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Sample Based Unit Liter Dose Estimates

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LIST OF TERMS

Bq/ μ Ci	Becquerel per microcurie
BIO	Basis for Interim Operation
Ci	Curies
DCF	dose conversion factor
DST	double-shell tank
FDH	Fluor Daniel Hanford, Inc.
FSAR	Final Safety Analysis Report
g/L	grams per liter
NS&L	Nuclear Safety and Licensing
TL	tolerance limit
μ Ci/g	microcuries per gram
μ Ci/L	microcuries per liter
%	percent
SST	single-shell tank
Sv/L	sieverts per liter
Sv/ μ Ci	sieverts per microcurie
TCD	Tank Characterization Database
ULD	unit liter dose
WHC	Westinghouse Hanford Company

INTRODUCTION

The Tank Waste Characterization Program has taken many core samples, grab samples, and auger samples from the single-shell and double-shell tanks during the past 10 years. Consequently, the amount of sample data available has increased, both in terms of quantity of sample results and the number of tanks characterized. More and better data is available than when the current radiological and toxicological source terms used in the Basis for Interim Operation (BIO) (FDH 1999) and the Final Safety Analysis Report (FSAR) (FDH 1999) were developed.

The Nuclear Safety and Licensing (NS&L) organization wants to use the new data to upgrade the radiological and toxicological source terms used in the BIO and FSAR. The NS&L organization requested assistance in developing a statistically based process for developing the source terms. This report describes the statistical techniques used and the assumptions made to support the development of a new radiological source term for liquid and solid wastes stored in single-shell and double-shell tanks.

1.0 SUMMARY

Estimates of unit liter doses (ULDs) for waste in the single-shell tanks (SSTs) and double-shell tanks (DSTs) were computed based on recent sampling data from the tanks. The data was obtained from the Tank Characterization Database. There was sufficient data to estimate a ULD for 51 SSTs with solid samples, 20 SSTs with liquid samples, 13 DSTs with solid samples, and 25 DSTs with liquid samples.

If it is assumed that the tanks selected for characterization were selected at random, then the ULDs given in this document are unbiased estimates of the ULDs for all SSTs and DSTs. However, it may not be appropriate to assume that the characterized tanks were chosen at random. Many of the tanks that were selected were chosen because they were known to contain wastes that were of concern to Hanford's unresolved safety questions and safety issues. Consequently, if the data from the characterized tanks are an upper bound for all of the tanks then the ULDs are also an upper bound for all tanks.

The lognormal probability distribution was fit to the ULDs. ULD quantiles corresponding to the 95th and 99th percentiles of the lognormal distribution were computed. The ULDs corresponding to the 95/95 and 95/99 tolerance limits (TLs) were also computed (the interpretation of the TLs are, we are 95 % confident that at least 95 % (99 %) of the population is less than the limit). The ULD quantiles and TLs are compared to the ULDs for the BIO (FDH 1999). In all six cases, the ULD for the BIO is less than the 95/99 TL. In four of the six cases, the ULD for the BIO is approximately equal to the 95/95 TL.

2.0 AVAILABLE SAMPLE DATA

The TCD (Tank Characterization Database) contains the waste characterization data from tank samples obtained since 1989. This database was the source of data used to estimate the ULD for each waste storage tank.

From TCD, all of the data for the following seven isotopes were obtained, ^{137}Cs , gross alpha, total alpha (total alpha energy emitted from ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu), ^{241}Am , $^{239/240}\text{Pu}$, $^{89/90}\text{Sr}$, and ^{90}Sr . There were a total of 13,132 observations. There were 3,180 observations with the qualifiers "U" and "R." The "U" denotes an observation below the detection limit and an "R" denotes that the observation is unusable. All observations with these two qualifiers were deleted. The remaining 9,943 observations consisted of 2,541 on liquid samples and 7,402 on solid samples. The units are $\mu\text{Ci/g}$ or $\mu\text{Ci/L}$. Not every tank had data from each of the seven isotopes.

All observations below detection limits were deleted. Consequently, the quantile estimates in the tables and figures apply to the proportion of the population with analyte concentrations above detection limits.

The ULDs were computed based on the isotopes ^{137}Cs , ^{90}Sr and ^{90}Y and on alpha. The validity of this assumption is outlined in section 2.0 and 3.0 of Jensen et al. (1998) and in Table 3 of WHC-SD-WM-SARR-037 (WHC 1996).

2.1 TANK SPECIFIC RADIOISOTOPE CONCENTRATIONS

For each tank, the arithmetic mean ($\mu\text{Ci/g}$ or $\mu\text{Ci/L}$) of the data for each of the seven isotopes was computed. The data from the different analytical procedures were combined. That is, the data from the water, the acid and the fusion dissolution were combined.

The following methods were used to select the data used in the ULD calculations.

For ^{137}Cs : The mean of the ^{137}Cs data was used.

For alpha: If available, the mean for gross alpha was used. If there was no gross alpha mean, the mean of the total alpha (total alpha energy emitted from ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu) was used. If there were means for both gross alpha and total alpha, the mean of the combined data was used. If there was no mean for gross alpha or total alpha, the mean from ^{241}Am was used. If there was no mean for gross alpha or total alpha or ^{241}Am , the mean from $^{239/240}\text{Pu}$ was used.

For ^{90}Sr : If available, the mean for $^{89/90}\text{Sr}$ was used. If there was no mean for $^{89/90}\text{Sr}$, the mean for ^{90}Sr was used. If there was a mean for both $^{89/90}\text{Sr}$ and ^{90}Sr , the mean of the combined data was used.

To be included in the ULD computations a tank had to have a mean for ^{137}Cs , for alpha, and for ^{90}Sr . There were 51 SSTs with the three means for solid samples and 20 with the three means for liquid samples. For the DSTs, there were 13 tanks with the three means from solid samples and 25 with means from liquid samples. Tables A-1, A-2, A-3, and A-4 in Appendix A list the three means.

There are a total of 149 SSTs and 28 DSTs and the ULDs can only be estimated for a subset of the total number of tanks. The estimates of the ULDs given in this document are unbiased estimates of the ULDs for all SSTs and DSTs if it is assumed that the tanks with a mean for ^{137}Cs , for alpha, and for ^{90}Sr (Tables A-1 through A-4) are a random sample of the tanks. Alternatively, if it is assumed that the tanks with a mean for ^{137}Cs , for alpha, and for ^{90}Sr are an upper bound to the means for all of the other tanks then the ULDs based on the sampled tanks are an upper bound for the ULDs for all tanks.

2.2 TANK SPECIFIC UNIT LITER DOSE

The units of the means in Tables A-1, A-2, A-3, and A-4 are $\mu\text{Ci/g}$ or $\mu\text{Ci/L}$. The units for the ULD are Sv/L (sieverts per liter). The conversions factors used are given in Table 1. The third row of this table are the dose conversion factors (DCF) for ^{137}Cs , alpha and ^{90}Sr . It is assumed that the concentration for ^{90}Y is the same as that for ^{90}Sr .

Table 1. Conversion Factors, $\mu\text{Ci/g}$ or $\mu\text{Ci/L}$ to Sv/L

Units	^{137}Cs	Alpha ²	^{90}Sr	^{90}Y
Bq/ μCi	3.70E+04	3.70E+04	3.70E+04	3.70E+04
g/L ³	1.60E+03	1.60E+03	1.60E+03	1.60E+03
Sv/Bq ¹	8.63E-09	1.20E-04	6.47E-08	2.28E-09

¹The DCF for Sv/Bq are reported on page 10 of the *Attachment to CO-TWRS-154* (Brevick 1999).

²It is assumed that alpha is all from ^{241}Am .

³The conversion g/L from a weight basis to a liquid basis is given on page 7 of Brevick et al. (1996).

For solid samples, the equations used to convert $\mu\text{Ci/g}$ to Sv/L are

$$\text{Sv/L}(^{137}\text{Cs}) = \text{mean}(^{137}\text{Cs}) \times (3.70\text{E}+04) \times (1.60\text{E}+03) \times (8.63\text{E}-09)$$

$$\text{Sv/L}(\text{alpha}) = \text{mean}(\text{alpha}) \times (3.70\text{E}+04) \times (1.60\text{E}+03) \times (1.20\text{E}-04)$$

$$\text{Sv/L}(^{90}\text{Sr} + ^{90}\text{Y}) = \text{mean}(^{90}\text{Sr}) \times (3.70\text{E}+04) \times (1.60\text{E}+03) \times (6.47\text{E}-08 + 2.28\text{E}-09).$$

For liquid samples, the equations used to convert $\mu\text{Ci/L}$ to Sv/L are

$$\text{Sv/L}(^{137}\text{Cs}) = \text{mean}(^{137}\text{Cs}) \times (3.70\text{E}+04) \times (8.63\text{E}-09)$$

$$\text{Sv/L}(\alpha) = \text{mean}(\alpha) \times (3.70\text{E}+04) \times (1.20\text{E}-04)$$

$$\text{Sv/L}(^{90}\text{Sr} + ^{90}\text{Y}) = \text{mean}(^{90}\text{Sr}) \times (3.70\text{E}+04) \times (6.47\text{E}-08 + 2.28\text{E}-09).$$

The ULD is defined to be the sum of the Sv/L for the four isotopes. For each tank and waste type, Tables A-5, A-6, A-7, and A-8 report the individual Sv/L and the ULD. ULDs for tanks 241-AY-101 and 241-AY-102 are included in Tables A-7 and A-8. These two tanks are "aging waste tanks." In the computations, the ULDs for these two tanks are treated separately. Tanks 241-AZ-101 and 241-AZ-102 are also "aging waste tanks." It was not possible to compute a ULD for these two tanks using data from TCD.

3.0 LOGNORMAL DISTRIBUTION

Three probability distributions were fit to the ULD data, a lognormal, a gamma, and a Weibull. A goodness-of-fit test was used to test the appropriateness of the three distributions. Based on the goodness-of-fit test, the lognormal distribution cannot be rejected, but the gamma and Weibull distributions are rejected. These three distributions were also fit to ULDs used in the gas release event safety analysis tool (Jensen et al. 1998). For that project, the lognormal distribution was the recommended distribution. In addition, tolerance limits can be computed for the lognormal distribution. They cannot be computed for gamma or Weibull distributions (tolerance limits are discussed in Section 3.2). To be consistent with Jensen et al. (1998) and since the lognormal distribution cannot be rejected, a lognormal distribution is the recommended distribution for the ULDs.

The lognormal distribution is defined as follows. A random variable X has a lognormal distribution if $Y = \log(X)$ has a normal distribution. The lognormal density function has the form

$$f(x) = \frac{1}{x \sqrt{2\pi} \sigma} \exp\left\{-\frac{(\log(x) - \mu)^2}{2\sigma^2}\right\}, x > 0$$

$$= 0, x \leq 0$$

where μ is the mean of $Y = \log(X)$ and σ^2 is the variance of $Y = \log(X)$. The unbiased estimates of μ and σ^2 are the sample mean, $\hat{\mu}$, and sample variance, $\hat{\sigma}^2$, on the natural log

scale. Table 2 gives the estimates of the means and variances for the six types of samples. The individual ULDs are given in Tables A-5 through A-8.

Table 2. Estimates of Means and Variances for the Lognormal Distribution

Type of sample	$\hat{\mu}$	$\hat{\sigma}^2$
SST solid samples	7.82E+00	2.72E+00
SST liquid samples	4.87E+00	3.50E+00
DST solid samples	8.50E+00	4.26E+00
DST liquid samples	4.09E+00	3.77E+00
DST solid samples without AY tanks	7.88E+00	2.09E+00
DST liquid samples without AY tanks	4.11E+00	3.76E+00

The Kolmogorov-Smirnov goodness-of-fit test was used to determine the appropriateness of the lognormal, the gamma and the Weibull distribution. Based on this test, the lognormal distribution cannot be rejected for each of the six types of waste listed in Table 2. However, the gamma distribution is rejected for the SST solid and liquid samples and the Weibull distribution is rejected for the SST liquid samples. The level of significance of the goodness-of-fit tests was 0.05.

Figures 1 through 6 are plots of the lognormal density functions for the six types of waste listed in Table 2. Superimposed on these plots are histograms of the corresponding ULDs. A probability density function is non-negative and integrates to one. The lognormal density functions, Figures 1 through 6, do not integrate to one. They have been normalized so that they can be viewed when superimposed on the histograms.

3.1 QUANTILES AND PERCENTILES

The ULDs in the BIO (FDH 1999), for the six types of waste, need to be compared to the quantiles corresponding to the 95th and 99th percentiles of the lognormal distributions. Table 3 lists these quantiles. The quantiles are the ULD values such that 95% or 99% of the “population” is to the left of the value. The quantiles are also given in Figures 1 through 6. A more complete list of the quantiles, and a comparison with the observed, is given in Table A-9 and A-10 in Appendix A. Table 3 also lists the ULDs for the BIO (FDH 1999). The BIO ULD is greater than or approximately equal to the quantile corresponding to the 99th percentiles of the lognormal distribution for each of the six types of waste.

Table 3. Quantiles Corresponding to the 95th and 99th Percentiles of the Lognormal Distribution and the BIO ULD

Type of sample	95 th	99 th	BIO
SST solid samples	3.75E+04	1.15E+05	2.20E+05
SST liquid samples	2.83E+03	1.01E+04	1.10E+04
DST solid samples	1.47E+05	6.01E+05	5.30E+05
DST liquid samples	1.46E+03	5.50E+03	6.10E+03
DST solid samples without AY tanks	2.86E+04	7.67E+04	5.30E+05
DST liquid samples without AY tanks	1.49E+03	5.61E+03	6.10E+03

These quantiles should be used with caution. The reason is that the lognormal density functions are based on estimates of the means and variances. These estimates are subject to variability and this variability is not incorporated into the estimates of the quantiles. It is difficult to compute confidence statements for the quantiles and for the density functions. However, tolerance limits are similar to quantiles and they incorporate the uncertainty due to using estimates of the means and variances. Tolerance limits may be more appropriate than the quantiles. They are discussed in the next section.

3.2 TOLERANCE LIMITS

A one-sided tolerance interval is a confidence statement regarding the proportion of the population below a given limit. The advantage of using TLs is that a confidence statement is part of the TL; i.e., measures of uncertainty are in a TL and they are not in the quantiles. These limits are based on the normal distribution. The limits are of the form $\hat{\mu} + K \hat{\sigma}$ where $\hat{\mu}$ and $\hat{\sigma}$ are the sample mean and standard deviation on the log scale. The values of K are tabulated (e.g. Table A-7 in Natrella 1963), they are a function of the number of observations, the confidence level and the proportion. The value $\exp(\hat{\mu} + K \hat{\sigma})$ is the tolerance limit for the lognormal distribution.

The notation for a 95% TL is 95/P where P is the proportion of the population. The interpretation of the tolerance interval is that we are 95% confident that at least P% of the population (distribution) is below the limit $\exp(\hat{\mu} + K \hat{\sigma})$. Table 4 gives the values of K used to compute the 95/95 and 95/99 TLs. The TLs and the ULD for the BIO (FDH 1999) are given in Table 5. Figures 1 through 6 also plot the TLs and the ULD for the BIO (FDH 1999) for the specific type of waste.

Table 4. Values of K^1 for One-sided 95% Tolerance Limits

Proportion	Number of Observations					
	11	13	20	23	25	51
P=0.95	2.815	2.670	2.396	2.329	2.292	2.060
P=0.99	3.852	3.659	3.295	3.206	3.158	2.850

¹ Natrella (1963), page T-15.

**Table 5. One-sided 95% Tolerance Limits for the Proportion
P=0.95 and P=0.99 and the BIO ULD**

Type of sample	95/95 TL	95/99 TL	BIO
SST solid samples	7.44E+04	2.73E+05	2.20E+05
SST liquid samples	1.16E+04	6.22E+04	1.10E+04
DST solid samples	1.22E+06	9.39E+06	5.30E+05
DST liquid samples	5.15E+03	2.77E+04	6.10E+03
DST solid samples without AY tanks	1.56E+05	6.97E+05	5.30E+05
DST liquid samples without AY tanks	5.64E+03	3.09E+04	6.10E+03

The ULD for the BIO is less than the 95/99 TL for all of the waste types. The ULD for the BIO is approximately equal to the 95/95 TL except for the SST solid waste and the DST solid waste without the two AY tanks.

Figures 3 and 4 are the plots of the lognormal distributions for solid and liquid samples for DSTs including tanks 241-AY-101 and 241-AY-102. Figures 5 and 6 are the corresponding plots without the two AY tanks. There is little difference between the two plots for the DST liquid samples. There is a big difference between the two plots for the DST solid samples. The reason for the difference is that ULDs for the solid portion of waste from 241-AY-101 and 241-AY-102 are larger than the other ULDs.

All of the statistical computations and figures were completed using the statistical program S-PLUS (1997).

Figure 1. ULD Lognormal Density and Histogram
Single Shell Tanks, Solid Samples

Figure 2. ULD Lognormal Density and Histogram
Single Shell Tanks, Liquid Samples

Figure 3. ULD Lognormal Density and Histogram
Double Shell Tanks, Solid Samples

Figure 4. ULD Lognormal Density and Histogram
Double Shell Tanks, Liquid Samples

Figure 5. ULD Lognormal Density and Histogram
Double Shell Tanks, Solid Samples

Figure 6. ULD Lognormal Density and Histogram
Double Shell Tanks, Liquid Samples

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APPENDIX A

UNIT LITER DOSE TABLES

In Tables A1, A2, A3, and A4, the columns labeled "analyte" denote the type of data used to estimate the mean. That is, ^{137}Cs indicates that the mean of all the ^{137}Cs data for the tank is reported. For alpha, GA indicates that the mean of the gross alpha data is reported; TA, the mean of the total alpha data; GA&TA, the mean of the combined GA and TA data; ^{241}Am , the mean of the ^{241}Am data; and $^{239/240}\text{Pu}$, the mean of the $^{239/240}\text{Pu}$ data. For strontium, $^{89/90}\text{Sr}$ indicates that the mean of $^{89/90}\text{Sr}$ is reported; ^{90}Sr , the mean of ^{90}Sr data; $^{89/90}\text{Sr}$ & ^{90}Sr , the mean of the combined $^{89/90}\text{Sr}$ and ^{90}Sr data.

Table A-1. Mean Analyte Concentration ($\mu\text{Ci/g}$), SST Solid Samples (2 Sheets)

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-A-101	^{137}Cs	2.03E+02	GA	6.15E-02	$^{89/90}\text{Sr}$	1.55E+01
241-AX-101	^{137}Cs	1.99E+02	GA	5.17E-02	$^{89/90}\text{Sr}$	1.82E+01
241-AX-104	^{137}Cs	6.07E+02	GA	1.38E+01	$^{89/90}\text{Sr}$	1.88E+04
241-B-106	^{137}Cs	2.03E+01	GA	4.92E-02	$^{89/90}\text{Sr}$	7.18E+01
241-B-108	^{137}Cs	1.72E+01	GA	7.90E-03	$^{89/90}\text{Sr}$	2.87E+00
241-B-111	^{137}Cs	1.49E+02	GA&TA	1.24E-01	^{90}Sr	2.48E+02
241-B-201	^{137}Cs	4.59E+00	GA&TA	1.06E+00	^{90}Sr	2.70E+00
241-B-202	^{137}Cs	1.26E-01	GA&TA	4.15E-01	^{90}Sr	3.99E+00
241-BX-107	^{137}Cs	2.21E+01	GA&TA	1.19E-01	^{90}Sr	9.87E+00
241-BX-109	^{137}Cs	1.32E+01	GA	4.99E-02	$^{89/90}\text{Sr}$	1.62E+02
241-BX-112	^{137}Cs	5.09E+01	GA	1.90E-01	^{90}Sr	6.17E+00
241-BY-104	^{137}Cs	1.03E+02	GA	1.13E-01	$^{89/90}\text{Sr}$	1.84E+02
241-BY-105	^{137}Cs	6.55E+01	GA	1.04E-01	$^{89/90}\text{Sr}$	1.26E+02
241-BY-106	^{137}Cs	1.00E+02	GA	2.59E-02	$^{89/90}\text{Sr}$	2.67E+01
241-BY-107	^{137}Cs	1.25E+02	GA	4.68E-02	$^{89/90}\text{Sr}$	2.21E+01
241-BY-110	^{137}Cs	9.29E+01	GA	7.24E-02	$^{89/90}\text{Sr}$	1.08E+02
241-C-103	^{137}Cs	1.35E+02	GA	1.14E+01	$^{89/90}\text{Sr}$	4. $^{90}\text{E}+03$
241-C-104	^{137}Cs	6.15E+01	GA	6.37E+00	$^{89/90}\text{Sr}$	3.23E+02
241-C-106	^{137}Cs	5.53E+02	GA	2.77E+00	$^{89/90}\text{Sr}$	5.17E+02
241-C-108	^{137}Cs	1.66E+02	GA	7.81E-02	$^{89/90}\text{Sr}$	1.95E+02
241-C-109	^{137}Cs	4.77E+02	GA&TA	2.26E-01	^{90}Sr	9.58E+02
241-C-110	^{137}Cs	1.86E+01	GA&TA	1.34E-01	^{90}Sr	5.04E+00
241-C-111	^{137}Cs	4.32E+01	GA	8.21E-01	^{90}Sr	4.21E+03
241-C-112	^{137}Cs	2.04E+02	GA	3.35E-01	^{90}Sr	1.29E+03
241-S-101	^{137}Cs	1.29E+02	GA	3.49E-01	$^{89/90}\text{Sr}$	2.52E+02
241-S-102	^{137}Cs	1.17E+02	GA	1.78E-01	$^{89/90}\text{Sr}$	2.54E+01
241-S-104	^{137}Cs	5.84E+01	GA&TA	4.73E-01	^{90}Sr	3.10E+02
241-S-106	^{137}Cs	1.01E+02	GA	3.09E-02	$^{89/90}\text{Sr}$	1.49E+01
241-S-107	^{137}Cs	8.22E+01	GA	9.24E-01	$^{89/90}\text{Sr}$	1.60E+02
241-S-109	^{137}Cs	7.58E+00	GA	7.74E-03	$^{89/90}\text{Sr}$	5.31E+00
241-S-110	^{137}Cs	8.78E+01	GA	3.12E-01	$^{89/90}\text{Sr}$	1.22E+02
241-S-111	^{137}Cs	1.16E+02	GA	3.29E-02	$^{89/90}\text{Sr}$	1.34E+02
241-SX-101	^{137}Cs	1.07E+02	GA	4.85E-01	$^{89/90}\text{Sr}$	1.20E+02
241-SX-102	^{137}Cs	1.49E+02	GA	2.13E-01	$^{89/90}\text{Sr}$	1.03E+02
241-SX-103	^{137}Cs	1.27E+02	GA	1.71E-01	$^{89/90}\text{Sr}$	1.29E+02
241-SX-108	^{137}Cs	1.95E+02	GA	3.29E+00	$^{89/90}\text{Sr}$	3.06E+03
241-T-102	^{137}Cs	2.09E+01	GA&TA	9.86E-02	^{90}Sr	2.38E+02
241-T-104	^{137}Cs	2.07E-01	GA&TA	1.38E-01	^{90}Sr	2.63E+00
241-T-105	^{137}Cs	4.57E+01	GA&TA	3.61E-01	^{90}Sr	2.80E+02

Table A-1. Mean Analyte Concentration ($\mu\text{Ci/g}$), SST Solid Samples (2 Sheets)

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-T-107	^{137}Cs	2.06E+01	GA&TA	1.87E-01	^{90}Sr	1.20E+02
241-T-111	^{137}Cs	1.34E-01	GA&TA	3.91E-01	^{90}Sr	5.41E+00
241-T-201	^{137}Cs	3.46E-02	GA	7.57E-01	$^{89/90}\text{Sr}$	8.58E-02
241-T-204	^{137}Cs	7.76E-03	GA	1.52E-01	$^{89/90}\text{Sr}$	4.60E-03
241-TX-118	^{137}Cs	1.10E+01	GA	1.71E+01	$^{89/90}\text{Sr}$	2.18E+02
241-U-102	^{137}Cs	1.61E+02	GA	1.80E-01	$^{89/90}\text{Sr}$	4.06E+01
241-U-105	^{137}Cs	1.53E+02	GA	7.39E-01	$^{89/90}\text{Sr}$	5.97E+01
241-U-106	^{137}Cs	1.52E+02	GA	1.15E+00	$^{89/90}\text{Sr}$	7.72E+01
241-U-107	^{137}Cs	8.55E+01	GA	2.19E-01	$^{89/90}\text{Sr}$	4.34E+00
241-U-108	^{137}Cs	1.44E+02	GA	5.25E-02	$^{89/90}\text{Sr}$	1.03E+01
241-U-109	^{137}Cs	1.16E+02	GA	3.71E-02	$^{89/90}\text{Sr}$	8.81E+00
241-U-110	^{137}Cs	2.41E+01	GA	7.47E-01	$^{89/90}\text{Sr}$ & ^{90}Sr	1.57E+02

Table A-2. Mean Analyte Concentrations ($\mu\text{Ci/L}$), SST Liquid Samples

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-A-101	^{137}Cs	3.53E+05	GA	5.68E+00	$^{89/90}\text{Sr}$	6.82E+01
241-BY-105	^{137}Cs	2.10E+05	GA	2.99E+01	$^{89/90}\text{Sr}$	1.10E+02
241-C-106	^{137}Cs	1.25E+05	GA	1.02E+03	$^{89/90}\text{Sr}$	6.10E+02
241-C-110	^{137}Cs	3.88E+03	GA	2.07E+00	^{90}Sr	2.78E+01
241-S-102	^{137}Cs	3.24E+05	GA	1.21E+01	$^{89/90}\text{Sr}$	3.11E+02
241-S-103	^{137}Cs	3.65E+05	^{241}Am	1.19E+00	$^{89/90}\text{Sr}$	4.20E+02
241-S-106	^{137}Cs	2.67E+05	GA	2.20E+00	$^{89/90}\text{Sr}$	5.67E+01
241-SX-101	^{137}Cs	4.03E+05	GA	8.22E+02	$^{89/90}\text{Sr}$	8.03E+01
241-SX-102	^{137}Cs	4.38E+05	GA	5.87E+00	$^{89/90}\text{Sr}$	2.34E+01
241-SX-103	^{137}Cs	4.40E+05	GA	1.24E+01	$^{89/90}\text{Sr}$	1.15E+02
241-SX-104	^{137}Cs	2.83E+05	^{241}Am	2.62E-02	$^{89/90}\text{Sr}$	6.33E+01
241-SX-105	^{137}Cs	3.84E+05	GA	7.32E+00	$^{89/90}\text{Sr}$	1.60E+02
241-SX-106	^{137}Cs	3.77E+05	GA	4.11E+00	$^{89/90}\text{Sr}$	3.40E+02
241-T-107	^{137}Cs	8.43E+03	GA	6.01E+00	^{90}Sr	5.94E+01
241-T-110	^{137}Cs	3.43E+00	GA	1.02E-01	^{90}Sr	5.30E-01
241-U-102	^{137}Cs	3.40E+05	GA	3.12E+01	$^{89/90}\text{Sr}$	8.83E+03
241-U-103	^{137}Cs	3.77E+05	GA	3.01E+01	$^{89/90}\text{Sr}$	1.05E+04
241-U-107	^{137}Cs	3.52E+05	GA	1.12E+01	$^{89/90}\text{Sr}$	3.61E+02
241-U-108	^{137}Cs	4.16E+05	GA	8.88E+00	$^{89/90}\text{Sr}$	3.45E+02
241-U-109	^{137}Cs	3.66E+05	GA	1.07E+00	$^{89/90}\text{Sr}$	9.31E+02

Table A-3. Mean Analyte Concentrations ($\mu\text{Ci/g}$), DST Solid Samples

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-AN-102	^{137}Cs	2.39E+02	GA	5.52E-01	$^{89/90}\text{Sr}$	1.17E+02
241-AN-103	^{137}Cs	2.51E+02	GA	1.72E-02	$^{89/90}\text{Sr}$	2.66E+00
241-AN-104	^{137}Cs	3.46E+02	GA	4.07E-02	$^{89/90}\text{Sr}$	3.36E+01
241-AN-105	^{137}Cs	2.67E+02	GA	2.78E-02	$^{89/90}\text{Sr}$	1.87E+01
241-AN-107	^{137}Cs	1.74E+02	GA	1.00E+00	$^{89/90}\text{Sr}$	2.53E+02
241-AW-101	^{137}Cs	2.30E+02	GA	1.34E-01	$^{89/90}\text{Sr}$	8.28E+01
241-AW-102	^{137}Cs	8.64E+01	GA	2.40E+00	$^{89/90}\text{Sr}$	6.64E+02
241-AW-105	^{137}Cs	3.82E+01	GA	1.75E+00	$^{89/90}\text{Sr}$ & ^{90}Sr	6.22E+01
241-AW-106	^{137}Cs	1.15E+02	GA	2.22E-01	$^{89/90}\text{Sr}$	2.26E+01
241-AY-101	^{137}Cs	8.56E+01	GA	4.39E+00	$^{89/90}\text{Sr}$	4.61E+03
241-AY-102	^{137}Cs	2.83E+02	^{241}Am	2.24E+01	$^{89/90}\text{Sr}$	7.67E+04
241-SY-101	^{137}Cs	3.50E+02	GA	8.17E-01	^{90}Sr	2.97E+01
241-SY-103	^{137}Cs	2.26E+02	GA	8.93E-01	$^{89/90}\text{Sr}$	9.64E+00

Table A-4. Mean Analyte Concentrations ($\mu\text{Ci/L}$), DST Liquid Samples (2 Sheets)

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-AN-101	^{137}Cs	1.01E+05	^{241}Am	3.86E-02	$^{89/90}\text{Sr}$	2.09E+02
241-AN-102	^{137}Cs	3.66E+05	GA	1.76E+02	$^{89/90}\text{Sr}$	8.47E+04
241-AN-103	^{137}Cs	7.86E+05	GA	5.77E+01	$^{89/90}\text{Sr}$	2.08E+01
241-AN-104	^{137}Cs	6.54E+05	GA	1.23E+01	$^{89/90}\text{Sr}$	1.31E+02
241-AN-105	^{137}Cs	4.02E+05	GA	2.84E+01	$^{89/90}\text{Sr}$	4.14E+01
241-AN-107	^{137}Cs	3.63E+05	GA	8.17E+02	$^{89/90}\text{Sr}$	1.01E+05
241-AP-101	^{137}Cs	1.61E+05	GA	5.95E-03	$^{89/90}\text{Sr}$ & ^{90}Sr	1.33E+02
241-AP-102	^{137}Cs	2.25E+05	^{241}Am	4.34E-01	^{90}Sr	1.45E+03
241-AP-103	^{137}Cs	6.53E+03	$^{239/240}\text{Pu}$	4.31E-03	$^{89/90}\text{Sr}$ & ^{90}Sr	7.04E+00
241-AP-104	^{137}Cs	4.97E+03	GA	3.28E-01	$^{89/90}\text{Sr}$	8.28E+01
241-AP-105	^{137}Cs	2.10E+05	GA	1.01E+01	$^{89/90}\text{Sr}$ & ^{90}Sr	2.06E+02
241-AP-106	^{137}Cs	3.98E+04	^{241}Am	3.65E-01	$^{89/90}\text{Sr}$ & ^{90}Sr	1.54E+02
241-AP-107	^{137}Cs	1.20E+04	$^{239/240}\text{Pu}$	9.29E-02	$^{89/90}\text{Sr}$ & ^{90}Sr	4.63E+01
241-AP-108	^{137}Cs	5.59E+04	^{241}Am	1.99E-01	$^{89/90}\text{Sr}$	1.95E+02
241-AW-101	^{137}Cs	3.88E+05	GA	7.85E+00	$^{89/90}\text{Sr}$	2.92E+02
241-AW-102	^{137}Cs	3.53E+04	GA	1.68E+00	$^{89/90}\text{Sr}$ & ^{90}Sr	2.09E+02
241-AW-103	^{137}Cs	2.06E+04	$^{239/240}\text{Pu}$	9.86E-03	^{90}Sr	2.20E-01
241-AW-104	^{137}Cs	4.54E+03	GA	4.45E+00	^{90}Sr	7.79E+00
241-AW-105	^{137}Cs	1.41E+04	GA	1.83E+00	$^{89/90}\text{Sr}$ & ^{90}Sr	6.51E+01
241-AW-106	^{137}Cs	1.86E+05	GA	2.87E+01	$^{89/90}\text{Sr}$ & ^{90}Sr	3.82E+02
241-AY-101	^{137}Cs	8.81E+04	GA	6.36E+01	$^{89/90}\text{Sr}$	1.89E+03

Table A-4. Mean Analyte Concentrations (μCi/L), DST Liquid Samples (2 Sheets)

Tank	Analyte	Mean	Analyte	Mean	Analyte	Mean
241-AY-102	¹³⁷ Cs	3.59E+03	²⁴¹ Am	5.17E-01	^{89/90} Sr& ⁹⁰ Sr	1.19E+03
241-SY-101	¹³⁷ Cs	9.06E+05	GA	3.72E+01	⁹⁰ Sr	1.53E+03
241-SY-102	¹³⁷ Cs	3.05E+04	GA	2.26E+01	^{89/90} Sr	2.47E+02
241-SY-103	¹³⁷ Cs	3.99E+05	²⁴¹ Am	1.87E+00	^{89/90} Sr	2.69E+03

Table A-5. Sv/L by Analyte and ULD, SST Solid Samples (2 Sheets)

Tank	¹³⁷ Cs	Alpha	⁹⁰ Sr+ ⁹⁰ Y	ULD
241-A-101	1.04E+02	4.37E+02	6.15E+01	6.02E+02
241-AX-101	1.02E+02	3.67E+02	7.22E+01	5.41E+02
241-AX-104	3.10E+02	9.83E+04	7.44E+04	1.73E+05
241-B-106	1.04E+01	3.49E+02	2.85E+02	6.44E+02
241-B-108	8.80E+00	5.61E+01	1.14E+01	7.63E+01
241-B-111	7.61E+01	8.77E+02	9.83E+02	2.07E+03
241-B-201	2.35E+00	7.55E+03	1.07E+01	4.51E+03
241-B-202	6.43E-02	2.95E+03	1.58E+01	2.89E+03
241-BX-107	1.13E+01	8.47E+02	3.91E+01	9.26E+02
241-BX-109	6.74E+00	3.54E+02	6.43E+02	1.00E+03
241-BX-112	2.60E+01	1.35E+03	2.45E+01	1.40E+03
241-BY-104	5.27E+01	8.00E+02	7.28E+02	1.58E+03
241-BY-105	3.35E+01	7.39E+02	4.99E+02	1.27E+03
241-BY-106	5.12E+01	1.84E+02	1.06E+02	3.41E+02
241-BY-107	6.37E+01	3.33E+02	8.77E+01	4.84E+02
241-BY-110	4.75E+01	5.15E+02	4.27E+02	8.57E+02
241-C-103	6.91E+01	8.08E+04	1.94E+04	1.00E+05
241-C-104	3.14E+01	4.53E+04	1.28E+03	4.66E+04
241-C-106	2.83E+02	1.97E+04	2.05E+03	2.20E+04
241-C-108	8.50E+01	5.54E+02	7.74E+02	2.65E+03
241-C-109	2.44E+02	1.60E+03	3.80E+03	5.18E+03
241-C-110	9.51E+00	9.50E+02	2.00E+01	9.16E+02
241-C-111	2.21E+01	5.83E+03	1.67E+04	2.26E+04
241-C-112	1.04E+02	2.38E+03	5.12E+03	7.60E+03
241-S-101	6.58E+01	2.48E+03	9.99E+02	3.54E+03
241-S-102	5.97E+01	1.27E+03	1.01E+02	1.67E+03
241-S-104	2.98E+01	3.36E+03	1.23E+03	5.18E+03
241-S-106	5.17E+01	2.19E+02	5.92E+01	3.30E+02
241-S-107	4.20E+01	6.57E+03	6.36E+02	7.25E+03
241-S-109	3.87E+00	5.50E+01	2.10E+01	7.99E+01

Table A-5. Sv/L by Analyte and ULD, SST Solid Samples (2 Sheets)

Tank	¹³⁷ Cs	Alpha	⁹⁰ Sr+ ⁹⁰ Y	ULD
241-S-110	4.49E+01	2.22E+03	4.85E+02	2.75E+03
241-S-111	5.94E+01	2.33E+02	5.31E+02	8.24E+02
241-SX-101	5.47E+01	3.45E+03	4.78E+02	3.98E+03
241-SX-102	7.62E+01	1.51E+03	4.08E+02	2.00E+03
241-SX-103	6.51E+01	1.22E+03	5.10E+02	1.79E+03
241-SX-108	9.96E+01	2.34E+04	1.21E+04	3.56E+04
241-T-102	1.07E+01	7.01E+02	9.44E+02	3.14E+03
241-T-104	1.06E-01	9.81E+02	1.04E+01	1.01E+03
241-T-105	2.33E+01	2.56E+03	1.11E+03	3.47E+03
241-T-107	1.05E+01	1.33E+03	4.75E+02	1.74E+03
241-T-111	6.84E-02	2.78E+03	2.15E+01	2.66E+03
241-T-201	1.77E-02	5.37E+03	3.40E-01	5.37E+03
241-T-204	3.96E-03	1.08E+03	1.82E-02	1.08E+03
241-TX-118	5.63E+00	1.22E+05	8.63E+02	1.22E+05
241-U-102	8.20E+01	1.28E+03	1.61E+02	1.52E+03
241-U-105	7.80E+01	5.25E+03	2.37E+02	5.56E+03
241-U-106	7.76E+01	8.15E+03	3.06E+02	8.54E+03
241-U-107	4.37E+01	1.55E+03	1.72E+01	1.61E+03
241-U-108	7.34E+01	3.73E+02	4.10E+01	4.88E+02
241-U-109	5.92E+01	2.64E+02	3.49E+01	3.58E+02
241-U-110	1.23E+01	5.31E+03	6.23E+02	5.94E+03

Table A-6. Sv/L by Analyte and ULD, SST Liquid Samples

Tank	¹³⁷ Cs	Alpha	⁹⁰ Sr+ ⁹⁰ Y	ULD
241-A-101	1.13E+02	2.52E+01	1.69E-01	1.38E+02
241-BY-105	6.72E+01	1.33E+02	2.72E-01	2.00E+02
241-C-106	3.98E+01	4.55E+03	1.51E+00	4.59E+03
241-C-110	1.24E+00	9.19E+00	6.88E-02	1.05E+01
241-S-102	1.04E+02	5.37E+01	7.70E-01	1.58E+02
241-S-103	1.17E+02	5.28E+00	1.04E+00	1.23E+02
241-S-106	8.52E+01	9.75E+00	1.41E-01	9.51E+01
241-SX-101	1.29E+02	3.65E+03	1.99E-01	3.78E+03
241-SX-102	1.40E+02	2.60E+01	5.80E-02	1.66E+02
241-SX-103	1.40E+02	5.49E+01	2.85E-01	1.95E+02
241-SX-104	9.04E+01	1.16E-01	1.57E-01	9.06E+01
241-SX-105	1.23E+02	3.25E+01	3.96E-01	1.55E+02
241-SX-106	1.20E+02	1.82E+01	8.43E-01	1.40E+02
241-T-107	2.69E+00	2.67E+01	1.47E-01	2.95E+01
241-T-110	1.10E-03	4.53E-01	1.31E-03	4.55E-01
241-U-102	1.08E+02	1.39E+02	2.19E+01	2.69E+02
241-U-103	1.20E+02	1.34E+02	2.60E+01	2.80E+02
241-U-107	1.12E+02	4.98E+01	8.94E-01	1.63E+02
241-U-108	1.33E+02	3.94E+01	8.54E-01	1.73E+02
241-U-109	1.17E+02	4.75E+00	2.31E+00	1.24E+02

Table A-7. Sv/L by Analyte and ULD, DST Solid Samples

Tank	¹³⁷ Cs	Alpha	⁹⁰ Sr+ ⁹⁰ Y	ULD
241-AN-102	1.22E+02	3.92E+03	4.63E+02	4.51E+03
241-AN-103	1.28E+02	1.22E+02	1.05E+01	2.61E+02
241-AN-104	1.77E+02	2.89E+02	1.33E+02	5.99E+02
241-AN-105	1.36E+02	1.98E+02	7.43E+01	4.08E+02
241-AN-107	8.88E+01	7.13E+03	1.00E+03	8.22E+03
241-AW-101	1.17E+02	9.54E+02	3.28E+02	1.40E+03
241-AW-102	4.41E+01	1.71E+04	2.63E+03	1.97E+04
241-AW-105	1.95E+01	1.25E+04	2.47E+02	1.27E+04
241-AW-106	5.85E+01	1.57E+03	8.96E+01	1.72E+03
241-AY-101	4.37E+01	3.12E+04	1.83E+04	4.95E+04
241-AY-102	1.45E+02	1.59E+05	3.04E+05	4.63E+05
241-SY-101	1.79E+02	5.80E+03	1.18E+02	6.10E+03
241-SY-103	1.16E+02	6.35E+03	3.82E+01	5.34E+03

Table A-8. Sv/L by Analyte and ULD, DST Liquid Samples

Tank	¹³⁷ Cs	Alpha	⁹⁰ Sr+ ⁹⁰ Y	ULD
241-AN-101	3.24E+01	1.71E-01	5.18E-01	3.31E+01
241-AN-102	1.17E+02	7.82E+02	2.10E+02	1.11E+03
241-AN-103	2.51E+02	2.56E+02	5.15E-02	5.07E+02
241-AN-104	2.09E+02	5.45E+01	3.24E-01	2.64E+02
241-AN-105	1.28E+02	1.26E+02	1.03E-01	2.55E+02
241-AN-107	1.16E+02	3.63E+03	2.51E+02	3.99E+03
241-AP-101	5.15E+01	2.64E-02	3.30E-01	5.19E+01
241-AP-102	7.19E+01	1.93E+00	3.59E+00	7.74E+01
241-AP-103	2.09E+00	1.91E-02	1.74E-02	2.12E+00
241-AP-104	1.59E+00	1.46E+00	2.05E-01	3.25E+00
241-AP-105	6.70E+01	4.47E+01	5.12E-01	1.12E+02
241-AP-106	1.27E+01	1.62E+00	3.82E-01	1.47E+01
241-AP-107	3.82E+00	4.12E-01	1.15E-01	4.35E+00
241-AP-108	1.78E+01	8.85E-01	4.84E-01	1.92E+01
241-AW-101	1.24E+02	3.48E+01	7.24E-01	1.59E+02
241-AW-102	1.13E+01	7.46E+00	5.19E-01	1.92E+01
241-AW-103	6.58E+00	4.38E-02	5.44E-04	6.62E+00
241-AW-104	1.45E+00	1.97E+01	1.93E-02	2.12E+01
241-AW-105	4.50E+00	8.14E+00	1.61E-01	1.28E+01
241-AW-106	5.93E+01	1.27E+02	9.47E-01	1.88E+02
241-AY-101	2.81E+01	2.82E+02	4.69E+00	3.15E+02
241-AY-102	1.15E+00	2.30E+00	2.94E+00	6.39E+00
241-SY-101	2.89E+02	1.65E+02	3.80E+00	4.58E+02
241-SY-102	9.74E+00	1.00E+02	6.11E-01	1.11E+02
241-SY-103	1.27E+02	8.31E+00	6.67E+00	1.42E+02

Table A-9. Comparison of Observed and Estimated ULD Quantiles for SSTs

Percentile Point	SST Solid Samples		SST Liquid Samples	
	Observed Quantile	Lognormal Quantile	Observed Quantile	Lognormal Quantile
0%	76	NA	0	NA
5%	336	166	10	6
10%	484	302	28	12
15%	572	452	81	19
20%	824	623	94	27
25%	921	821	116	37
30%	1010	1051	124	49
35%	1335	1322	133	64
40%	1580	1643	139	81
45%	1705	2028	148	103
50%	2000	2495	157	131
55%	2655	3069	160	165
60%	2890	3788	164	210
65%	3505	4708	168	269
70%	4510	5921	180	349
75%	5275	7582	196	462
80%	5940	9986	214	631
85%	8070	13767	271	909
90%	22600	20619	630	1437
95%	73300	37521	3821	2837
100%	173000	NA	4590	NA

Table A-10. Comparison of Observed and Estimated ULD Quantiles for DSTs

Percentile Point	DST Solid Samples		DST Liquid Samples		DST Solid Samples, without AY Tanks		DST Liquid Samples, without AY Tanks	
	Observed Quantile	Lognormal Quantile	Observed Quantile	Lognormal Quantile	Observed Quantile	Lognormal Quantile	Observed Quantile	Lognormal Quantile
0%	261	NA	2	NA	261	NA	2	NA
5%	349	166	3	2	335	246	3	3
10%	446	352	5	5	408	416	5	5
15%	561	583	7	8	504	593	8	8
20%	919	872	12	12	599	787	14	12
25%	1400	1230	15	16	1000	1002	17	17
30%	1592	1677	19	22	1400	1244	19	22
35%	2278	2234	20	28	1560	1521	21	29
40%	3952	2933	28	37	1720	1841	31	38
45%	4842	3818	48	47	3115	2215	50	48
50%	5340	4947	77	60	4510	2656	77	62
55%	5796	6411	111	77	4925	3185	111	79
60%	6524	8344	124	98	5340	3831	118	101
65%	7796	10954	152	127	5720	4637	147	130
70%	10012	14595	182	166	6100	5670	171	170
75%	12700	19891	255	222	7160	7044	222	228
80%	16900	28081	274	308	8220	8969	260	315
85%	25660	41970	372	449	10460	11888	400	459
90%	43540	69591	487	723	12700	16944	497	739
95%	214900	147248	989	1464	16200	28653	1050	1495
100%	463000	NA	3990	NA	19700	NA	3990	NA

APPENDIX B

INDEPENDENT REVIEW

REVIEW CHECKLIST

Document Reviewed:

Sample Based Unit Liter Dose Estimates, HNF-4534, Rev 0

Scope of Review:

Check of Statistical Calculations and conversions of number values

Yes	No	NA	
☒	☐	☐	* Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☒	☐	☐	Problem completely defined.
☐	☐	☒	Accident scenarios developed in a clear and logical manner.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☒	☐	☐	Computer codes and data files documented.
☒	☐	☐	Data used in calculations explicitly stated in document.
☒	☐	☐	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivation checked including dimensional consistency of results.
☒	☐	☐	Models appropriate and used within range of validity or use outside range of established validity justified.
☒	☐	☒	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
☒	☐	☐	Software input correct and consistent with document reviewed.
☒	☐	☐	Software output consistent with input and with results reported in document reviewed.
☐	☐	☒	Limits/criteria/guidelines applied to analysis results are appropriate and referenced.
☐	☐	☒	Limits/criteria/guidelines checked against references.
☐	☐	☒	Safety margins consistent with good engineering practices.
☒	☐	☐	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.
☐	☐	☒	Format consistent with appropriate NRC Regulatory Guide or other standards.
☐	☐	☒	* Review calculations, comments, and/or notes are attached.
☒	☐	☐	Document approved.

Steven A. Barker

Reviewer (Printed Name and Signature)

7/8/99

Date

*Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution	Data Development and Interpretation	Date 06/23/99
Project Title/Work Order		EDT No. EDT-611473
HNF-4534, Rev. 0, "Sample Based Unit Liter Dose Estimates"		ECN No. N/A

Name	MSIN	Text With All Attach.	Text Only	Attach./Appendix Only	EDT/ECN Only
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