Verification of the Accountability Method as a Means to Classify Radioactive Wastes Processed Using THOR Fluidized Bed Steam Reforming at the Studsvik Processing Facility in Erwin, Tennessee, USA – 13087

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ABSTRACT

Studsviks' Processing Facility Erwin (SPFE) has been treating Low-Level Radioactive Waste using its patented THOR process for over 13 years. Studsvik has been mixing and processing wastes of the same waste classification but different chemical and isotopic characteristics for the full extent of this period as a general matter of operations. Studsvik utilizes the accountability method to track the movement of radionuclides from acceptance of waste, through processing, and finally in the classification of waste for disposal.

Recently the NRC has proposed to revise the 1995 Branch Technical Position on Concentration Averaging and Encapsulation (1995 BTP on CA) with additional clarification (draft BTP on CA). The draft BTP on CA has paved the way for large scale blending of higher activity and lower activity waste to produce a single waste for the purpose of classification. With the onset of blending in the waste treatment industry, there is concern from the public and state regulators as to the robustness of the accountability method and the ability of processors to prevent the inclusion of hot spots in waste.

To address these concerns and verify the accountability method as applied by the SPFE, as well as the SPFE's ability to control waste package classification, testing of actual waste packages was performed. Testing consisted of a comprehensive dose rate survey of a container of processed waste. Separately, the waste package was modeled chemically and radiologically. Comparing the observed and theoretical data demonstrated that actual dose rates were lower than, but consistent with, modeled dose rates. Moreover, the distribution of radioactivity confirms that the SPFE can produce a radiologically homogeneous waste form.

The results of the study demonstrate: 1) the accountability method as applied by the SPFE is valid and produces expected results; 2) the SPFE can produce a radiologically homogeneous waste; and 3) the SPFE can effectively control the waste package classification.

INTRODUCTION

Nuclear power plants (NPPs) have been generating and shipping Low Level Radioactive Waste (LLRW) for processing and/or disposal for over 30 years. For the last 13 years, Studsvik has been receiving and processing low level radioactive wastes (e.g. – spent resins, filters, sludges, DAW, liquids, etc.) for disposal off-site. Studsvik's patented THOR process destroys organics, chemically reforms, and homogenizes the wastes into an inert, granular waste form. Several processes in the system ensure a homogeneous mixture of the radioactive wastes. First, pumpable wastes are sluiced into a mixing and dewatering tanks which homogenizes the influent waste streams. This step is critical, as a homogeneous input to the THOR system results in simplified processing and reduced stress on components. Next, the physically-mixed waste is pumped to the processing vessel, which is a Fluidized Bed Steam Reformer called the Pyractor. A Fluidized Bed is a vessel partially filled with small, sand-like particles which are suspended and mixed via the injection of so-called 'fluidizing gases'. The mixing nature of the Pyractor further homogenizes the influent radioactive wastes. Inside the Pyractor, water is vaporized, organics are destroyed, and radionuclides are trapped by inclusion into minerals. The small mineral particulate is then carried up and out of the Pyractor with the flow of process gas through the vessel. The particulate minerals are filtered from the gas flow, cooled by mixing with N_2 gas, and transferred to a disposal container. To facilitate complete filling and to further enhance mixing, the disposal container is also agitated. The resulting waste product is a solid, dry, homogeneous, and is considerably more chemically stable than the original wastes. An illustration of the THOR process with spent ion exchange resins as the radioactive waste is shown in Figure 1.

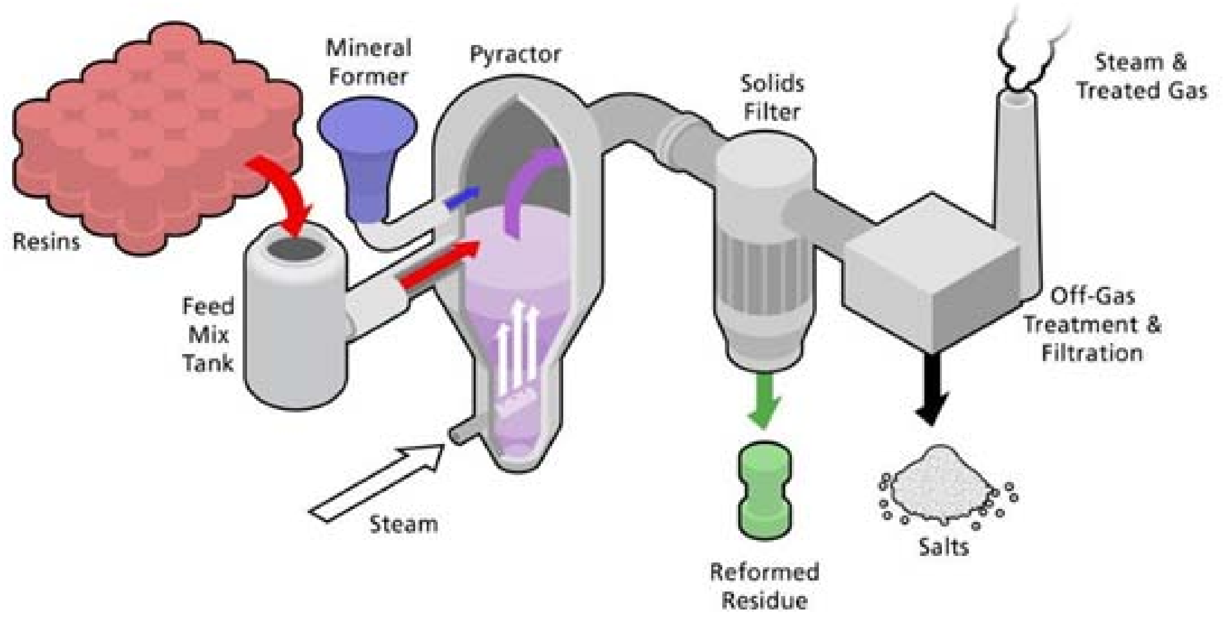


Figure 1 - THOR Technology for Processing Spent Ion Exchange Resins

Tracking and managing radionuclides in the THOR process and more broadly at the SPFE is accomplished using the accountability method as dictated by 10 CFR Part 20 [1], NUREG/BR-0204 [2], and 10 CFR 61.55 [3] (and is the industry standard). These documents implicitly deny the need for processors to take radiological measures of wastes for the purposes of classification. Rather, when generating a manifest, the regulations only explicitly require that the processor to:

"provide the waste description applicable to the mixture and the volume of the waste attributed to each generator" [20]

Classification of the waste prior to transport and disposal is regulated under 10 CFR 61.55 with guidance from the 1995 Branch Technical Position on Concentration Averaging and Encapsulation (1995 BTP on CA) [4]. 10 CFR 61.55 and the 1995 BTP on CA classify waste based on the volume and mass concentrations of radionuclides. The radioactive waste generator is the source of knowledge on the isotopic composition and quantities in a waste. The generator has the deepest and broadest understanding of the origin and evolution of the radioactive waste. Testing by other entities (e.g. – processors, disposal sites) can at best confirm the results of the generator. As the non-generator lacks the quantity and quality of information on the radioactive waste that the generator contains, any testing would necessarily be based on a weaker analytical foundation. As such, 10 CFR 61.55 and the 1995 BTP on CA depend on the waste generator to provide an accurate accounting of the isotopic inventory and the 'downstream entities' (e.g. – transporters, processors, disposal sites) to properly apply the accountability method to generate accurate waste classifications.

"The concentration of a radionuclide may be determined by indirect methods such as use of scaling factors which relate the inferred concentration of one radionuclide to another that is measured, or radionuclide material accountability, if there is reasonable assurance that the indirect methods can be correlated with actual measurements" [3]

Downstream entities cannot be expected to re-characterize unaltered radioactive waste any more than generators can be expected to operate processing facilities and disposal sites.

Recently, the NRC has proposed a revision to the 1995 BTP on CA (draft BTP on CA) [5] that removes the 'Factor of 10 Rule' which previously set limitations on the radiological range of wastes that could be mixed with the separate activities averaged over the aggregate. This modification has opened the door for large scale blending of radioactive wastes and the potential for disposal of large volumes of radioactive wastes near 10 CFR 61.55 waste class limits. The NRC has replaced the 'Factor of 10 Rule' with limitations on the size and activity of 'hot spots' in a disposal container and preferential treatment for wastes with certain physical properties. Moreover, the NRC has provided bounding conditions above which verification of radioactive homogeneity is recommended (Table 1). Despite these restrictions and the long track record of performance for the accountability method, there has recently been some concern on the part of the public and state regulators as to the efficacy of the accountability method when the activity concentration of a waste approaches waste class limits.

Table 1 – Concentrations and Volumes of Waste Above Which Demonstrating Waste Homogeneity is Required (reproduced from 'Draft Branch Technical Position on Concentration Averaging and Encapsulation, Revision 1, May 2012')

Sum of Fractions in Most Concentrated Influent Waste Stream	Annual Volume of Waste [m^3/yr (ft^3/yr)]	
	If Blended Product is Class A	If Blended Product is Class B or C
Less than 10 times the Class Limit	No Homogeneity Demonstration Recommended	No Homogeneity Demonstration Recommended
Between 10 and 100 times Class Limit	74 (2,600)	0.7 (25)
Greater than 100 times Class Limit	0.6 (21)	0.6 (21)

The draft BTP on CA provides a decision flowchart to aid in waste classification. These flowcharts are reproduced in Figures 2 and 3, with the path that applies to the SPFE and SEMPRASAFE highlighted in red.

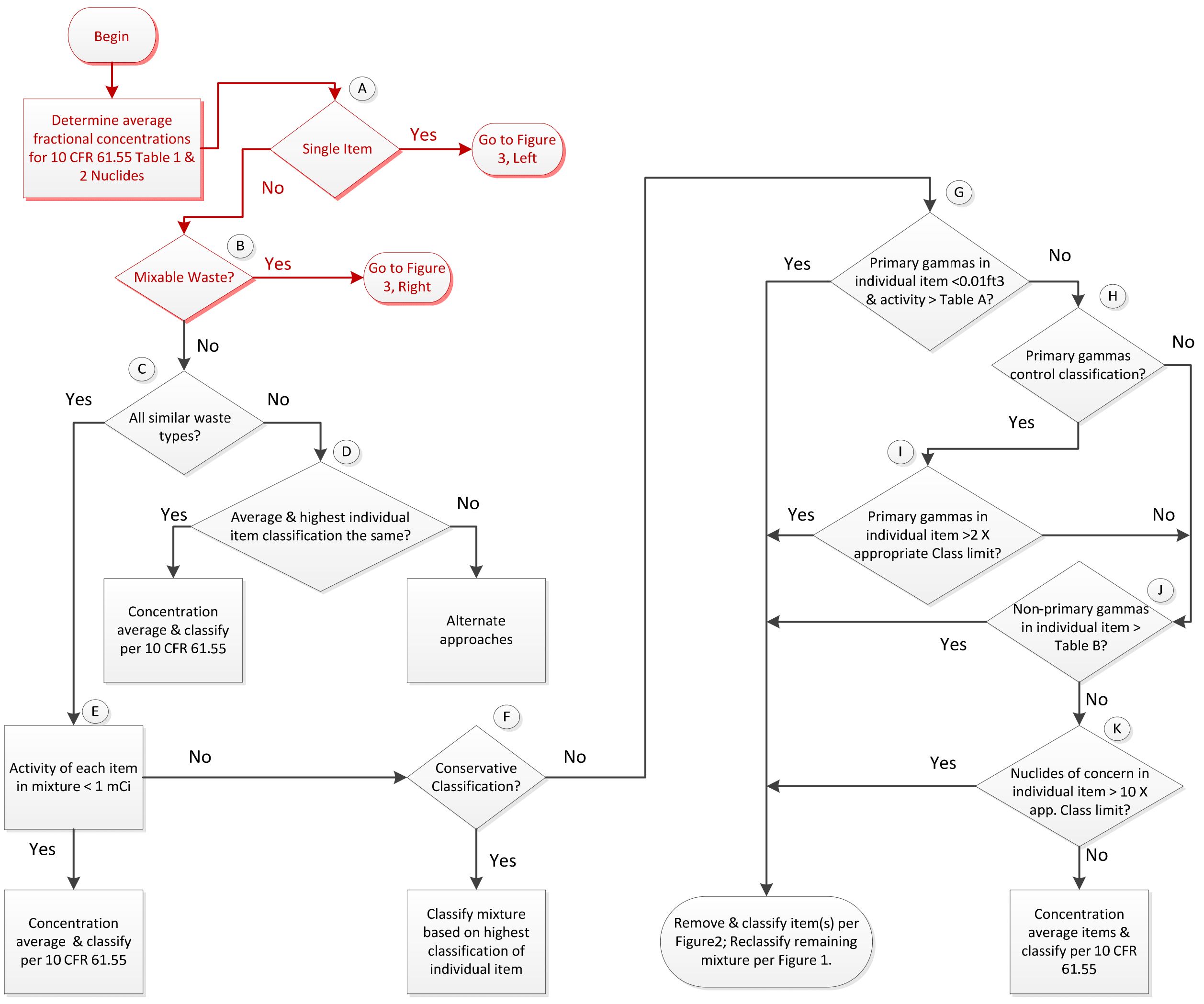


Figure 2 - Reproduced Decision Matrix from the draft BTP on CA (continued in Figure 3)

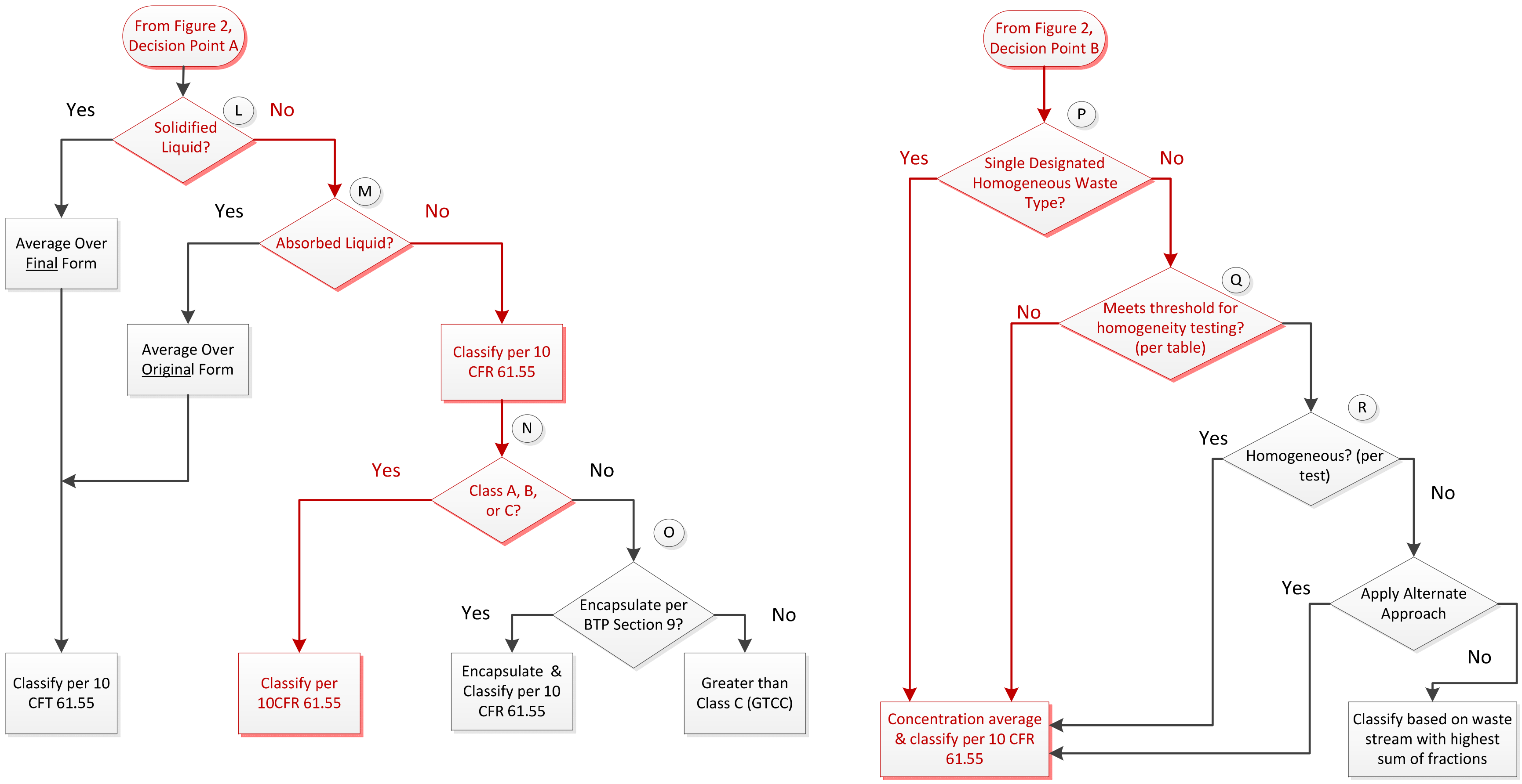


Figure 3 - Reproduced Decision Matrix from the draft BTP on CA (continued from Figure 2)

From Figures 2 and 3 it is clear that the SPFE is not required to perform additional verification of waste classification per the branch draft BTP on CA. Note that at decision point 'A', Studsvik may treat either a single item (e.g. – a shipment of spent resin from a single NPP under a single manifest) or multiple items (e.g. – multiple spent resin shipments under different manifests). The accountability method provides framework for the radionuclides of different waste streams (e.g. - resins, carbon beds, sludges) to be applied to the produced waste. The waste produced by the THOR process at the SPFE is a single homogeneous waste type. Studsvik does not intend to process and concentration average wastes with SOFs greater than 10 times the applicable waste class limits, therefore Studsvik is not required to demonstrate homogeneity in its product waste. Despite the fact that Studsvik has no regulatory obligation for further testing, Studsvik decided, as a service to the public and regulators, to verify that the process and applicable regulations effectively control waste classification.

Verification involved comparing dose estimates of processed waste with actual surveys. The dose estimates were generated from *in silico* chemical and radiological models of the processed waste. *In silico* models leveraged proven software coupled with extensive testing to generate theoretical dose rates that would only be valid if the accountability method was an appropriate tool and the SPFE produced a radiologically and physically homogeneous waste. A survey of the disposal container was performed with 408 separate dose measurements taken at 1m, 30 cm, and on contact with the container. Comparison of the real-world measurement with theoretical modeling showed that the SPFE's THOR process can produce a radioactively homogeneous waste and that the accountability method is appropriate when coupled with the THOR process. All survey dose measurements were below modeled dose rates while the overall dose survey map showed that the radioactivity was evenly distributed in the waste package.

METHODS

A container of processed resin was chosen to perform the verification study. The influent spent resins are described Table 2. All influent waste was above the Class A limits. As such, this waste could not have been processed to a Class A waste without increasing the overall radioactive waste volume. This type of "extreme method to reduce waste classification" is specifically forbidden in the draft BTP on CA, and is contrary to Studsvik's stance on proper management of radioactive waste. Despite all waste being above Class A limits, the influent stream had a wide variety of isotopic, chemical, and physical traits. In particular, the pronounced isotopic variation made this mixture of resins appropriate for verifying the efficacy of the regulations and the accountability processes at the SPFE. Examining the manifests also showed the physical variation between the wastes; the radioactive wastes included organic resins (cationic, anionic, powdered, and bead) and inorganic media (zeolites and granular activated carbon). It is Studsvik's experience that without specially designed equipment, operating proficiency, and procedural control these radioactive wastes will segregate when pumped into a disposal container or processing vessel. As a proceduralized aspect of processing, the SPFE makes great effort to ensure that even so-called 'homogeneous' waste types are mixed to homogeneity in the waste storage and feed tanks at the facility. The downstream processing equipment acts to maintain and increase the homogeneity of the waste.

The radioactive wastes were processed under the following conditions:

- The waste was processed from one tank at the SPFE.
- The waste and additives were fed into the process at a constant rate.

- The waste consisted of bead and powder ion exchange resins of cationic and anionic composition, granular activated carbon, and zeolites from commercial NPPs.
- The waste came from multiple sources.
- The waste had a wide range of activities and compositions.

Incoming Waste Composition

The radioactive wastes that were processed contained typical physical and radiological characteristics that make waste segregation possible and worrisome. Namely:

- the wastes were of different particle sizes and densities that would lead to segregation if disposed of without controlled mixing or treatment such as is done at the SPFE; and
- the waste contained a wide variety of activity concentrations and isotopic compositions that make the potential for ‘hot spots’ very real if the radionuclides are not homogeneously distributed.

A summary of the influent wastes is provided in Table 2.

Table 2 – Physical and Isotopic Composition of Influent Radioactive Wastes for Verification Study

Radioactive Materials	**Volume m3 (ft3)**	**Bulk Density g/cc (lbs/ft3)**	**Class A SOF**	**Primary Sources of Activity**					**Physical Composition**
Liner 1	2.24 (79)	1.06 (66)	24.4	Ni-63: 94%					mixed bead
Liner 2	0.89 (31)	1.11 (69)	7.07	Co-60: 42%	Fe-55: 12%	Co-58: 11%	Cs-137: 11%	Cs-134: 11%	mixed bead
Liner 3	0.83 (29)	1.04 (65)	4.31	Ni-63: 72%	Co-60: 19%				mixed bead/powder
Liner 4	1.31 (46)	1.08 (67)	3.50	Ni-63: 73%	Fe-55: 21%				mixed bead
Liner 5	1.03 (36)	1.13 (70)	3.36	Ni-63: 42%	Cs-137: 29%	Co-60: 12%	Cs-134: 8%		mixed bead, carbon, zeolite
Liner 6	1.31 (46)	1.17 (73)	3.04	Ni-63: 42%	Cs-137: 29%	Co-60: 12%	Cs-134: 8%		mixed bead, carbon, zeolite
Liner 7	2.09 (74)	1.03 (65)	2.53	Co-60: 54%	Ni-63: 29%	Cs-137: 8%			powder anion
Liner 8	0.75 (26)	1.17 (73)	2.29	Ni-63: 59%	Co-60: 22%	Fe-55: 9%	Cs-137: 7%		mixed bead/powder
Liner 9	1.81 (64)	1.04 (65)	1.81	Co-60: 51%	Ni-63: 26%	Cs-137: 14%			powder anion
Liner 10	2.09 (74)	1.04 (65)	1.48	Co-60: 53%	Ni-63: 27%	Cs-137: 10%			powder anion
Total	14.4 (507)	1.08 (67)	6.26						

Potential for Segregation of Wastes

The NRC has recognized the danger of blending physically dissimilar waste streams in the draft BTP on CA with the statement:

"Blending of physically dissimilar mixable waste streams (e.g., mixing ion exchange resins with soils) should be considered on a case-by-case basis. Proposals to blend physically dissimilar waste streams should address the physical and chemical compatibility of the waste streams"

The concern of the NRC appears to not be in regards to segregation of wastes within a container, but rather whether or not wastes would adequately mix to homogeneity in an intruder scenario. A natural consequence of the THOR process at the SPFE is dissimilar waste streams are homogenized during processing into a continuous powdered waste form which can be subsequently solidified if necessary. The NRC suggests that a waste type such as produced by the THOR process is considered homogeneous in the draft BTP on CA:

"Spent ion-exchange resins filter media, evaporator bottom concentrates, ash, and contaminated soil are considered a homogeneous waste type because they are flowable, and the radionuclides in these waste streams are expected to be uniformly distributed when exhumed under reasonably foreseeable intruder scenarios"

Moreover, the NRC deemed actions to remediate hot spots unnecessary when the waste is homogeneous:

"The NRC staff has determined that it is unnecessary and inconsistent with ALARA principles to specify any additional actions for licensees to take if hot spots are detected in waste that is designated as a homogeneous waste type"

Furthermore, the NRC recommends demonstrating homogeneity using in-direct methods when possible:

"The guidance…emphasizes [SIC] the use of process knowledge and reasoned explanations instead of direct measurements to demonstrate homogeneity when possible, in an effort to minimize worker dose"

Range of Activity and Potential for Hot Spots

The concern with waste segregation noted by the NRC is only present if the segregated waste incurs higher risk levels to an inadvertent intruder. Segregated waste with different isotopic characteristics but resulting in the same, or lower, total dose to the public or an inadvertent intruder is of no consequence. As such, the NRC, in its draft BTP on CA, has linked the risk to an inadvertent intruder to the 10 CFR 61.55 Sum of Fractions (SOF) of a segregated waste and the volume of that segregated waste (see Table 1). Segregated wastes with a higher SOF -and thus an increased risk- within a container are termed 'hot spots'. For the THOR process at the SPFE, the maximum hot spot obtainable can be estimated by assuming that influent radioactive wastes are packaged separately from one another, into discrete vertical columns which are placed into the disposal container. This is not physically possibly at the SPFE, but it provides an extremely conservative bounding case.

The highest risk waste for the container examined had a Class A SOF (SOF:A) of ~24.43. The lowest risk waste had a SOF:A of 1.48. The risk gradient (highest SOF present/lowest SOF present) within the container was ~16.5. This degree of risk variability is similar to blending traditionally Class B/C waste with traditionally Class A waste down to a waste classification of A, with the aggregate requiring homogeneity verification testing.

For example, consider a container of 3 m^3 (106 ft^3) (e.g. – PL8-120) of blended radioactive waste that is Classified as Class A under the 10 CFR 61.55 and the draft BTP on CA. The waste has not been tested for homogeneity so it can be concluded that the highest activity portion of the waste is not greater than 10 times the Class A SOF. With a risk gradient of 16.5 the lower activity waste would have a SOF of 0.606. Given these parameters the container could have only ~0.125 m^3 (4.4 ft^3) of the SOF:A 10 waste, with the remaining ~2.875 m^3 (101.6 ft^3) consisting of the SOF:A 0.606 waste; otherwise, the waste would be Classified as above Class A. The ~0.125 m^3 (4.4 ft^3) of SOF:A 10 waste is the 'hot spot' threat in the container. Thus, the risk gradient of the tested waste could hypothetically be observed in a blended waste that would require homogeneity testing.

Though the study did not involve the blending of wastes categorized in different waste classes, the risk gradient was sufficiently high to mimic the limiting case of the draft BTP on CA; namely, inclusion of waste up to 10 times the class limits.

At this point, it is important to consider the actual processing system and internal regulations of the SPFE. As previously noted, the SPFE makes great effort, using specialized equipment, to mix influent wastes to a homogeneous composition. This homogeneity is increased by the mixing in the Pyractor and downstream filter vessels. These systems and processes prevent so-called hot spots from being generated. Moreover, waste is deposited in containers in a horizontal -not vertical- layers. Therefore, if all mixing equipment, procedural control, and operation know-how were to simultaneously be removed the worst case scenario for 'stratified waste' would be horizontal layers. The NRC has addressed horizontal stratification in the draft BTP on CA by noting that the intruder scenario would result in mixing between horizontal layers:

"Waste stratification into even layers is not expected to affect an intruder. For stratification to affect dose, an intruder would need to exhume only the layers of waste in a disposal container that have the greatest radionuclide concentration."

Part of the verification study involved extremely detailed dose measurements of the disposal container. Any stratification of the waste (as a result of equipment or procedural ineffectiveness) would have shown up in the dose surveys. No stratification was found.

Lastly, it is important to note that the SPFE self-regulates waste SOFs not to exceed 90% of the respective limits. In the example above, this reduces the volume of higher activity wastes to ~0.093 m^3 (3.3 ft^3). Further, it must be remembered that even in the worst case scenario (i.e. – complete mixing equipment and procedural failure at the SPFE) the waste will be deposited in horizontal layers, so the overall activity would be homogenized during an intruder scenario. It could be further assumed (though it was deemed extremely unlikely by the NRC) that all of the activity is at the very top of the disposal container and the intruder only drills through the higher activity waste. In this case the waste would be ~5 cm (~2 in) deep and given a bore of 20 cm (8 in) in diameter (as is assumed in the draft BTP on CA) the intruder would exhume ~0.002 m^3 (~0.06 ft^3) of SOF:A 10 waste. Assuming the inherent SOF:A of the surrounding soil does not exceed ~0.00043 [6] , the intruder would only need to drill ~57 cm (~22.6 in) into the ground to bring the overall risk of the exhumed wastes to a SOF:A of 1 equivalent.

By examining hypothetical scenarios such as provided above it becomes clear that the proposed controls of the NRC are more than adequate to protect the public and inadvertent intruders if the activity manifested by radioactive waste generators is accurate and the accountability method is properly applied by ‘downstream entities’.

Dose Rate Modeling

The modeling software MicroShield® was utilized to convert the radionuclides present in the waste according to the received manifests and movement of radionuclides in the process (i.e. – the accountability method) into dose rates at various locations on and distances from the waste container. A key aspect of the MicroShield® analyses was an assumption of volume-distributed radionuclide homogeneity. The following inputs were provided to MicroShield® program:

- chemical composition of the waste (determined from testing and HSC Chemistry® analysis, see Table 2)
- bulk density of the waste (determined using crane-attached scale, see Table 2)
- radionuclide inventory of the waste (determined from generator-supplied manifests and the accountability method, see Table 3)
- density of the waste container (from vendor, verified through direct measurement and analysis)
- geometry of the waste container (from vendor-provided data)
- density of the ambient air (from NOAA on day and time of analysis)
- location of the dose meter (matched to actual dose survey distances)

Composition of the Waste

Understanding the chemical composition of the waste is an important factor in optimizing the THOR process. The chemical composition is determined by running an *in silico* model of the inputs (e.g. - resin, steam, coal) and processing parameters such as temperature and pressure. Resins and other incoming radioactive wastes are analyzed at the SPFE using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine the inorganic constituents. The incoming wastes are also analyzed for water content and bulk density. This information is leveraged to tailor the additives and processing parameters used to treat the wastes safely and efficiently.

The data from the ICP-MS analysis, the actual utilities and coal usage, and processing parameters for the waste package were input into the HSC chemistry model. Samples of the waste product were taken from the container and analyzed to validate the *in silico* model results. A summary of the chemical composition and physical characteristics of the waste is provided in Table 3.

Table 3 - Chemical and Physical Characteristics of the Waste

Compound	Percent Mass
Polycrystalline Graphite	31%
Aluminum Borates	25%
Alumina	13%
Bound Water	13%
Hercynite	10%
Lithium Aluminates	2%
Lithium Borates	2%
Sodium Borates	2%
Calcium Aluminates	1%
Spinel	0.5%
Potassium Borates	0.3%
Bunsenite	0.1%
Galaxite	0.1%
Various Fe-, Al-Spinels	0.5%

Mass kg (lbs)	3,620 (7,980)
Volume m3 (ft3)	3 (106)
Bulk Density g/cc (lbs/ft3)	1.21 (75)

Radionuclide Inventory of the Waste

The radionuclides present in the waste were determined based upon the manifested activity received from the generators and the accountability method. Processing occurred from a single waste storage tank containing wastes from ten separately manifested waste streams. As is the procedure for the SPFE, the wastes -and consequently the radionuclides- were completely mixed prior to processing. A summary of the radioactive composition of the waste produced is provided in Table 4 below.

Table 4 - Radionuclide Composition and Classification of the Waste

Nuclides	GBq (Ci)	% Activity
Ni-63	8154 (220)	64%
Co-60	2216 (60)	17%
Cs-137	860 (23)	7%
Fe-55	568 (15)	4%
Co-58	450 (12)	4%
Cs-134	297 (8)	2%
Mn-54	122 (3)	1%
Others*	135 (4)	0%

	Table 1	Table 2
SOF A	0.50	29.99
SOF B	---	1.22
SOF C	0.05	0.11

Waste Container

The density and geometry of the waste container were determined based on drawings and information provided by the vendor. The container was modeled as a cylinder although the actual container has a beveled top. This was done to simplify the calculation load placed on MicroShield® and should not affect the dose estimate for the straight wall sections of the container.

Air Density

Air density was calculated using the local atmospheric conditions at the time of testing and atmospheric gas composition as reported by the National Oceanic and Atmospheric Administration.

Location of Dose Meter

The location of the dose meter was set to contact, 30 cm, and 1 m from the waste container as these are standard industry measurement locations. The vertical location of the dose meter was varied to check for differences in fluence.

Dose Measurement

Dose measurements were performed using a MGP Instruments Telepole at 408 locations (34 points along 4 vertical, equally-spaced axes, at contact, 30 cm, and 1 m from the waste container). Distance from the container was marked ahead of time, and the dose meter was secured during all measurements. The same dose meter was used for all measurements. Figure 4 is a map of the measurement points.

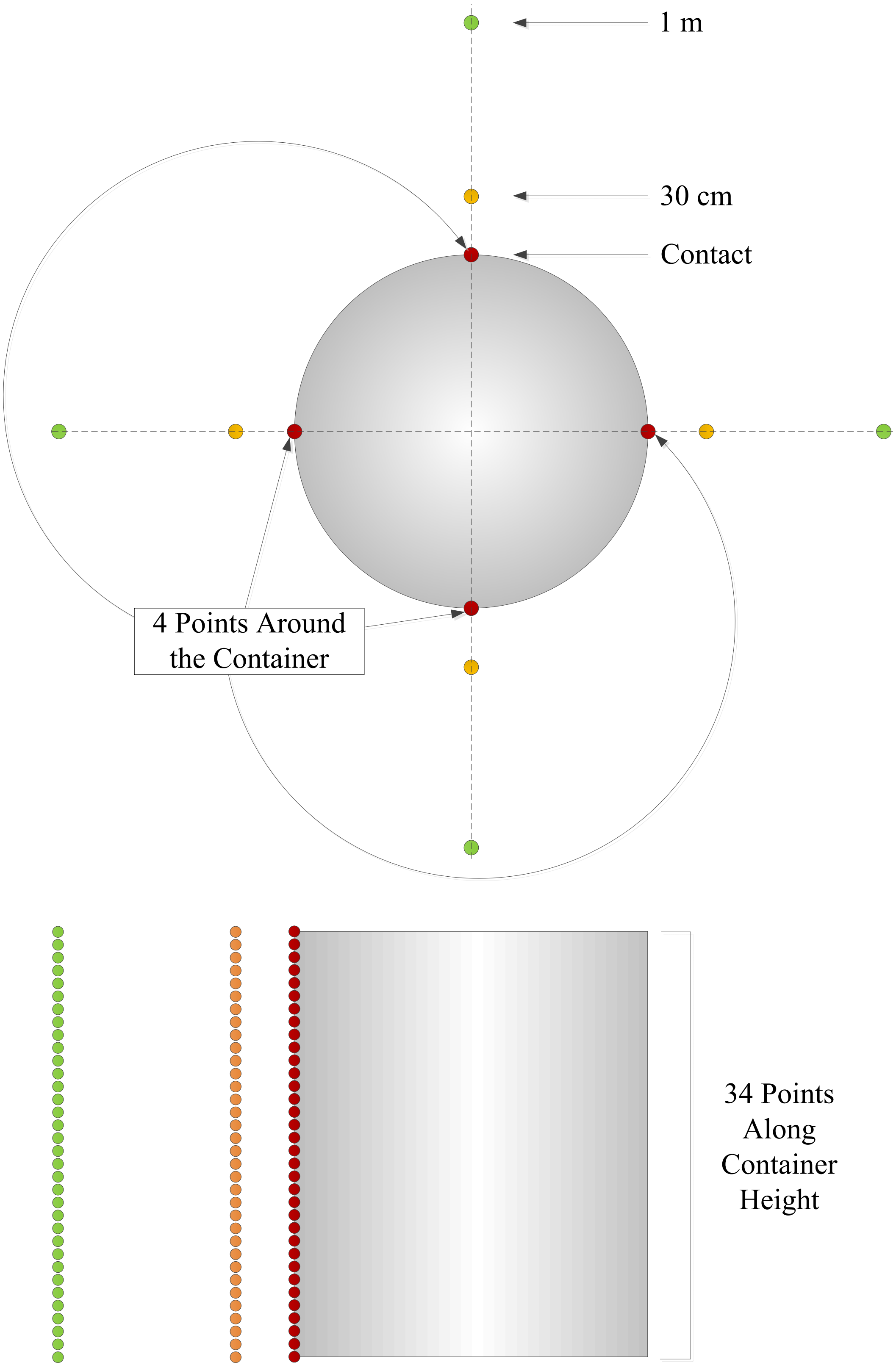


Figure 4 - Dose Measurement Locations

RESULTS

A comparison of the measured and modeled dose rates is shown in Figure 5.

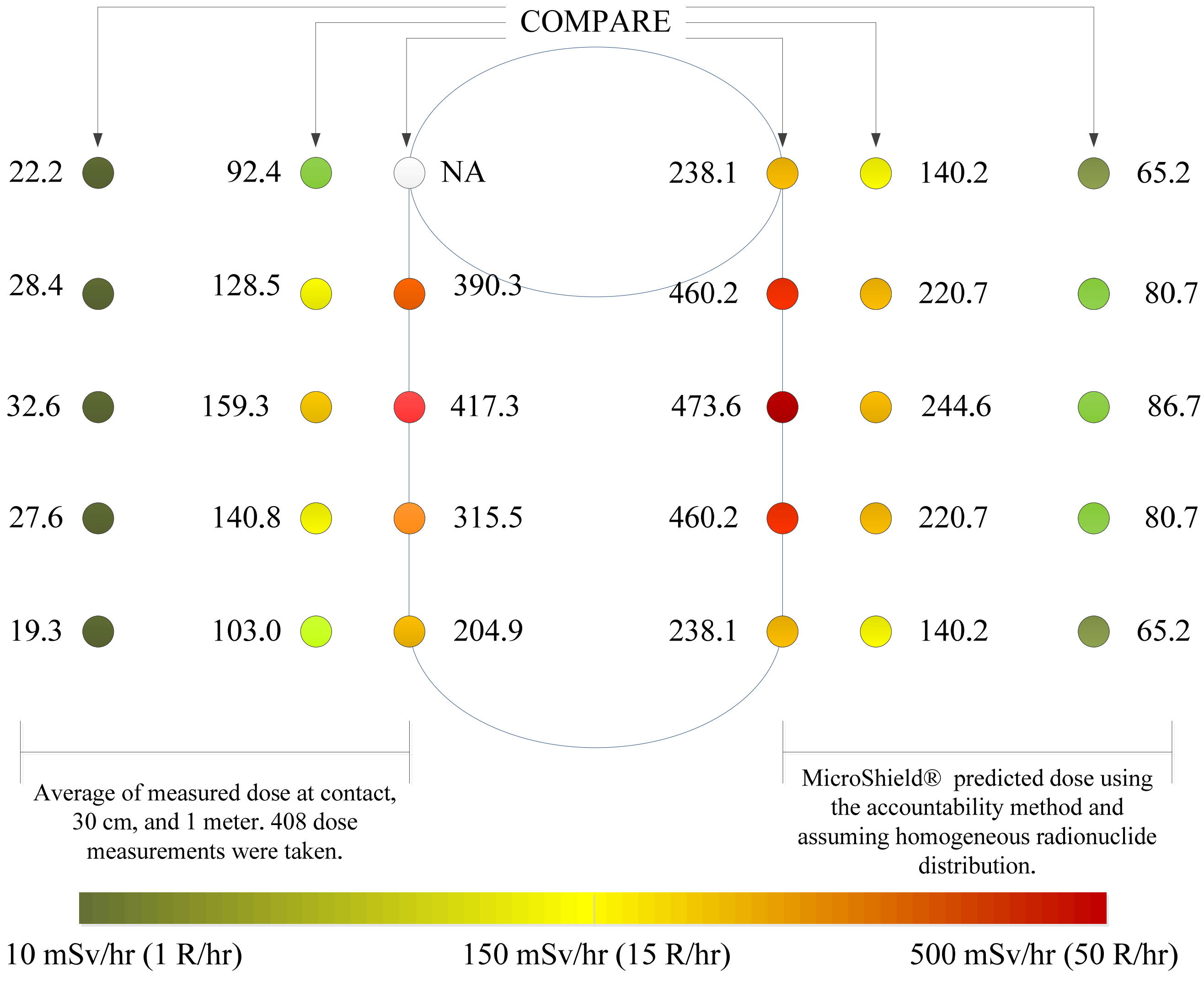
Note that the measured contact dose rates at the top of the container are not available due to the geometry of the container and shielding present at the SPFE. Both the contact and 30 cm dose measurements contained no shielding between the container and the dose meter; however, some backscatter from nearby equipment and structures may have increased these dose rates above a completely unshielded condition.

Due to local geometries, at 1 meter the dose meter was exposed to only ~54% of the unshielded surface of the container. If this partial fluence is taken into account, the measured dose rate relative to the predicted dose rate at 1 meter becomes consistent with those at 30 cm. It should also be noted that there existed a background radiation from other radioactive sources within the SPFE at the time of measurement. No correction was made for background radiation; this lack of correction was considered to produce conservatively high measured dose rates.

The data indicates that the measured dose rates do not exceed the modeled dose rates. The pattern of the dose rates measured is consistent with that predicted by MicroShield® for a homogeneous, volume-distributed radioactive waste. The decline in dose rate vertically away from the center of the container is attributed to the location of the measurement relative to the geometry of the source material. In other words, the average distance between the distributed radioactive elements and the measurement device increases as the devices moves vertically away from the centerline of the container.

Table 5 below summarizes the percent difference between the measured and modeled dose rates. The negative values indicate that the measured dose rates were always less than the values predicted by the modeling software; this verifies that the accountability method results in a conservative classification of the waste. It is important to recall that the MicroShield® model assumes homogeneous distribution of radionuclides throughout the waste; the consistent percent difference between the measured and modeled dose rates at each distance indicates that the actual waste had a homogeneous distribution of radionuclides. In other words, the fact that the dose rate pattern observed closely matches the predicted pattern provides confirmation that radionuclide distribution was homogeneously volume-distributed in the actual waste package.

The difference between modeled and observed dose rates on contact was substantially less than at 30 cm and 1 meter. This difference is hypothesized to be due to Bremsstrahlung radiation from the high Ni-63 content in the waste. Bremsstrahlung radiation is not accounted for in the MicroShield® program. Ni-63 is a beta (electron) emitter. As the released electron travels past another atom it is slowed down by interaction with the electron cloud. This energy is released as a gamma ray. The power of the gamma ray is proportional to the deceleration of the electron. The deceleration of the electron is proportional to coulomb force of the electron cloud. Thus, higher Z number materials (e.g. – lead) will generate more penetrating gamma rays as they contain larger electron clouds. Low density materials (e.g. – Lucite, water) can effectively prevent the formation of penetrating Bremsstrahlung radiation by slowly decelerating electrons. The bulk density of the waste 1.21 g/cc (~75 lb/ft^3) was only slightly higher than that of Lucite 1.18 g/cc (~73 lb/ft^3), so meaningful Bremsstrahlung radiation should not have been expected. However, the waste contains various compounds (see Table 3), many of which are substantially denser than the bulk density (e.g. – Al, Fe, and Ni containing minerals). An emitted electron only needs to interact with a high Z material before encountering a low Z-material in order to produce a penetrating gamma ray. In other words, the electron is ignorant of the bulk density of the waste and is only decelerated by its atomic neighbors. Importantly, the waste does not contain extremely high Z-number materials such as lead (82); the highest Z-number constituent in the waste was copper (29). As a result, the hypothesized gamma rays would have limited penetrating ability; moreover, gamma rays not generated near the point of measurement would need to travel not just through air and the high density polyethylene of the HIC, but also through any waste between it and the dosimeter. In short, it is hypothesized that the high Ni-63 content of the waste, coupled with modest Z-number constituents, resulted in the production of weak gamma rays that were only detected by on contact dose measurements.



Average of measured dose at contact, 30 cm, and 1 meter. 408 dose measurements were taken.

MicroShield® predicted dose using the accountability method and assuming homogeneous radionuclide distribution.

Figure 5 - Comparison of Measured and Modeled Dose Rates

Table 5 - Percent Difference from Predicted Dose Rate, Negative Values Indicate Observed Dose was less than Predicted Values

	Contact	30 cm	1 m
Top	--NA--	-34%	-33%
¾ Up	-15%	-42%	-32%
Middle	-12%	-35%	-31%
¼ Up	-31%	-36%	-33%
Bottom	-14%	-27%	-35%

CONCLUSIONS

The results from the study clearly demonstrate that the accountability method provides a conservative and sufficiently accurate estimate of the actual radioactivity in the processed waste as verified by comparing the actual dose rate measurements to the modeled dose rates. Furthermore, the dose survey verified that the SPFE, and more generally the THOR process, can produce a physically, chemically, and isotopically homogeneous waste form without the inclusion of ‘hot spots’ as defined in the draft BTP on CA. The lower than modeled dose rates seem to confirm the industry belief that NPPs and other generators are conservative when manifesting radionuclide inventories. The accountability method provides a conservative method of determining waste classification when combined with the THOR process as implemented at the SPFE. Studsvik does not intend to use the verification methodology laid out in this document to re-classify wastes or lower waste classification.

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