Rate Calculations for One Drum with the Combined Aqueous Waste Stream With and Without Pu, Cs, and Sr. The legend provides the waste classification, number of drums generated, and radionuclide content of each option.

The dose rates at various decay times relative to the dose rate at the shortest time calculated, which corresponds to about 7 days after irradiation, are shown in Figure 4. (Note that time and dose are both plotted on a logarithmic scale, and that the ratios of the dose rates are the same at all distances from the drum.) The curves indicate that the benefits of removing Pu and Cs from the aqueous waste streams on the dose are small during the first year, but become increasingly significant thereafter. After 1 year, the dose rates for waste forms containing Cs have decreased to about 0.60% of the dose rates at 7 days, whereas the dose rates for waste forms without Cs have decreased to about 0.35% of the values at 7 days. The relative values have decreased to 0.38% and 0.14%, respectively, after 2 years and then to 0.26% and 0.03% after 4 years.

Finally, Figure 5 shows the dose rates per drum for the combination of all waste streams in a single waste form at 2 cm, 30 cm, and 100 cm from the surface of the drum. Results are shown for one drum of a waste form that fills the minimum of 6.9 drums with Class C waste and

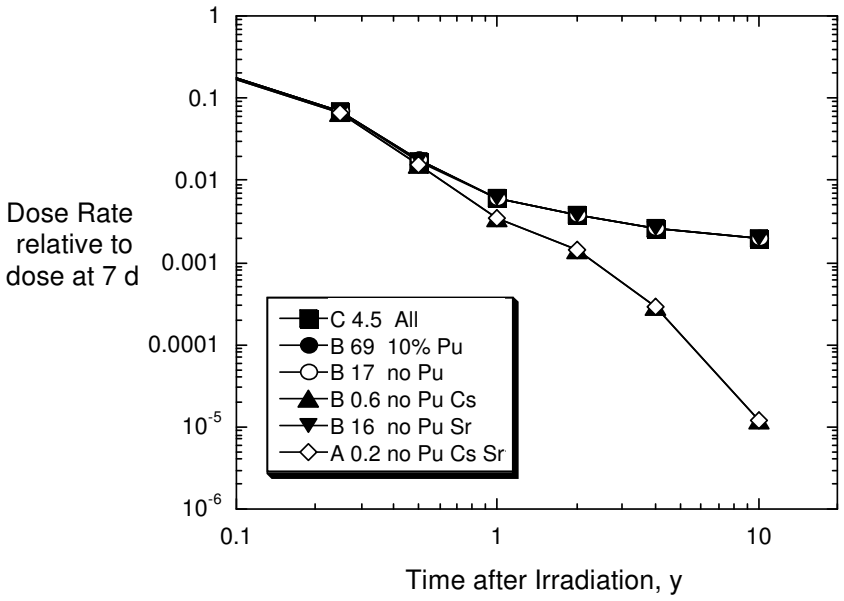

FIGURE 4 Dose Rate Calculations for One Drum Waste Form with the Combined Aqueous Waste Stream With and Without Pu, Cs, and Sr. The legend provides the waste classification, number of drums generated, and radionuclide content of each option.

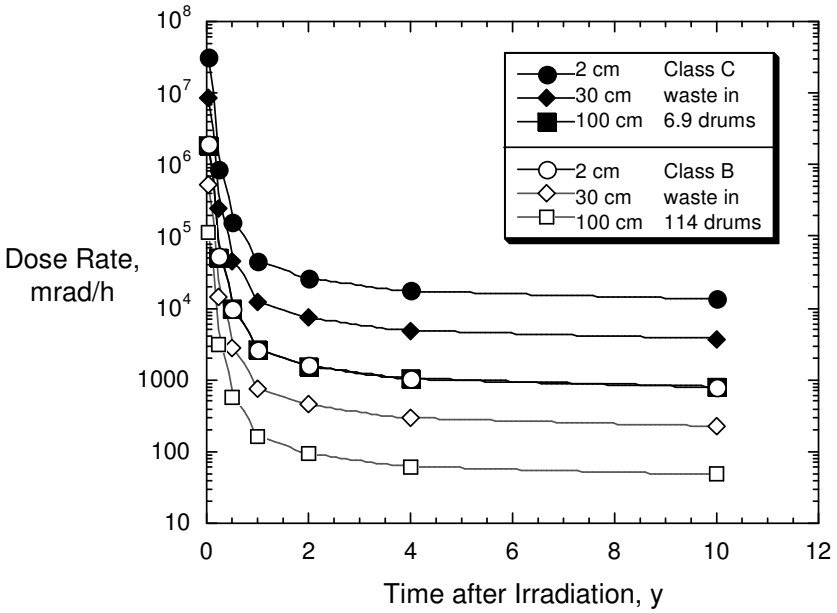

FIGURE 5 Dose Rate Calculations for One Drum Waste Form for the Combined-All Waste Stream Formulated to Generate 6.9 Drums of Class C or 114 Drums of Class B Waste Form using all Waste Water.

for one drum of a waste form that accommodates all of the process water for a 4-cycle cleanup schedule that fills 114 drums with Class B. The dose rates scale according to the mass of waste disposed in each drum. The dose rates in the Class B waste form are still about twice the transportation limits of 1 rem/h at the surface and 10 rem/h at 2 meters. Removing a portion of the Cs-137 inventory from the waste would significantly lower the dose rate to meet transportation limits. This will be evaluated further when the waste form formulations are more mature.

It is important to remember that the isotopic compositions of the waste streams, waste loadings, and physical properties of the grout are all based on best-guess estimates. All values will change as grout formulations are revised on the basis of laboratory-scale testing and refinements of the separation and treatment operations. The present estimates are intended to identify likely benefits of optional waste treatment and pathways to waste form production. These calculations should be repeated when estimates of grout formulations and isotopic distributions between waste streams can be improved based on results of ongoing and planned testing, and when information regarding other waste streams not included in this analysis (such as captured off-gas wastes) becomes available. Nevertheless, this preliminary work has provided methods to utilize that information to address key issues in waste form formation and qualification for disposal.

5 SUMMARY

The isotopic compositions of grouted waste forms for waste streams from several processing operations meeting NRC regulations were determined based on Origen calculations for radioisotope generation for 4-cycle and 50-cycle cleanup schedules. These were used to calculate the impacts on the amounts and classifications of compliant grouted waste form formulations of the following:

- UREX cleanup schedule,
- combining different waste streams in a common waste form,
- the removal of Pu, Cs, and Sr from the waste streams, and
- the amount of waste water used to make waste form.

Maximum waste loadings for regulated radionuclides were calculated for comparison with NRC Class C, B, and A limits to provide confidence that compliant waste forms can be produced from the SHINE waste streams. All waste streams can be treated to produce compliant waste forms having reasonable waste loadings and final volumes. The compliant formulations that were calculated provide lower bounds for the waste form volumes and number of drums that will be required to meet radioactivity limits. It is likely that processed waste forms will have lower waste loadings than those calculated in this evaluation of compliance for several waste streams. For example, some waste streams from which Pu, Cs, and Sr have been removed are compliant without further treatment, but may be grouted to consolidate the material.

Waste loadings on the order of 20% waste solutions are typical of grouted waste forms [Westsik et al. 2013]. A waste form made with 10% loading of waste solids is a reasonable target for the combined waste streams from the SHINE process. The amount of GWF made with this waste loading is expected to require about 750 kg of water and will fill fewer than eight 55-gal drums to about 90% capacity. This amount of water is only about 7% of the water in the combined waste streams generated by the 8-cycle cleanup schedule. Although waste water can be utilized to transport waste streams as slurries, some of the aqueous waste streams could be concentrated significantly to recover clean water. Most of the formulated waste forms discussed in this report included only the amount of water necessary to produce grout with the waste. The impact of including all of the process water in the grout waste forms was evaluated for the formulations combining all waste streams generated in a single waste form (i.e., the combined all-waste forms) for the 4-, 8-, and 50-cycle cleanup schedules. This resulted in approximately 17-, 13-, and 9-fold increases in the numbers of grouted waste forms generated for the 4-, 8-, and 50-cycle cleanup schedules, respectively. The waste forms for the 4- and 8-cycle cleanup schedules were Class B, but the waste form for the 50-cycle cleanup schedule remained Class C.

Waste forms having the maximum loading that meet Class C limits may not be practical to produce or physically acceptable. For example, the amount of dry mix may be insufficient to encapsulate all the waste solids to provide acceptable physical and chemical integrity, or higher

water/cement mix ratios may be required for higher fluidity to allow the fresh grout to flow into the drum and encapsulate other waste materials, such as discarded process equipment. Although these issues may require lower waste loadings and more drums, these waste forms will remain compliant with radioactivity limits.

Other issues that may require a further decrease in waste loadings include handling and storing the waste streams. Dose rates were calculated for the combined-aqueous, combined-columns, Ba/$SrSO_4$ precipitates, and combined all-waste streams over a 10-year decay period. The results provide insights into the benefits of removing Pu, Cs, and Sr from waste streams during separations and combining waste streams in common waste forms to be considered with the waste classification, transportation, and storage requirements and overall waste form production and disposal costs. The approach developed and used for this analysis can be used to formulate waste forms meeting requirements for storage, transportation, and disposal as processing options are selected, operations become better defined, and the waste form matrix is selected and developed.

6 CONCLUSIONS

The following conclusions are drawn from these initial analyses:

Compliance with NRC regulations

- Class C waste forms can be produced with all SHINE waste streams.
- About the same number of drums is required for waste forms made with individual or combined waste streams for process operations.
- Class B waste forms can be produced if more than 90% Pu is removed for separate disposition. Fewer drums of Class B waste forms will be produced if all Cs is removed from the waste streams.
- There is no benefit to removing Sr if Pu and Cs are not removed.
- Class A waste forms can be produced if more than 90% Pu and all Cs and Sr is removed. However, it appears that none of the NCR-compliant waste forms comply with Waste Control Specialists administrative limits.

Dose Rates

- Waste form dose rates are dominated by the Combined Aqueous waste streams.
- Dose rates benefit from combining all waste streams.
- Removing Cs from the waste streams provides the major benefit the dose rate, but not until after about 1 year of decay.
- The dose rate of a waste form made with the combined waste streams with all radionuclides and all processing water from a 4-cycle cleanup schedule exceeds the transportation limit. Removing most of the Cs-137 is expected to decrease the dose rate to compliant levels.
-

Operations

- Similar minimum amounts of waste forms are required for compliance for waste streams generated annually with 4-, 8, and 50-cycle cleanup schedules.
- The predominant effect of the cleanup schedule is the amount of waste water generated.

- Including all process water in the waste form increases number of drums above minimums by 17X (Class B), 13X (Class B), and 8.5X (Class C) for 4-, 8-, and 50-cycle cleanup schedules.

- The cleanup schedule might be optimized to generate a Class B waste form consuming all processing water and nuclides (about an 11-cycle cleanup schedule and 70 drums per TSV-year).

7 RECOMMENDATIONS FOR FURTHER WORK

Laboratory tests are needed to formulate acceptable grouted waste forms made with these waste streams and other waste materials added as aggregate to the grout or placed in some waste drums to be macro-encapsulated in the waste drums, such as hardware and column materials. Studies to optimize the waste form should address processing requirements (such as fluidity and set time) and performance requirements (such as resistance to leaching) in addition to waste minimization. Although a portland cement-based grout was used as a matrix to provide a waste form density for these calculations, the results do not otherwise depend on the identity of the matrix material. Such grouts have been used successfully at Savannah River and were demonstrated for use in supplemental treatment of Hanford wastes. The use of alternative materials should be evaluated for the SHINE waste streams, such as a clay-based geopolymer in which clay is used in the formulation instead of fly ash [Jantzen et al. 2013]. The testing approach for most other matrix materials will be the same as that recommended for grout.

A laboratory testing project is recommended to (1) demonstrate the efficacy of grouting the combined SHINE waste streams, (2) determine appropriate grout formulations of portland cement, blast furnace slag, fly ash, wastes, and water based on fluidity and residual free water, (3) evaluate interactions of the grout matrix with added zeolite and crushed glass regarding beneficial pozzolanic properties of the additives, (4) demonstrate adequate macro-encapsulation of large pieces of glassware and other waste materials by the grout matrix, and (5) demonstrate adequate physical and chemical durability (leach resistance) of the resulting waste forms.

Tests conducted to support development of the waste form(s) should provide insights for addressing future regulatory needs for the final waste form, in particular, those of consistency in the waste form product. Those needs are typically met through production controls. Some aspects can be monitored during production, such as radionuclide content and mix ratios of water and dry mix, but others address the cured waste form. It is anticipated that important properties of the waste form in drums will include the waste form and void volumes, evidence of the amount of free water, the physical uniformity of the waste form, and the heat generated during curing. The effect of decay heat generated by the waste on the grout properties will also be important. The grout formulation and processing methods can be modified to optimize the waste form. It is recommended that methods to economically monitor grout production and properties of the final waste forms be developed and calibrated in parallel with waste form development.

An outline of the proposed test plan is provided in Appendix F. The results would confirm the applicability of grout matrix material and allow for more accurate calculations of waste loading and total waste volumes and indicate the need for additional chemical treatment to adequately retain soluble nuclides and constituents regulated by the Resource Conservation and Recovery Act (RCRA), such as barium. The plan also addresses waste form consistency.

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APPENDIX A:

TOTAL CURIES OF REGULATED ISOTOPES GENERATED ANNUALLY PER TSV

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TABLE A.1 Total Curies of Radionuclides per TSV Generated during 4 Cycles that Remain at Various Times after Irradiation

		Total Curies after 4 Cycles				
	4 cycles	7 days	14 days	30 days	180 days	365 days
H-3	4.81E-2	4.81E-02	4.81E-02	4.80E-02	4.69E-02	4.55E-02
C-14	8.88E-5	8.88E-05	8.88E-05	8.88E-05	8.88E-05	8.88E-05
Co-60	9.52E-4	9.50E-04	9.50E-04	9.45E-04	8.95E-04	8.37E-04
Ni-59	1.83E-07	1.83E-07	1.83E-07	1.83E-07	1.83E-07	1.83E-07
Ni-63	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.28E-05
Sr-90	1.01E1	1.01E+01	1.01E+01	1.01E+01	9.96E+00	9.84E+00
Nb-94	8.84E-09	8.84E-09	8.84E-09	8.84E-09	8.84E-09	8.84E-09
Tc-99	7.23E-4	7.35E-04	7.36E-04	7.36E-04	7.36E-04	7.36E-04
I-129	1.56E-6	1.57E-06	1.57E-06	1.57E-06	1.57E-06	1.57E-06
Cs-137	1.02E1	1.02E+01	1.02E+01	1.02E+01	1.01E+01	9.99E+00
Np-237	6.41E-07	8.19E-07	9.14E-07	9.87E-07	1.01E-06	1.01E-06
Pu-239	1.59E-02	1.79E-02	1.82E-02	1.83E-02	1.83E-02	1.83E-02
Pu-240	9.62E-06	9.62E-06	9.62E-06	9.62E-06	9.62E-06	9.62E-06

TABLE A.2 Total Curies of Radionuclides per TSV Generated during 8 Cycles that Remain at Various Times after Irradiation

		Total Curies after 8 Cycles				
	8 cycles	7 days	14 days	30 days	180 days	365 days
H-3	9.61E-2	9.60E-02	9.60E-02	9.59E-02	9.48E-02	9.34E-02
C-14	1.78E-4	1.78E-04	1.78E-04	1.78E-04	1.78E-04	1.78E-04
Co-60	1.90E-3	1.90E-03	1.90E-03	1.89E-03	1.84E-03	1.78E-03
Ni-59	3.67E-7	3.67E-07	3.67E-07	3.67E-07	3.67E-07	3.67E-07
Ni-63	4.59E-5	4.59E-05	4.59E-05	4.59E-05	4.59E-05	4.59E-05
Sr-90	2.01E1	2.01E+01	2.01E+01	2.01E+01	2.00E+01	1.98E+01
Nb-94	1.77E-8	1.77E-08	1.77E-08	1.77E-08	1.77E-08	1.77E-08
Tc-99	1.46E-3	1.46E-03	1.46E-03	1.46E-03	1.46E-03	1.46E-03
I-129	3.13E-6	3.13E-06	3.13E-06	3.13E-06	3.13E-06	3.13E-06
Cs-137	2.04E1	2.04E+01	2.04E+01	2.04E+01	2.03E+01	2.02E+01
Np-237	1.62E-6	1.62E-06	1.62E-06	1.62E-06	1.62E-06	1.62E-06
Pu-239	3.42E-2	3.42E-02	3.42E-02	3.42E-02	3.42E-02	3.42E-02
Pu-240	4.24E-5	4.24E-05	4.24E-05	4.24E-05	4.24E-05	4.24E-05

TABLE A.3 Total Curies of Radionuclides per TSV Generated during 50 Cycles that Remain at Various Times after Irradiation

		Total Curies after 50 Cycles				
	50 cycles	7 days	14 days	30 days	180 days	365 days
H-3	5.88E-01	5.87E-01	5.87E-01	5.86E-01	5.73E-01	5.57E-01
C-14	1.11E-03	1.11E-03	1.11E-03	1.11E-03	1.11E-03	1.11E-03
Co-60	1.14E-03	1.13E-02	1.13E-02	1.13E-02	1.07E-02	9.99E-03
Ni-59	2.29E-06	2.29E-06	2.29E-06	2.29E-06	2.29E-06	2.29E-06
Ni-63	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.85E-04	2.84E-04
Sr-90	1.24E+02	1.24E+02	1.24E+02	1.24E+02	1.23E+02	1.21E+02
Nb-94	1.11E-07	1.11E-07	1.11E-07	1.11E-07	1.11E-07	1.11E-07
Tc-99	9.14E-03	9.16E-03	9.16E-03	9.16E-03	9.16E-03	9.16E-03
I-129	1.95E-05	1.95E-05	1.95E-05	1.95E-05	1.95E-05	1.95E-05
Cs-137	1.26E+02	1.26E+02	1.26E+02	1.26E+02	1.25E+02	1.24E+02
Np-237	1.28E-05	1.30E-05	1.30E-05	1.32E-05	1.32E-05	1.32E-05
Pu-239	2.25E-01	2.27E-01	2.27E-01	2.27E-01	2.27E-01	2.27E-01
Pu-240	1.80E-03	1.80E-03	1.80E-03	1.80E-03	1.80E-03	1.80E-03

APPENDIX B:

MASS FRACTIONS OF REGULATED ISOTOPES IN WASTE STREAMS

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TABLE B.1 Mass Fractions of Elements in Various Waste Streams after 4-Cycle Cleanup Schedule

		Mass Fraction Element in Waste Stream								
Element	Total Mass in Waste Streams, g	Ti-Column Sorbent	Anion Resin	$Ba/SrSO_4$	Spent Wash	Rotovap Condensate	Spent Eluate Solution	LMC Liquid Waste	Raffinate	Glassware
H	3.76E-05	5.02E-03	0	0	6.02E-03	7.53E-06	7.52E-02	7.41E-07	9.14E-01	3.74E-09
C	2.02E-06	3.73E-01	0	0	4.47E-01	6.42E-10	6.71E-06	0	1.80E-01	0
Co	4.81E-01	3.30E-02	0	0	9.64E-02	1.07E-12	3.72E-01	3.64E-05	4.99E-01	1.84E-07
Ni	9.24E+00	3.06E-02	0	0	6.37E-02	3.99E-13	1.38E-01	1.35E-05	7.68E-01	6.80E-08
Sr	2.95E+00	4.29E-02	0	8.26E-01	5.08E-02	1.05E-13	8.03E-02	7.87E-06	0	3.97E-08
Nb	3.09E-01	3.27E-02	0	0	7.00E-02	1.72E-10	1.32E-01	2.20E-04	7.60E-01	4.85E-03
Tc	5.90E-01	1.33E-02	8.65E-01	0	4.46E-02	6.06E-10	5.88E-04	5.82E-02	1.81E-02	2.94E-04
I	4.06E-01	4.56E-01	2.47E-01	0	9.05E-02	5.74E-07	8.28E-02	9.74E-07	1.24E-01	3.21E-05
Cs	2.71E+00	2.04E-02	0	0	7.11E-02	5.18E-14	9.16E-02	8.98E-06	8.17E-01	4.53E-08
Np	4.18E-01	2.88E-02	0	0	6.50E-02	2.31E-14	1.30E-01	1.27E-05	7.76E-01	6.41E-08
Pu	5.10E+00	3.44E-01	0	0	1.01E-01	0	2.57E-01	0	2.98E-01	0

TABLE B.2 Mass Fractions of Elements in Various Waste Streams after 8-Cycle Cleanup Schedule

		Mass Fraction Element in Waste Stream								
Element	Total Mass in Waste Streams, g	Ti-Column Sorbent	Anion Resin	$Ba/SrSO_4$	Spent Wash	Rotovap Condensate	Spent Eluate Solution	LMC Liquid Waste	Raffinate	Glassware
H	4.59E-05	7.47E-03	0	0	1.14E-02	1.42E-05	1.42E-01	1.40E-06	8.39E-01	3.30E-09
C	4.14E-06	3.29E-01	0	0	5.01E-01	7.20E-10	7.53E-06	0	1.70E-01	0
Co	4.67E-01	3.40E-02	0	0	1.15E-01	1.27E-12	4.42E-01	4.33E-05	4.10E-01	1.02E-07
Ni	6.69E+00	4.22E-02	0	0	1.02E-01	6.36E-13	2.19E-01	2.15E-05	6.37E-01	5.05E-08
Sr	3.93E+00	5.75E-02	0	7.19E-01	8.71E-02	1.78E-13	1.37E-01	1.34E-05	0	3.16E-08
Nb	2.38E-01	4.39E-02	0	0	1.12E-01	2.69E-10	2.07E-01	3.44E-04	6.34E-01	3.54E-03
Tc	7.52E-01	1.91E-02	7.76E-01	0	8.10E-02	1.10E-09	1.07E-03	1.06E-01	1.63E-02	2.49E-04
I	5.46E-01	4.88E-01	1.82E-01	0	1.28E-01	7.58E-07	1.09E-01	1.29E-06	9.20E-02	1.98E-05
Cs	3.79E+00	2.79E-02	0	0	1.21E-01	9.06E-14	1.60E-01	1.57E-05	6.90E-01	3.70E-08
Np	3.32E-01	3.98E-02	0	0	1.05E-01	3.73E-14	2.09E-01	2.05E-05	6.46E-01	4.83E-08
Pu	1.09E+01	3.21E-01	0	0	1.16E-01	0	3.08E-01	0	2.55E-01	0

TABLE B.3 Mass Fractions of Elements in Various Waste Streams after 50-Cycle Cleanup Schedule

		Mass Fraction Element in Waste Stream								
Element	Total Mass in Waste Streams, g	Ti-Column Sorbent	Anion Resin	$Ba/SrSO_4$	Spent Wash	Rotovap Condensate	Spent Eluate Solution	LMC Liquid Waste	Raffinate	Glassware
H	9.80E-05	1.89E-02	0	0	3.63E-02	4.54E-05	4.53E-01	4.47E-06	4.91E-01	1.38E-09
C	2.50E-05	2.94E-01	0	0	5.64E-01	8.10E-10	8.46E-06	0	1.42E-01	0
Co	4.17E-01	3.66E-02	0	0	1.39E-01	1.55E-12	5.37E-01	5.26E-05	2.88E-01	1.62E-08
Ni	3.88E+00	7.00E-02	0	0	1.91E-01	1.19E-12	4.12E-01	4.04E-05	3.28E-01	1.25E-08
Sr	1.21E+01	9.92E-02	0	4.13E-01	1.90E-01	3.88E-13	2.98E-01	2.92E-05	0	9.01E-09
Nb	2.09E-01	6.56E-02	0	0	2.34E-01	4.84E-10	3.72E-01	6.20E-04	3.27E-01	8.36E-04
Tc	1.89E+00	4.10E-02	4.41E-01	0	2.19E-01	2.99E-09	2.90E-03	2.87E-01	9.24E-03	8.86E-05
I	1.98E+00	5.36E-01	7.46E-02	0	1.98E-01	1.07E-06	1.54E-01	1.81E-06	3.76E-02	3.65E-06
Cs	1.20E+01	5.00E-02	0	0	2.69E-01	2.04E-13	3.61E-01	3.54E-05	3.20E-01	1.09E-08
Np	2.47E-01	6.70E-02	0	0	2.02E-01	7.19E-14	4.04E-01	3.96E-05	3.26E-01	1.22E-08
Pu	6.78E+01	3.07E-01	0	0	1.34E-01	0.00E+00	3.67E-01	0	1.92E-01	0

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APPENDIX C:

CHARACTERISTICS OF COMPLIANT WASTE FORMS FOR 4-CYCLE CLEANUP SCHEDULE

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TABLE C.1 Results for Bounding Formulations of Grouted Waste Forms for 4-Cycle Cleanup Schedule: Solid Waste Materials with and without Pu, Cs, and Sr

Waste Stream	Ti-Column Sorbent	$Ba/SrSO_4$	Anion Resin	Glassware
Recovered Uranium, kg	11.5	0	0	2E-5
Process	MEPS-021	UNCS-021	UNCS-022	MEPS-021
Waste stream identifiers	Recycle+spent	610A+610B	(623-619)	
Waste Stream Composition				
Fission products, g	15.2	5.35	0.610	7E-3
Chemical waste, kg	0[a]	51.8	6.43[a]	5E-5
Total waste solids, kg	0.0152	51.8	6.43	6E-5
Water, kg	0	3.04[b]	218	5E-3
Grouted Waste Form				
Waste form classification	**Class C**	**Class B**	**Class A**	**Class A**
Limiting nuclide	Pu-239	Sr-90	Tc-99	Sr-90
Maximum waste loading[c], mass%	0.00185	3.88	12.6	0.0227
Minimum mass GWF, kg	820	1334	52.3	0.25
Number of drums[d]	2.37	3.85	0.15	0.00
If 100% Pu removed from waste streams				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Cs-137	—	—	—
Maximum waste loading, mass%	0.0082	—	—	—
Minimum mass GWF, kg	185	—	—	—
Number of drums	0.53	—	—	—
If 100% Pu and 100% Cs removed from waste streams				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Sr-90	—	—	—
Maximum waste loading, mass%	0.022	—	—	—
Minimum mass GWF, kg	69.3	—	—	—
Number of drums	0.22	—	—	—
If 100% Pu and 100% Cs and 100% Sr removed from waste streams				
Waste form classification	**Class A**	—	—	—
Limiting nuclide	Tc-99	—	—	—
Maximum waste loading, mass%	0.22	—	—	—
Minimum mass GWF, kg	7.03	—	—	—
Number of drums	0.02	—	—	—

[a] Masses of TiO_2 beads and anion resin not included as waste for purpose of compliance calculations.
[b] Mass of waste stream precipitates slurried with 50 vol% water.
[c] Maximum waste solids loading that meets NRC limits for identified classification.
[d] Number of 55-gal drums filled to 90% capacity.

TABLE C.2 Results for Bounding Formulations of Grouted Waste Forms for 4-Cycle Cleanup Schedule: Aqueous Waste Streams with and without Pu, Cs, and Sr

Waste Stream	Spent Wash	Spent Eluate	Rotovap Concentrate	LMC	UREX Raffinate
Recovered Uranium, kg	1.72	37.7	7E-12	4E-3	2E-2
Process	RLWE-021	RLWE-021	RLWE-021	RLWE-021	RLWE-021
Waste stream identifiers	509	527	522	529	625
Waste Stream Composition					
Fission products, g	7.21	16.2	5E-7	0.105	66.6
Chemical waste, kg	1.32	2.51	1E-5	2E-2	5E-5
Total waste solids, kg	1.32	2.53	1E-5	2E-2	6E-5
Water, kg	724	1470	6E-2	10.5	5E-3
Grouted Waste Form					
Waste form classification	**Class C**	**Class C**	**Class A**	**Class A**	**Class C**
Limiting nuclide	Pu-239	Pu-239	none	Sr-90	Pu-239
Maximum waste loading, mass%	0.549	0.414	100	0.0374	8.39
Minimum mass GWF, kg	241	611	1E-5	49.9	710
Number of drums	0.70	1.76	0.00	0.14	2.05
If 100% Pu removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	**Class B**
Limiting nuclide	Cs-137	Cs-137	—	—	Cs-137
Maximum waste loading, mass%	0.276	0.394	—	—	1.30
Minimum mass GWF, kg	479	642	—	—	4581
Number of drums	1.38	1.85	—	—	13.23
If 100% Pu and 100% Cs removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	**Class A**
Limiting nuclide	Sr-90	Sr-90	—	—	none
Maximum waste loading, mass%	1.61	1.95	—	—	100
Minimum mass GWF, kg	82.2	130	—	—	59.6
Number of drums	0.24	0.37	—	—	0.17
If 100% Pu and 100% Sr removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	—
Limiting nuclide	Cs-137	Cs-137	—	—	—
Maximum waste loading, mass%	0.33	0.494	—	—	—
Minimum mass GWF, kg	397	512	—	—	—
Number of drums	1.15	1.48	—	—	—
If 100% Pu and 100% Cs and 100% Sr removed from waste streams					
Waste form classification	**Class A**	**Class A**	—	—	—
Limiting nuclide	Tc-99	none	—	—	—
Maximum waste loading, mass%	31.0	100	—	—	—
Minimum mass GWF, kg	4.27	2.53	—	—	—
Number of drums	0.01	0.01	—	—	—

TABLE C.3 Results for Bounding Formulations of Grouted Waste Forms for 4-Cycle Cleanup Schedule: Combined Waste Streams with and without Pu, Cs, and Sr

Waste Stream	Combined Columns[a]	Combined Aqueous[b]	Combined All-Waste Streams[c]
Recovered Uranium, kg	11.5	39.5	51.0
Waste Stream Composition			
Fission products, kg	15.8	90.1	111
Chemical waste, kg	6.43	63.3	122
Total waste solids, kg	6.44	63.4	122
Water, kg	218	10,093	13,081
Grouted Waste Form			
Waste form classification	**Class C**	**Class C**	**Class C**
Limiting nuclide	Pu-239	Pu-239	Pu-239
Maximum waste loading, mass%	0.781	4.06	5.09
Minimum mass GWF, kg	825	1562	2390
Number of drums	2.38	4.51	6.90
If 100% Pu removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	3.52	1.11	1.68
Minimum mass GWF, kg	183	5714	7240
Number of drums	0.53	16.50	20.90
If 100% Pu and 100% Cs removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Sr-90	Sr-90	Sr-90
Maximum waste loading, mass%	9.30	29.9	7.53
Minimum mass GWF, kg	69.3	212	1615
Number of drums	0.20	0.61	4.66
If 100% Pu and 100% Sr removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	5.66	1.15	2.17
Minimum mass GWF, kg	114	5515	5605
Number of drums	0.33	15.92	16.18
If 100% Pu and 100% Cs and 100% Sr removed from waste stream			
Waste form classification	**Class A**	**Class A**	**Class A**
Limiting nuclide	Tc-99	none	None
Maximum waste loading, mass%	11.4	100	100
Minimum mass GWF, kg	56.5	63.4	122
Number of drums	0.16	0.18	0.35

[a] Ti-column sorbent + anion resin + Glassware.

[b] Spent wash + Spent eluate + Rotovap concentrate +LMC + UREX raffinate.

[c] Combined columns + combined aqueous + Ba/$SrSO_4$.

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APPENDIX D:

CHARACTERISTICS OF COMPLIANT WASTE FORMS FOR 8-CYCLE CLEANUP SCHEDULE

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TABLE D.1 Results for Bounding Formulations of Grouted Waste Forms for 8-Cycle Cleanup Schedule: Solid Waste Materials with and without Pu, Cs, and Sr

Waste Stream	Ti-Column Sorbent	$Ba/SrSO_4$	Anion Resin	Glassware
Recovered Uranium, kg	11.5	0	0	1E-5
Process	MEPS-021	UNCS-021	UNCS-022	MEPS-021
Waste stream identifiers	Recycle+spent	610A+610B	(623-619)	
Waste Stream Composition				
Fission products, g	19.0	6.12	0.684	4E-3
Chemical waste, kg	0[a]	30.1	3.43[a]	3E-5
Total waste solids, kg	0.019	30.1	3.43	3E-5
Water, kg	0	3.54	1677	3E-3
Grouted Waste Form				
Waste form classification	**Class C**	**Class B**	**Class A**	**Class A**
Limiting nuclide	Pu-239	Sr-90	Tc-99	Sr-90
Maximum waste loading[c], mass%	0.00246	2.41	6.87	0.0144
Minimum mass GWF, kg	771	1250	49.9	0.216
Number of drums[d]	2.23	3.61	0.14	0.00
If 100% Pu removed from waste streams				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Cs-137	—	—	—
Maximum waste loading, mass%	0.0071	—	—	—
Minimum mass GWF, kg	267	—	—	—
Number of drums	0.77	—	—	—
If 100% Pu and 100% Cs removed from waste streams				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Sr-90	—	—	—
Maximum waste loading, mass%	0.019	—	—	—
Minimum mass GWF, kg	99.8	—	—	—
Number of drums	0.29	—	—	—
If 100% Pu and 100% Cs and 100% Sr removed from waste streams				
Waste form classification	**Class A**	—	—	—
Limiting nuclide	I-129	—	—	—
Maximum waste loading, mass%	0.410	—	—	—
Minimum mass GWF, kg	4.62	—	—	—
Number of drums	0.01	—	—	—

[a] Masses of TiO_2 beads and anion resin not included as waste for purpose of compliance calculations.

[b] Mass of waste stream precipitates slurried with 50 vol% water.

[c] Maximum loading of waste solids that meets NRC limits for identified classification.

[d] Number of 55-gal drums filled to 90% capacity.

TABLE D.2 Results for Bounding Formulations of Grouted Waste Forms for 8-Cycle Cleanup Schedule: Combined Waste Streams with and without Pu, Cs, and Sr

Waste Stream	Spent Wash	Spent Eluate	Rotovap Concentrate	LMC	UREX Raffinate
Recovered Uranium, kg	1.99	43.5	7E-12	4E-3	1.3E-2
Process	RLWE-021	RLWE-021	RLWE-021	RLWE-021	RLWE-021
Waste stream identifiers	509	527	522	529	625
Waste Stream Composition					
Fission products, kg	10.8	24.5	1E-6	0.21	49.9
Chemical waste, kg	1.52	2.90	2E-5	2.1E-2	32.5
Total waste solids, kg	1.53	2.92	2E-5	2.2E-2	32.6
Water, kg	835	1696	7E-2	12.1	4728
Grouted Waste Form					
Waste form classification	**Class C**	**Class C**	**Class A**	**Class A**	**Class C**
Limiting nuclide	Pu-239	Pu-239	none	Sr-90	Pu-239
Maximum waste loading, mass%	0.55	0.396	100	0.0236	5.32
Minimum mass GWF, kg	278	738	2E-5	91.7	612
Number of drums	0.80	2.13	0.00	0.26	1.77
If 100% Pu removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	**Class B**
Limiting nuclide	Cs-137	Cs-137	—	—	Cs-137
Maximum waste loading, mass%	0.173	0.243	—	—	0.785
Minimum mass GWF, kg	88.4	1203	—	—	4149
Number of drums	2.55	3.47	—	—	11.98
If 100% Pu and 100% Cs removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	**Class A**
Limiting nuclide	Sr-90	Sr-90	—	—	None
Maximum waste loading, mass%	1.01	1.23	—	—	100
Minimum mass GWF, kg	151	238	—	—	32.6
Number of drums	0.44	0.69	—	—	0.09
If 100% Pu and 100% Sr removed from waste streams					
Waste form classification	**Class B**	**Class B**	—	—	—
Limiting nuclide	Cs-137	Cs-137	—	—	—
Maximum waste loading, mass%	0.209	0.303	—	—	—
Minimum mass GWF, kg	732	965	—	—	—
Number of drums	2.11	2.79	—	—	—
If 100% Pu, 100% Cs, and 100% Sr removed from waste streams					
Waste form classification	**Class A**	**Class A**	—	—	—
Limiting nuclide	Tc-99	None	—	—	—
Maximum waste loading, mass%	21.2	100	—	—	—
Minimum mass GWF, kg	7.21	2.92	—	—	—
Number of drums	0.02	0.01	—	—	—

TABLE D.3 Results for Bounding Formulations of Grouted Waste Forms for 8-Cycle Cleanup Schedule: Solid Waste Materials with and without Pu, Cs, and Sr

Waste Stream	Combined Columns[a]	Combined Aqueous[b]	Combined All-Waste Streams[c]
Recovered Uranium, kg	11.5	45.5	57.0
Waste Stream Composition			
Fission products, kg	19.6	85.4	111
Chemical waste, kg	3.43	37.0	70.5
Total waste solids, kg	3.45	37.0	70.6
Water, kg	1,677	7,271	10,659
Grouted Waste Form			
Waste form classification	**Class C**	**Class C**	**Class C**
Limiting nuclide	Pu-239	Pu-239	Pu-239
Maximum waste loading, mass%	0.447	2.27	2.93
Minimum mass GWF, kg	771	1632	2410
Number of drums	2.23	4.71	6.96
If 100% Pu removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	1.29	0.595	0.912
Minimum mass GWF, kg	267	6225	7744
Number of drums	0.77	17.98	22.36
If 100% Pu and 100% Cs removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Sr-90	Sr-90	Sr-90
Maximum waste loading, mass%	3.45	9.53	4.07
Minimum mass GWF, kg	99.9	389	1735
Number of drums	0.29	1.12	5.01
If 100% Pu and 100% Sr removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	2.05	0.634	1.17
Minimum mass GWF, kg	178	5842	6036
Number of drums	0.51	16.87	17.43
If 100% Pu and 100% Cs and 100% Sr removed from waste stream			
Waste form classification	**Class A**	**Class A**	**Class A**
Limiting nuclide	Tc-99	None	Tc-99
Maximum waste loading, mass%	6.32	100	99.4
Minimum mass GWF, kg	54.5	37.0	71.0
Number of drums	0.16	0.11	0.21

[a] Ti-column sorbent + anion resin + glassware.
[b] Spent wash + spent eluate + rotovap concentrate + LMC + UREX raffinate.
[c] Combined columns + combined aqueous + Ba/$SrSO_4$.

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APPENDIX E:

CHARACTERISTICS OF COMPLIANT WASTE FORMS FOR 50-CYCLE CLEANUP SCHEDULE

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TABLE E.1 Results for Bounding Formulations of Grouted Waste Forms for 50-Cycle Cleanup Schedule: Solid Waste Materials with and without Pu, Cs, and Sr

Waste Stream	Ti-Column Sorbent	$Ba/SrSO_4$	Anion Resin	Glassware
Recovered Uranium, kg	11.0	0	0	1.4E-6
Process	MEPS-021	UNCS-021	UNCS-022	MEPS-021
Waste stream identifiers	Recycle+spent	610A+610B	(623-619)	
Waste Stream Composition				
Fission products, g	56.6	10.7	0.982	9E-4
Chemical waste, kg	0[a]	8.31	0.489[a]	4E-6
Total waste solids, kg	5.7E-2	8.32	0.490	6E-6
Water, kg	0	0.98[b]	1677	4E-4
Grouted Waste Form				
Waste form classification	**Class C**	**Class B**	**Class A**	**Class A**
Limiting nuclide	Pu-239	Sr-90	Tc-99	Sr-90
Maximum waste loading[c], mass%	0.00638	1.3	1.94	0.0116
Minimum mass GWF, kg	886	635	25.3	3E-5
Number of drums[d]	2.56	1.83	0.07	0.00
If 100% Pu removed from waste stream				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Cs-137	—	—	—
Maximum waste loading, mass%	0.00106	—	—	—
Minimum mass GWF, kg	5335	—	—	—
Number of drums	15.41	—	—	—
If 100% Pu and 100% Cs removed from waste stream				
Waste form classification	**Class B**	—	—	—
Limiting nuclide	Sr-90	—	—	—
Maximum waste loading, mass%	0.00145	—	—	—
Minimum mass GWF, kg	3900	—	—	—
Number of drums	11.26	—	—	—
If 100% Pu and 100% Cs and 100% Sr removed from waste stream				
Waste form classification	**Class A**	—	—	—
Limiting nuclide	I-129	—	—	—
Maximum waste loading, mass%	0.00445	—	—	—
Minimum mass GWF, kg	1271	—	—	—
Number of drums	3.67	—	—	—

[a] Masses of TiO_2 beads and anion resin not included as waste for purpose of compliance calculations.
[b] Mass of waste stream precipitates slurried with 50 vol% water.
[c] Maximum loading of waste solids that meets NRC limits for identified classification.
[d] Number of 55-gal drums filled to 90% capacity.

TABLE E.2 Results for Bounding Formulations of Grouted Waste Forms for 50-Cycle Cleanup Schedule: Aqueous Waste Streams with and without Pu, Cs, and Sr

Waste Stream	Spent Wash	Spent Eluate	Rotovap Concentrate	LMC	UREX Raffinate
Recovered Uranium, kg	2.2	47.4	8E-12	4.3E-3	1.4E-3
Process	RLWE-021	RLWE-021	RLWE-021	RLWE-021	RLWE-021
Waste stream identifiers	509	527	522	529	625
Waste Stream Composition					
Fission products, g	41.2	99.1	6E-6	1.30	54.0
Chemical waste, kg	1.65	3.16	2E-5	2.3E-2	5.37
Total waste solids, kg	1.69	3.26	2E-5	2.5E-2	5.43
Water, kg	909	1846	7E-2	13.2	1396
Grouted Waste Form					
Waste form classification	**Class C**	**Class C**	**Class A**	**Class A**	**Class C**
Limiting nuclide	Pu-239	Pu-239	none	Sr-90	Pu-239
Maximum waste loading, mass%	0.549	0.386	100	0.0139	1.23
Minimum mass GWF, kg	309	844	2E-5	177	441
Number of drums	0.89	2.44	0.00	0.51	1.27
If 100% Pu removed from waste stream					
Waste form classification	**Class B**	**Class B**	—	—	**Class B**
Limiting nuclide	Cs-137	Cs-137	—	—	Cs-137
Maximum waste loading, mass%	0.0985	0.137	—	—	0.319
Minimum mass GWF, kg	1720	2377	—	—	1702
Number of drums	4.97	6.86	—	—	4.91
If 100% Pu and 100% Cs removed from waste stream					
Waste form classification	**Class B**	**Class B**	—	—	**Class A**
Limiting nuclide	Sr-90	Sr-90	—	—	None
Maximum waste loading, mass%	0.58	0.713	—	—	100
Minimum mass GWF, kg	292	457	—	—	5.43
Number of drums	0.84	1.32	—	—	0.02
If 100% Pu and 100% Sr removed from waste stream					
Waste form classification	**Class B**	**Class B**	—	—	—
Limiting nuclide	Cs-137	Cs-137	—	—	—
Maximum waste loading, mass%	0.118	0.169	—		—
Minimum mass GWF, kg	1436	1927	—		—
Number of drums	4.15	5.56	—		—
If 100% Pu and 100% Cs and 100% Sr removed from waste stream					
Waste form classification	**Class A**	**Class A**	—	—	—
Limiting nuclide	Tc-99	None	—	—	—
Maximum waste loading, mass%	11.4	100	—	—	—
Minimum mass GWF, kg	14.86	3.26	—	—	—
Number of drums	0.04	0.01	—	—	—

TABLE E.3 Results for Bounding Formulations of Grouted Waste Forms for 50-Cycle Cleanup Schedule: Combined Waste Streams with and without Pu, Cs, and Sr

Waste Stream	Combined Columns[a]	Combined Aqueous[b]	Combined All-Waste Streams[c]
Uranium, kg	11.0	49.5	60.6
Waste Stream Composition			
Fission products, g	57.5	196	264
Chemical waste, kg	0.489	10.2	19.0
Total waste solids, kg	0.547	10.4	19.3
Water, kg	1677	4164	6474
Grouted Waste Form			
Waste form classification	**Class C**	**Class C**	**Class C**
Limiting nuclide	Pu-239	Pu-239	Pu-239
Maximum waste loading, mass%	2.72	0.652	0.839
Minimum mass GWF, kg	709	1596	2297
Number of drums	2.05	4.91	6.63
If 100% Pu removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	4.61	0.179	0.281
Minimum mass GWF, kg	418	5812	6858
Number of drums	1.21	16.78	19.80
If 100% Pu and 100% Cs removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Sr-90	Sr-90	Sr-90
Maximum waste loading, mass%	12.6	1.39	1.25
Minimum mass GWF, kg	153	748	1542
Number of drums	0.44	2.16	4.45
If 100% Pu and 100% Sr removed from waste stream			
Waste form classification	**Class B**	**Class B**	**Class B**
Limiting nuclide	Cs-137	Cs-137	Cs-137
Maximum waste loading, mass%	7.25	0.206	0.362
Minimum mass GWF, kg	266	5050	5324
Number of drums	0.77	14.58	15.37
If 100% Pu and 100% Cs and 100% Sr removed from waste stream			
Waste form classification	**Class A**	**Class A**	**Class A**
Limiting nuclide	Tc-99	Tc-99	Tc-99
Maximum waste loading, mass%	62.7	31.6	30.3
Minimum mass GWF, kg	30.7	32.9	63.6
Number of drums	0.09	0.10	0.18

[a] Ti-column sorbent + anion resin + glassware.
[b] Spent wash + spent eluate + rotovap concentrate + LMC + UREX raffinate.
[c] Combined columns + combined aqueous + Ba/$SrSO_4$.

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APPENDIX F:

OUTLINE OF RECOMMENDED LABORATORY TESTING PLAN FOR GROUT DEVELOPMENT

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APPENDIX F:

OUTLINE OF RECOMMENDED LABORATORY TESTING PLAN FOR GROUT DEVELOPMENT

Objective: Determine maximum practicable waste loadings of waste streams in grout that:

- Can be processed remotely
- Adequately accommodate/encapsulate waste solids with <10% void space
- Meet free liquid limit of 1 volume %
- Have adequate physical robustness (as defined by compressive strength)
- Have acceptable retention of radionuclides (as defined by leachability index)
- Meet appropriate Class C, B, or A radioactivity limit

<u>Prepare Grouted Materials</u>
Surrogate waste solutions
Actual sorbent media (titania and anion resin)
Commercially available portland cement, blast furnace slag, fly ash

<u>Measure Key Properties of Grouted Waste Forms</u>
Free liquids (during and after curing)
Flow consistency (ASTM C6103): slump test
Gel time (duration of slurry flow-ability): tip test
Setting (curing) time profile (ASTM C191): Vicat test
Heat of hydration (ASTM C1679): calorimetry measurement
Fresh density (ASTM D1475) and cured density
Gross and fine structure porosity: scanning electron microscopy (SEM) examinations

<u>Measure Grout Performance</u>
Integrity of interfaces with encapsulate glass fragments: SEM examinations
Leachability of contaminants (ASTM C1308): distinguish between constituents in pore space or durable phases
Characteristic toxic constituents Ag, Ba, Cd, Cr, Pb, and Se: Toxicity Characteristic Leaching Procedure
Compressive strength (ASTM C39)

<u>Production Consistency</u>
Acoustic monitoring calibrated by lab-scale measurements:
  free water content
  void content
  fresh and cured grout densities

<u>Full-Scale Production</u>
Poured vs. in-drum mixing
Acoustic monitoring of 55-gallon drums
Core sampling:
  Density, void content, encapsulation, leachability, compressive strength

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