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Basis for Dose Rate to Curie Assay Method

S. R. Gedeon

Westinghouse Hanford Company, Richland, WA 99352

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Abstract: Disposition of low-level solid waste packages at the Hanford Site requires quantifying the radioactive contents of each container. This study generated conversion factors to apply to the results of contact surveys that are performed with standard dose rate survey instruments by field health physics technicians. This study determined the accuracy of this method, and identified the major sources of uncertainty. It is concluded that the dominant error is associated with the possibility that the radioactive source is not homogeneously distributed.

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BASIS FOR DOSE RATE TO CURIE ASSAY METHOD

1.0 INTRODUCTION

The Hanford site remediation program will require processing large numbers of low-level solid waste packages. Disposition requires quantifying the radioactive content of each container. Although some of the containers can be processed using high resolution, shielded, gamma-ray scanning techniques to characterize the contents, time and cost constraints dictate the use of simpler field methods for most containers. Of specific interest is the validity of using the results of radiological field surveys of the surface dose rates of containers to categorize the waste contents. The purpose of the study presented here is to evaluate the limitations associated with the parameters relating surface dose rate and inventory. Although the calculations were limited to 55-gallon drums, the conclusions are applicable to other containers. The goal is to establish dose rates that assure the container can be processed as Category 1 waste (WHC-EP-0063-4).

2.0 SUMMARY AND CONCLUSIONS

Monte Carlo calculations were made to evaluate the accuracy and limitations associated with quantifying the inventory of radioisotopes within a 55-gallon drum based on six-point average surface dose rate measurements. It is concluded that the dominant error is associated with the possibility that the radioactive source is not homogeneously distributed. For a 55-gallon drum, the bias associated with an actual local source of radiation could be as much as a factor of four. The second major source of error is that associated with the gamma ray source. For the radioactive mix that was investigated, the surface dose rate was dominated by the presence of a single radioisotope, ¹³⁷Cs. Thus, quantification of all other radioisotopes is by inference based on the assumed mix. The uncertainty associated with other parameters, such as the elemental composition of the waste, the accuracy of the dose rate measurements, and the accuracy of the weight determination was found to be small in comparison to the homogeneity and radioactive source assumptions. The bias associated with point kernel buildup factor calculations can be eliminated by the use of Monte Carlo calculations. These same conclusions are expected to apply to other types of containers. This study validates the method of quantifying the radioactive inventory within a container based on surface dose rate measurements. When the variation in surface dose rates indicates the source to be heterogenous, allowance should be made by assuming the worst-case distribution.

3.0 BACKGROUND

Estimating the curie content of containers based on surface dose rate information has been standard practice for some time (Greenborg 1985). However, it is well known that it is not possible to establish rigorously the radionuclide inventory within a sealed container because of the infinite possible combination of parameters. The purpose of this work was to evaluate the limitations that exist and to define a practical procedure that will satisfactorily, and with sufficient accuracy, establish that the container contents meet defined limits. Of specific interest is the ability to separate containers whose contents are within Category 1 limits from those that might exceed those limits.

Hanford solid waste is characterized on the basis of half life and curie content. Low activity waste that will not be hazardous to an intruder after an active institutional control period is defined as Category 1. Such waste must have very low concentrations of long-lived radionuclides. Tables have been generated that define the concentration (curies per cubic meter) of individual radioisotopes that meet the Category 1 definition. For containers with mixtures of radioisotopes, the sum of the fractional category contributions must be less than unity to remain within Category 1. Government regulations permit the use of both direct and indirect methods to infer the concentration of individual isotopes. Because the surface dose rate of a container is related only to radioisotopes emitting relatively high energy photons, the use of indirect methods to infer the inventory of most of the contained radioisotopes is required.

Each of the sources of uncertainty associated with establishing the radionuclide inventory in a sealed container based on surface dose rate measurements has been evaluated in this study and will be described in the following sections. This study specifically addresses the uncertainties associated with 55-gallon drums. Subsequent analyses are required to quantify these parameters for other waste containers, such as 4 foot by 4 foot by 8 foot wood boxes and even larger metal containers. Because of the size of these containers, it is likely that larger biases exist. This fact does not invalidate the method for such containers. However, more detailed survey and analysis methods may be appropriate to categorize the waste in the larger containers.

4.0 SOURCES OF UNCERTAINTY

The seven identified sources of uncertainty associated with using the average value of six surface dose rate measurements to determine the radioactive inventory in a waste container are:

1. The radioisotope mix that defines the gamma ray spectrum
2. The uniformity of the source distribution within the container
3. The potential existence of voids or low density regions

4. The elemental composition of the contained material
5. The accuracy of the field dose rate measurements
6. The accuracy of the calculations that relate the source to the measured dose rates
7. The weight of the waste material within the container

Each of these items is discussed in some detail in the following sections to indicate its impact on the use of surface dose rate measurements to categorize the waste contents.

4.1 Radioisotope Source

Hanford waste is associated primarily with the processing of fuel that was irradiated in the production reactors. In addition to uranium isotopes, the waste can contain a number of different transuranics, fission products, and activation isotopes. It is Hanford practice to maintain process records that characterize the material associated with each process stream that produces waste. For this study we used specifically the waste from Tank 241-SY-101, which is typical of a number of other waste streams. The normalized composition of this material is presented in Table 1.

Table 1. Normalized Radionuclide Contents of Waste Tank 241-SY-101

Nuclide	Curies	Nuclide	Curies
U & TRU	3.96 E-4	⁹⁰ Sr	5.34 E-2
¹²⁹ I	1.68 E-5	⁹⁰ Y	5.34 E-2
⁹⁴ Nb	5.34 E-8	⁹⁹ Tc	4.28 E-4
¹⁴ C	1.10 E-6	⁷⁹ Se	3.82 E-7
¹³⁷ Cs	4.57 E-1	^{93m} Nb	4.57 E-6
^{137m} Ba	4.32 E-1	⁶⁰ Co	5.94 E-4
		¹⁵⁴ Eu	4.25 E-3
		Total	1.00 E+0

Many of the radioisotopes listed in Table 1 either emit no photons or only very low energy photons. When these radioisotopes are placed in a large waste container together with inert carrier material, very few of the low energy photons reach the surface and contribute to the dose rate. Table 2 presents the energy-dependent gamma ray source associated the isotopic mix in Table 1. This source spectrum was generated using the ISOSHL (Engel 1966, Rittman 1995) code. The large source at 0.65 MeV is actually the 0.662 MeV photon associated with the decay chain ¹³⁷Cs-^{137m}Ba. It is found that the

surface dose rate on a 55- gallon drum containing this gamma ray source distribution is dominated by the presence of the 0.662 MeV photon. In the Monte Carlo calculations to evaluate the effect of voids and point sources, only the 0.662 MeV source associated with one curie of ^{137}Cs was used.

Table 2. Gamma Ray Source Spectrum Associated with One Curie of Tank 241-SY-101 Material

Group	Average Energy, Mev	Source Total photons/sec	Group	Average Energy, Mev	Source Total photons/sec
1	1.500E-02	1.323E+08	12	3.500E-01	5.341E+06
2	2.500E-02	7.545E+07	13	4.750E-01	4.782E+06
3	3.500E-02	1.206E+09	14	6.500E-01	1.443E+10
4	4.500E-02	2.707E+07	15	8.250E-01	2.641E+07
5	5.500E-02	2.371E+07	16	1.000E+00	4.876E+07
6	6.500E-02	1.537E+07	17	1.225E+00	1.042E+08
7	7.500E-02	1.310E+07	18	1.475E+00	1.188E+06
8	8.500E-02	1.113E+07	19	1.700E+00	2.821E+06
9	9.500E-02	9.380E+06	20	1.900E+00	4.236E+03
10	1.500E-01	9.874E+07	21	2.100E+00	3.014E+03
11	2.500E-01	2.277E+07			
TOTAL					1.626E+10

It can be seen in Table 2 that group 14, which is from decay of chain 137 isotopes, accounts for approximately 89% of the photons emitted by this particular mix. More importantly, group 14 contains about 98% of the photon energy associated with the mix. It is for this reason that the surface dose is completely dominated by the presence of ^{137}Cs in the mixture.

It can be concluded from this information that the use of surface dose rate information only provides an indication of the inventory of the 137 mass chain within the waste. The inventory of all other radioisotopes must be inferred from the relationships presented in Table 1. To the extent that Table 1 accurately describes the isotopic mix, there is no error introduced into the categorization of the waste. If the fractional categorization contribution of isotopes other than chain 137 is small compared to chain 137, the uncertainty associated with assuming this particular mix is also small. However, if the fractional categorization contribution of the other radioisotopes is large compared to chain 137, the uncertainty in the categorization will depend on the accuracy of the assumed mix. This situation might be the case if the waste stream mixture had been depleted in ^{137}Cs .

Table 3 presents the category 1 curie limits for the isotopes listed in Table 1 as the mix from waste tank 241-SY-101. If these curie per curie values are weighted with the curie per cubic meter limits in Table 3 and the corresponding fractional limits normalized to unity, then the ^{137}Cs fractional limit becomes 0.854. Thus, for this particular mix, the measured limit for ^{137}Cs , which is essentially the only radioisotope contributing to the external

dose rate, becomes 5.38 millicuries per cubic meter (rather than 6.3 under the assumption ^{137}Cs were the only isotope that was present). The rest of the fractional category 1 limit would be allotted primarily to accommodate ^{90}Sr with negligible contributions from other isotopes. In this table it is assumed that the category 1 limit for U+TRU is 10^{-2} whereas the acceptance criteria (WHC-EP-0063-4) actually provides values for individual isotopes. The value in Table 3 provides a reasonable upper limit assuming that ^{238}U and ^{239}Pu would be dominant isotopes in the mixture.

Table 3. Normalized Fractional Inventory Limits For Waste Tank 241-SY-101 Composition

Isotope	Mix Ci/Ci	^{137}Cs base Ci/m ³	Cat 1 Limit Ci/m ³	Cat 1 Fractional Inventory	Required Fract Inv
U-TRU	3.96×10^{-4}	5.46×10^{-6}	10^{-2}	0	0
^{129}I	1.68×10^{-5}	2.31×10^{-7}	2.9×10^{-3}		
^{94}Nb	5.38×10^{-8}	7.42×10^{-10}	2.6×10^{-4}		
^{14}C	1.10×10^{-6}	1.38×10^{-8}	4.0×10^{-2}		
^{137}Cs	4.57×10^{-1}	6.30×10^{-3}	6.3×10^{-3}	1.000	0.854
$^{137\text{m}}\text{Ba}$	4.32×10^{-1}	5.95×10^{-3}			
^{90}Sr	5.34×10^{-2}	7.36×10^{-4}	4.3×10^{-3}	0.171	0.146
^{90}Y	5.34×10^{-2}	7.36×10^{-4}			
^{99}Tc	4.28×10^{-4}	5.9×10^{-6}	5.6×10^{-3}		
^{79}Se	3.87×10^{-7}	5.0×10^{-9}	3.8×10^{-1}		
$^{93\text{m}}\text{Nb}$	4.57×10^{-6}	6.3×10^{-8}			
^{60}Co	5.94×10^{-4}	8.19×10^{-6}	7.1×10^1		
^{154}Eu	4.25×10^{-3}	5.86×10^{-5}	8.3×10^{-1}		
Total	1.000	1.38×10^{-3}		1.171	1.000

In summary, the categorization of waste based on surface dose rates is constrained by the assumed composition of the radioisotope inventory. The limiting inventory of the measured radioisotope (^{137}Cs for the study mix) needs to be reduced to accommodate the contributions of the non-measured isotopes. Spectral information outside the container might be of marginal value in improving the assay of those other radioisotopes that emit few, if any, photons. If waste streams exist in which isotopes other than ^{137}Cs make a major contribution to the surface dose rate, additional calculations will be required to categorize containers with such mixes.

The curves provided in Appendix A are based on 1 curie of ^{137}Cs . If these curves are used in a situation where, for example, 90% on the instrument response is due to ^{137}Cs decay chain, and 10% due to other isotopes, then as a rough rule of thumb the ^{137}Cs content will be overestimated by 10%, and by extension, everything else as well.

4.2 Source Distribution (Hot Spots)

A basic assumption is made that the radioisotopes are uniformly distributed throughout the non-radioactive carrier material. It is then possible to calculate a six point average surface dose rate that can be compared to the field measurements. Under homogeneous conditions, the correlation between the calculated and measured values is valid and the radioisotope inventory is determined realistically.

4.2.1 Point Source Calculations

It is also possible that the radioisotopes can be localized within the non-radioactive carrier material. The existence of off-center localized sources would be detectable by the asymmetry associated with the six surface point dose rates. That is, the measured dose rate near the localized source would be much higher than those far from the source and much higher than the average dose rate. However, for a hot spot or source distributed near the center of the container, no such asymmetry in the measured dose rates would exist. Calculations were made assuming point sources at various locations to estimate the bias in the derived inventory based on surface dose rate information.

Results of the point source calculations are summarized in Table 4 together with the homogeneous source assumption. The radial location of the point source was either on-axis ($r=0$), or midway between the axis and the surface ($r = R/2$). The height of the point was either at the midplane elevation of the barrel ($h = H/2$), or midway between the surface and the center of the barrel ($h = H/4$). The results are also illustrated in Figure 1, comparing a central point source with a homogeneous distribution as a function of the mass of waste within the drum.

Table 4. Calculated Surface Dose Rates (R/hr per Ci) Associated With ^{137}Cs for Homogenous and Point Sources

Mass (Kg)	Source Location	Radial Average	Axial Average	6 Pt. Average
0	Uniform	2.203	2.163	2.190
	OR , 0.5H	2.560	1.290	2.137
	OR , 0.75H	1.828	2.321	1.992
	0.5R, 0.5H	3.089	1.189	2.456
	0.5R, 0.75H	1.909	1.879	1.899
100	Uniform	1.582	1.612	1.592
	OR , 0.5H	1.737	0.666	1.380
	OR , 0.75H	1.111	1.645	1.289
	0.5R, 0.5H	2.278	0.585	1.714
	0.5R, 0.75H	1.213	1.249	1.225
300	Uniform	0.825	0.953	0.868
	OR , 0.5H	0.515	0.088	0.373
	OR , 0.75H	0.246	0.680	0.391
	0.5R, 0.5H	1.014	0.072	0.700
	0.5R, 0.75H	0.360	0.440	0.387
400	Uniform	0.645	0.770	0.687
	OR , 0.5H	0.251	0.027	0.176

Figure 1. Inventory Uncertainty Associated With Source Distribution

It can be seen in Table 4 that in the case of low weight containers the average measured surface dose rate is similar for both centrally located sources or hot spots and homogeneous source distributions. However, for heavily loaded containers, the central point source yields a significantly lower average surface dose rate. The measurements would only detect the presence of hot spots that are significantly off-center. All of these differences do not appear in the calculated results (Table 4) because only circumferential and axial averages were obtained as opposed to discrete locations. It is possible to calculate dose rate information at discrete positions around the drum, but this was not done in these cases because of the computer time involved. However, such asymmetry would be apparent from the measurements, indicating that special processing of the results would be appropriate to reduce the uncertainty associated with the off-center hot spot.

Because it is not possible to differentiate between centrally located hot spots and homogeneous distributions, it is concluded that the only way to accommodate the uncertainty in a conservative manner is to assume that all readings are associated with centralized sources. As illustrated in Figure 1, the assumption of a central hot spot would introduce a conservative bias of up to almost 400% at the maximum drum waste weight of 400 kg. The uncertainty introduced by the potential that centrally embedded sources could exist is far

greater than that introduced by other parameters. Because of the small probability that an ideally located centralized hot spot exists, it is realistic to assume the source is homogeneous unless asymmetric dose rate readings are obtained.

4.2.2 Small Sector Source Calculations

As a result of the information derived from the point source calculations described previously, an additional series of Monte Carlo calculations was made using the computer code MCNP (Briesmeister 1993 and Carter 1994). The 55-gallon drum model was divided into 205 equal source regions, consisting of five layers with each layer containing 41 sectors, as illustrated in Figure 2. Dose rates were calculated at each of the six surface dose rate measurement locations (radial positions are indicated in Figure 2) for a unit source in each of the 205 source regions. By symmetry there are only 27 unique source-detector relations. The calculations were made for only one material (concrete) at a loading weight of 300 kg. Results of these calculations are summarized in Table 5. The Source Mesh index "k" identifies the layer, where 1 is at the bottom of the drum and 3 at the midplane elevation of the drum. The Source Mesh index "i" is associated with the sector within a layer, as illustrated in Figure 2. The Source Index 0,0 is for one curie of ^{137}Cs homogeneously distributed throughout the drum.

The six listed Detector Response values for each Source Mesh are for the four radial positions and the bottom and top, respectively. The Average column is the simple average of the six readings in R/hr per Ci of ^{137}Cs in the individual Source Mesh sector. The Maximum/Average column provides the ratio of the maximum detector reading to the average for the particular unit source. The Curie Ratio column provides the inventory that would be derived by assuming the unit source was homogeneously distributed rather than being in the local sector.

It is obvious from these results that the homogeneous assumption will seldom give an accurate inventory if the source is actually heterogeneously distributed. If a small source is located adjacent to one of the detectors the resultant Maximum/Average will be quite large (greater than 5.5) and the inventory will be quantified conservatively. However, if the Maximum/Average ratio is in the range 1.2-5.5, the inventory would be quantified non-conservatively under the assumption of homogeneity. In the extremely rare event of a centrally distributed hot spot, the Maximum/Average reading could be similar to that associated with a homogeneous distribution, yet the inventory determination would be quite non-conservative. These results are consistent with the point source calculations.

If asymmetric dose rate readings are measured around the waste container, it is theoretically possible to unfold a source inventory that would yield such a distribution. Computer codes exist for providing this service, but these have not been tested for this particular application. It would not be possible to quantify an inventory if the local source were centrally located, thereby generating a surface dose rate distribution similar to that associated with homogeneously distributed sources.

Table 5. Inventory Ratio: Homogeneous to Non-Homogeneous Source Distribution

Source k	Mesh i	Detector Responses (mrem/hr)			Average	Maximum/ Average	Curie Ratio
1	1	0.1039E+03 0.1039E+03	0.1039E+03 0.2075E+03	0.1039E+03 0.1941E+01	0.3528E+04	5.88	4.08
1	2	0.1874E+03 0.1009E+03	0.1009E+03 0.1168E+05	0.5199E+02 0.2241E+01	0.2021E+04	5.78	2.34
1	6	0.3209E+03 0.8365E+02	0.8365E+02 0.5748E+04	0.2846E+02 0.1761E+01	0.1044E+04	5.50	1.21
1	7	0.2099E+03 0.3824E+02	0.2099E+03 0.5748E+04	0.3824E+02 0.1761E+01	0.1041E+04	5.52	1.20
1	14	0.5521E+03 0.6470E+02	0.6470E+02 0.2886E+04	0.1518E+02 0.1432E+01	0.5973E+03	4.83	0.69
1	15	0.3876E+03 0.3123E+02	0.1639E+03 0.2886E+04	0.1782E+02 0.1432E+01	0.5813E+03	4.96	0.67
1	26	0.1125E+04 0.4552E+02	0.4552E+02 0.1486E+04	0.7772E+01 0.1320E+01	0.4519E+03	3.29	0.52
1	27	0.8095E+03 0.2168E+02	0.1070E+03 0.1486E+04	0.9815E+01 0.1320E+01	0.4059E+03	3.66	0.47
1	28	0.3200E+03 0.1321E+02	0.3200E+03 0.1486E+04	0.1321E+02 0.1320E+01	0.3590E+03	4.14	0.41
2	1	0.3219E+03 0.3219E+03	0.3219E+03 0.9732E+03	0.3219E+03 0.1407E+02	0.3791E+03	2.57	0.44
2	2	0.6969E+03 0.3098E+03	0.3098E+03 0.8585E+03	0.1392E+03 0.1343E+02	0.3879E+03	2.21	0.45
2	6	0.1462E+04 0.2475E+03	0.2475E+03 0.6672E+03	0.7189E+02 0.1141E+02	0.4513E+03	3.24	0.52
2	7	0.8015E+03 0.9849E+02	0.8015E+03 0.6672E+03	0.9849E+02 0.1141E+02	0.4131E+03	1.94	0.48
2	14	0.3093E+04 0.1830E+03	0.1830E+03 0.4547E+03	0.3441E+02 0.1002E+02	0.6597E+03	4.69	0.76
2	15	0.1809E+04 0.7407E+02	0.5739E+03 0.4547E+03	0.4199E+02 0.1002E+02	0.4939E+03	3.66	0.57
2	26	0.6871E+04 0.1210E+03	0.1210E+03 0.2796E+03	0.1746E+02 0.7732E+01	0.1236E+04	5.56	1.43
2	27	0.3962E+04 0.5248E+02	0.3436E+03 0.2796E+03	0.1917E+02 0.7732E+01	0.7774E+03	5.10	0.90
2	28	0.1200E+04 0.2849E+02	0.1200E+04 0.2798E+03	0.2849E+02 0.7732E+01	0.4573E+03	2.62	0.53
3	1	0.5083E+03 0.5083E+03	0.5083E+03 0.1068E+03	0.5083E+03 0.1068E+03	0.3745E+03	1.36	0.43
3	2	0.1235E+04 0.4871E+03	0.4871E+03 0.1015E+03	0.2045E+03 0.1015E+03	0.4361E+03	2.83	0.50
3	6	0.3016E+04 0.3876E+03	0.3876E+03 0.8566E+02	0.9641E+02 0.8566E+02	0.6765E+03	4.46	0.78
3	7	0.1470E+04 0.1404E+03	0.1470E+04 0.8566E+02	0.1404E+03 0.8566E+02	0.5654E+03	2.60	0.65
3	14	0.8414E+04 0.2711E+03	0.2711E+03 0.6764E+02	0.4586E+02 0.6764E+02	0.1523E+04	5.52	1.76
3	15	0.3953E+04 0.1033E+03	0.9764E+03 0.6764E+02	0.5760E+02 0.6764E+02	0.8710E+03	4.54	1.01
3	26	0.3179E+05 0.1712E+03	0.1712E+03 0.4693E+02	0.2156E+02 0.4693E+02	0.5375E+04	5.91	6.21
3	27	0.1102E+05 0.7256E+02	0.5398E+03 0.4693E+02	0.2540E+02 0.4693E+02	0.1958E+04	5.63	2.26
3	28	0.2253E+04 0.3761E+02	0.2253E+04 0.4693E+02	0.3761E+02 0.4693E+02	0.7793E+03	2.89	0.90
0	0	0.8226E+03 0.8226E+03	0.8226E+03 0.9501E+03	0.8226E+03 0.9501E+03	0.8651E+03	1.10	1.00

Figure 2. Small Sector Source Distribution

Whenever the six surface dose rate readings are not essentially identical, the source is not homogeneously distributed throughout the container. Under these conditions it is not realistic to use the homogeneous assumption to quantify the inventory. The problem of conservatively quantifying the inventory when the Maximum/Average dose rate reading is greater than the value associated with a homogeneous distribution can be handled as follows:

- i. In addition to a homogeneous source curve, generate a worst case "hidden" source curve for each type of container relating R/hr per Ci as a function of weight. This could be done using either a central point source or a centralized volume source.
- ii. If the Maximum/Average reading is significantly greater than unity, use the "hidden" source curve to categorize the waste. If this procedure indicates the waste is below Category 1 limits, it can safely be handled as Category 1 material. If the container exceeds Category 1 limits under this assumption, either unfold a realistic inventory using the individual dose rate readings, or use an alternate method (e.g. barrel assayer).
- iii. If the Maximum/Average reading is close to unity, the homogeneous R/hr per curie curve may be used to quantify the inventory. If the inventory exceeds the Category 1 limit using the homogeneous curve, it can safely be assumed the limit is exceeded even if the contents are heterogeneous.

4.3 Impact of Voids

Although it can probably be established that a drum or container is not full by tapping on the surface, it is not possible to identify and locate with accuracy all the void regions that might exist. To obtain an estimate of the uncertainty introduced by the possible existence of void regions, calculations were made by introducing idealized 10% void regions at three locations within a 55-gallon drum. The density of the rest of the region was increased in order to maintain the mass of waste within the container the same as in the homogeneous base case. The three void cases included a cylinder located at the center of the drum, an annular region at the midplane elevation surface, and a flat cylinder at one end of the drum. Results of the calculations are summarized in Table 6.

Table 6. Calculated Surface Dose Rates Associated with ^{137}Cs for Voids In Homogeneous Material (200 kg concrete)

Void Location	Radial Average	Axial Average	6 Point Average
No Void	1.116	1.211	1.148
Top 10% Void	1.144	1.048	1.112
Center 10% Void	1.138	1.275	1.184
Annulus 10% Void	1.023	1.278	1.108

Although only a limited number of void distributions was considered, the results indicate that the determined inventory is insensitive to the presence of voids. Thus, it is practical to assume that no voids exist within otherwise homogeneous material because the bias introduced by this assumption is small, less than 5% for the weight and voids that were calculated. Additional calculations could be made at various masses to determine the effect of voids as a function of waste weight.

It is not intuitively obvious that the presence of a void within homogeneous material will in all cases introduce only a small bias into the inventory determination. The limited number of configurations that were calculated indicate that the enhanced attenuation associated with the denser material (to maintain weight constant) offsets the distance variation introduced by the void. This tradeoff between distance and density exists in the calculated cases and apparently explains the small effect introduced by the presence of voids. As in the case of the off-center point sources, off-center and asymmetric voids are expected to generate asymmetric dose rate readings that would indicate a need for more detailed evaluation of the data than simply using the average dose rate based on a homogeneous distribution.

Based on the single 200 kg case, the existence of voids within homogeneous waste material is calculated to introduce a relatively small bias in the inventory determined from surface dose rate measurements. This bias could be accommodated by including an appropriate uncertainty factor. Additional calculations would be required to establish the uncertainty as a function of weight. Any significant asymmetry in the dose rate readings would be the basis for more detailed and rigorous evaluation of the dose rate information, including the potential that voids exist.

In summary, the effect of voids within otherwise homogeneously distributed material does not appear to introduce a significant bias into the inventory determination. Of greater concern would be the combination of voids and heterogeneous source distributions. It is not practical to pursue this complication in detail. It is believed that the assumption of source heterogeneity will adequately accommodate the potential that localized voids also exist.

4.4 Elemental Composition of Contents

Figure 3 presents the result of Monte Carlo calculations of the cesium inventory (curies per R/hr) in a 55-gallon drum as a function of waste weight for various assumed elemental compositions of the material based on the six point average surface dose rate and a homogeneous source distribution. It can be seen that the inventory determination is relatively insensitive to the elemental composition of the waste material. In many cases the composition of the material in a drum is known and can be included directly in the calculation. The uncertainty associated with the composition will introduce a small uncertainty in the derived inventory when compared to other sources of uncertainty. When the elemental composition is not known, a conservative determination can be made by assuming a worst case composition.

Figure 3. Curie Inventory as a Function of Barrel Mass for Various Materials.

The fact that the surface dose rate is relatively insensitive to the elemental composition of the material is related primarily to the source energy (0.662 MeV) and the atomic number of the materials considered. At first there was concern that the dose rate contribution of down-scattered photons might be significantly different in (for example) carbon and iron-rich mixtures. However, these Monte Carlo calculations, which rigorously take this effect into account, do not indicate a large difference. Early point kernel calculations with ISOSHL (Engel 1966, Rittman 1995) indicated significant differences as a function of composition. These differences appear to be associated with limitations associated with the buildup factors required in point kernel calculations. This does not negate the value of using point kernel calculations for dose rate calculations, it simply indicates that the method has accuracy limitations.

In summary, Monte Carlo calculations show that the uncertainty in the elemental composition of the waste will introduce a very small uncertainty in the inventory determination based on the six point average surface dose rate measurements. If necessary, the small bias can be made conservative by assuming the worst-case composition for all containers.

4.5 Dose Rate Measurements

Dose rate measurements in the field are made routinely using a survey instrument called the CP or Cutie Pie. This device consists of an "air equivalent" wall ionization chamber three inches in diameter by four inches long. This chamber is permanently attached to the electronic instrumentation that creates an electric field within the chamber and measures the current that is generated by ionization produced by the interaction of the photon field with the gas in the chamber. The meter is calibrated to read the radiation field directly rather than the magnitude of the current. The instrument has four linear ranges of operation: 0 to 5 mR/hr, 0 to 50 mR/hr, 0 to 500 mR/hr, and 0 to 5000 mR/hr. Linearity is + 5% of full scale. Response time is relatively rapid, requiring only about 5 seconds on the lower range scales to achieve 90% of the final reading.

For gamma ray measurements, the thin film end of the chamber is covered by a phenolic resin shield to eliminate the potential contribution of beta rays. With the shield in place, the chamber has a uniform response to photons in the energy range from about 0.1 MeV up to about 1.3 MeV. With temperature corrections, the instrument can be used from -20° F up to 120° F; however, in the temperature range from about 50° F to 90° F the correction factor is less than 5%. When properly calibrated and used in the field, the dose rate readings are valid to better than $\pm 10\%$. However, the minimum reliable reading is greater than 0.1 mR/hr, and great care is required to obtain meaningful readings in the low range. Count rate instruments should be used to measure gamma ray fields less than about 0.5 mR/hr.

There is a calculated gradient in the dose rate near the surface of a drum or container. In order to determine the magnitude of this gradient, Monte Carlo calculations were made at the surface of a drum and at distances of two, four, and six inches. With the end window of the CP held against the surface of the 55-gallon drum, the integral of the dose rate over the volume of the CP chamber is almost identical to the calculated dose rate at a distance of two inches. Therefore, the calculated dose rates at a distance of two inches were used for comparison to measured dose rates. The bias associated with this assumption is estimated to be less than 2%.

It is concluded that the major uncertainty associated with relating the calculations to the measurements is that of the measurements. Under the assumption that the measurements are made carefully (i.e., held steady in the measurement position for greater than five seconds and read so as to eliminate parallax or other effects), the uncertainty associated with the measurements in the higher ranges is about 10%. At the low end of the most sensitive range the uncertainty in the reading is estimated to be 100 percent.

Another uncertainty introduced into the dose rate reading is that associated with background radiation. If the waste container were far removed from other containers, the background gamma ray field would probably be small (of the order of 0.01 mR/hr) and not bias the readings. However, if the surface dose rate readings are made in the presence of other waste containers, care needs to be exercised to assure that the background dose rate does not bias the measurements. If the background dose rate is on the order of tenths of an mR/hr, the background might severely compromise the ability to categorize accurately the material within a given container.

4.6 Calculational Accuracy

The dose rate calculations in this study were made using the Monte Carlo method as incorporated in the MCNP computer code (Briesmeister 93, Carter 94). This is the most accurate method available today. The geometry can be incorporated in as much detail as desired, eliminating the need for any uncertainty associated with this parameter. Cross sections are pointwise from the evaluated file ENDF/B-V. Photon cross sections are well known and not subject to the resonance phenomena associated with neutrons. Finally, the flux-to-dose conversion factors are those contained in the latest (1991) ANSI standard. Enough case histories were calculated to assure reliable statistics. It is concluded that the uncertainty introduced by the calculations is less than 5% in all cases.

As described in the previous section, calculations were made as a function of distance from the surface of the barrel to establish that the calculated dose rate at a distance of two inches was valid for comparison to the dose rates measured by the CP. Also, as described in previous sections, it was possible to determine the uncertainty associated with localized hot spots or point sources, and that associated with voids. The uncertainty introduced by the specific calculations is minimal; however, it must be recognized that an infinite combination of localized sources and voids is possible and their impact must be inferred from the limited number of calculations that was made. Based on these studies, it has been concluded that the limiting uncertainty is introduced by the potential for localized sources near the center of the container.

As discussed in Section 4.4, the Monte Carlo calculations indicate very little dependence on the elemental composition of the contents whereas the point kernel calculations showed a significant dependence. In addition, a significant non-conservative bias (for this application) was associated with the point kernel results. This non-conservative bias associated with point kernel calculations when compared to the more rigorous Monte Carlo calculations indicates that Monte Carlo, rather than point kernel, should be employed to generate the relationship between inventory and dose rate. If point kernel calculations were to be employed, it would be necessary to do Monte Carlo calculations in order to establish the magnitude of the non-conservative bias in order that it might be accommodated in the categorization

process. This redundancy can be eliminated by simply doing the calculations using only the Monte Carlo method.

4.7 Weight

The uncertainty associated with the weight of the waste material can be inferred from the curves obtained from the parametric calculations. No attempt was made in this study to quantify the uncertainty associated with weight. Given the uncertainty in weight (as a function of weight) it would be possible to determine the impact of the weighing accuracy on the inventory determination. It is believed that this uncertainty will be relatively small.

5.0 DISCUSSION

It is concluded from this study that the primary problem associated with quantifying the radioisotope inventory in 55-gallon drums or other waste containers is the potential non-conservative bias that might be introduced by the presence of localized sources near the center of the container as illustrated in Figure 4. Because of the symmetry that can be associated with such sources, there is no known way (based solely on surface dose rate information) to differentiate such sources from near-homogeneous source distributions. Therefore, given no additional information or basis, it is necessary to assume the existence of such sources to assure that the radioisotope inventory is conservatively defined. Figure 4 illustrates the uncertain zone in defining Category 1 waste in 55-gallon drums because of worst-case potential source inhomogeneities. Because of the small probability that the worst-case scenario exists, it would be practical to assume homogeneity when the individual dose rate readings are close to the average. However, when the Maximum/Average ratio significantly exceeds unity, it is a strong indication that the source is not homogeneously distributed.

The next most important source of uncertainty is that associated with the mix of radioisotopes. The surface dose rate is only associated with the higher energy photons emitted by the radioisotopes that are present. For the given mixture of isotopes from Tank 241-SY-101, the surface dose rate is almost entirely associated with the 0.662 MeV photon from the chain decay of ^{137}Cs - ^{137m}Ba . The inventory of all other radioisotopes must be inferred from the assumed mix. Gamma-ray spectrometer measurements might assist in assaying the inventory of other radioisotopes; however, detection of some photon emitters might be severely compromised by the downscattering associated with the attenuation of higher energy photons. cursory examination of barrel scanner measurements indicates that isotopes other than chain 137 are seldom quantified except by noting that the limiting value has not been detected. In any case, spectrometry is a more time consuming process than the field dose rate measurements and would only need to be utilized if the field method determination fails to assure proper categorization.

Figure 4. Uncertainty in 55-gallon Drum Characterization Because of Potential Source Inhomogeneity

Although only a few calculations were made to evaluate the impact of void regions within the container, these indicated that the uncertainty introduced by the voids is relatively small. Additional calculations would be required to quantify the uncertainty as a function of waste weight. Because it is not possible to evaluate all possible void configurations, there may be distributions where the estimates are not valid. Of particular concern would be situations where both localized sources and voids exist. It is not practical to pursue this problem in detail and it must be assumed that accommodating heterogeneous source distributions will also accommodate distributed voids.

The presence of either voids or hot spots can introduce significant asymmetries into the dose rates measured at the six surface dose point. For a homogeneous source distribution, all six of the 55-gallon drum surface dose rate readings will be within about 10% of the average. If one or more of the individual readings differs from the average significantly, it would be a strong indication that either localized hot spots and/or voids exist. In such cases more detailed evaluation using the individual (rather than the six point average) dose rate readings could be used to quantify the inventory.

Alternatively, limiting inventories could be calculated assuming worst-case hidden local sources. Preliminary calculations in which the volume of the barrel was divided into a number of small source regions indicates the potential for reducing the inventory uncertainty associated with off-centered hot spots. However, the method would not be able to differentiate between centralized hot spots and homogeneous distributions.

6.0 RESULTS

A procedure for using surface dose rate measurements to categorize and inventory the radioactive waste in standard low level waste containers is given in Appendix A. This procedure has also been disseminated as a separate document. (WHC-SD-WM-PROC-020).

7.0 FUTURE WORK

Similar calculations are required to quantify the uncertainty associated with categorizing the waste material within other containers, such as wood or metal boxes of standard size. Based on the calculations for the 55-gallon drum, the uncertainty associated with the larger containers is expected to be greater and the sensitivity is expected to be reduced. However, these effects are not expected to invalidate the application of the method to the larger containers. Calculations are required to quantify these conclusions.

In addition to establishing the sensitivity and uncertainty associated with the six point average dose rate method for categorizing waste in other containers, the improvement that can be made in using the individual dose rate readings (as opposed to the average) needs to be evaluated to establish the ultimate limit that can be achieved based solely on surface dose rate information. As a follow on to these dose rate studies, the incremental improvement that might be achieved using gamma ray spectral information should be evaluated. In addition to simply identifying the source radioisotopes, it is anticipated that spectral information can be employed to differentiate between localized and homogeneous sources. Such information could clearly reduce the uncertainty associated with quantifying the radioisotope inventory within a sealed container.

8.0 ACKNOWLEDGMENTS

The Monte Carlo calculations used to prepare this report were performed by Jay Lan and Lee Carter. The input data concerning isotopic compositions, gamma ray spectra, container dimensions, waste categorization limits, and instrument details were supplied by Dave Hetzer. Technical assistance in defining and interpreting the analytical results was provided by Lee Carter and Jess Greenborg. It is only through the efforts of these individuals that this study was completed.

9.0 REFERENCES

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APPENDIX A

PROCEDURE FOR CATEGORIZING AND INVENTORYING WASTE IN STANDARD CONTAINERS

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PROCEDURE FOR CATEGORIZING AND INVENTORING WASTE IN STANDARD CONTAINERS

1.0 INTRODUCTION

The attached procedure is a method for using surface dose rate measurements to categorize and inventory the radioactive waste in a container. This procedure is based on calculations that relate the inventory to the surface dose rate (Gedeon 1996).

2.0 BASIS AND ACCURACY

These calculations (Gedeon 1996) also examined the parameters that affect the surface dose rate-to-radioisotope inventory relationship. This leads to the following conclusions and requirements:

1. The surface dose rate is relatively insensitive to the composition of the waste material; therefore, a single (upper limit composition) curve yields a mildly conservative inventory. This conservative bias accommodates some of the uncertainty associated with the method.
2. For the waste streams evaluated, the surface dose rate is dominated by ^{137}Cs . By assuming the surface dose rate defines the inventory of ^{137}Cs , a conservative bias is introduced into the overall inventory determination and categorization. The greater the surface dose contribution of isotopes other than ^{137}Cs , the greater the bias. These conservative biases generally accommodate the uncertainty of the method.
3. This procedure is only applicable if ^{137}Cs is known to exist in the waste in significant amounts.
4. This procedure should not be used if the waste is known to contain sufficient quantity of other dose dominate isotopes, such as ^{60}Co .
5. Voids, located within otherwise uniformly distributed waste material, will not introduce significant error into the inventory determination.
6. Localized source concentrations, other than those centrally distributed, can be detected by the variation in individual surface dose rate readings from the average. For standard containers, a Max/Avg ratio greater than 2.5 indicates the source distribution to be significantly heterogeneous.

7. If there is reason to believe the inventory is approximately a centrally located point source or other significantly heterogeneous source, it is always conservative to assume the point source option. Alternately the container can be analyzed outside of this procedure as a special case.
8. Measured dose rates are to be contact readings made with a CP meter. The calculations assume that the center of the CP detector volume is approximately 2 inches from the container surface. If an instrument other than a CP is used, care must be taken to ensure that the center of that detector volume is 2 inches from the container surface.
9. The 6 points where the dose rates should be measured are the geometric center of each face of the container. For barrels, four of the measurements should be taken 90° apart on the circumference, half-way along the length of the barrel.
10. For large containers, it may be necessary to take more than 6 readings. An alternative procedure is available for use with 4' x 4' x 8' wood boxes. Specifically, if general contact readings along the length of the box vary by a factor of 2.5 or more, then a 14 point survey should be performed.

The supporting calculations (Gedeon 1996) were performed with the MCNP (Monte Carlo N-Particle) computer code (Briesmeister et al 1993, Carter 1994).

3.0 PROCEDURE

1. Enter the curies of each isotope in the waste stream mix in column 2 of Table 1. Attach a reference copy of the Waste Stream Mix to the table or identify an appropriate reference.
2. Sum the curie values in column 2 and enter the value at the bottom of the column in the space for Σ .
3. Normalize the waste stream mix of Category 1 constituents by dividing the curie value of each isotope in column 2 by the sum Σ of column 2. The sum of column 3 should be unity.
4. Obtain the six surface dose rate values and enter these in the work sheet, including information concerning the radiation detector (see item 8, above). An optional 14 point survey work sheet is available for 4' x 4' x 8' wood boxes. This option should be selected if the dose varies along the length of the box by more than a factor of 2.5.

5. Obtain average surface dose rate by summing the six readings (14 readings if that option is selected) and dividing the sum by six (or 14 if applicable). Subtract background. Record corrected average on work sheet.

Note: Convert the corrected average value reading into units R/hr even though they were obtained as cpm, mR/hr, or other.

6. Divide the background corrected maximum of the six individual readings by the background corrected average value and enter this on the worksheet as the Max/Avg value.
7. Weigh the waste container and enter this value on the worksheet.
8. Subtract the standard empty container weight from the gross weight obtained in step 7 and enter this net weight value on the worksheet.
9. Using the net weight from step 8, go to the appropriate attached figure for the type of container to determine the Ci of ^{137}Cs per R/hr. If the Max/Avg value in step 6 is equal to or less than 2.5, use the homogeneous (distributed source) curve. If the Max/Avg value from step 6 is greater than 2.5 use the heterogenous (point source) curve, or subject the container to an alternative assay procedure or a case-by-case assessment.
10. Multiply the Ci of ^{137}Cs per R/hr from step 9 by the average surface dose rate value (in R/hr) from step 5. Enter this curie value of ^{137}Cs in column 4 in the ^{137}Cs row of Table 1.
11. Divide the Ci value for ^{137}Cs in Column 4 by the value for ^{137}Cs in column 3 and enter this value in the space for "factor" at the top of column 4. This is the factor for quantifying the curie inventory of other radioisotopes.
12. Multiply each curie value in Column 3 by the normalizing "factor" at the top of Column 4 (see step 11) and enter the resulting value for each isotope in the appropriate row in Column 4.
13. Enter the standard volume of the container on the worksheet.
14. Divide the curie inventory in each row of Column 4 by the standard container volume from the worksheet to obtain the curies per cubic meter for each radioisotope that has a known Category 1 limit.
15. Divide the curie concentration of each isotope in Column 5 by its Category 1 limit listed in Column 6 and enter the resulting value in Column 7 as the fractional contribution of the isotope.

Note: The fractional contributions might vary by several orders of magnitude; therefore, care must be taken in recording each value.

16. Sum the fractional contributions of each isotope in Column 7 to obtain the value for the container. Enter this value at the bottom of Column 7.

Note: Be sure the decimal point for each fractional contribution is correctly taken into account.

WORKSHEET FOR STANDARD CONTAINERS

SURFACE DOSE RATE MEASUREMENTS

Instrument _____ Calib or Cert _____

Surface dose rates

Side 1	_____	
Side 2	_____	Max Reading _____
Side 3	_____	Background (-) _____
Side 4	_____	Max Net value _____
Top	_____	
Bottom	_____	

Sum	_____	divide by 6 = _____
		Background (-) _____
		Average _____

Max/Avg = _____

CONTAINER INFORMATION

Type _____ Empty weight _____ kg Volume _____ m³

Scale information _____

Gross weight	_____	(kilograms)
Empty weight	_____	(kilograms)
Net weight	_____	(use this value in step 9)

OPTIONAL WORKSHEET FOR LARGE WOODEN BOX (4' x 4' x 8')

SURFACE DOSE RATE MEASUREMENTS

Instrument _____ Calib or Cert _____

Surface dose rates*

Side 1	_____	_____	_____
Side 2	_____	_____	_____
Side 3	_____	_____	_____
Side 4	_____	_____	_____
End 1	_____	_____	_____
End 2	_____	_____	_____

Max Reading _____
 Background (-) _____
 Max Net value _____

Sum _____ divide by 14 = _____
 Background (-) _____
 Average _____

Max/Avg = _____

CONTAINER INFORMATION

Type 4' x 4' x 8' wood box Empty weight 277 kg Volume 3.6 m³

Scale information _____

Gross weight _____ (kilograms)
 Empty weight _____ (kilograms)
 Net weight _____ (use this value in step 9)

*Measurements should be taken at 2 foot intervals along the long centerline of the long (4' x 8') faces, and at the center of the end (4' x 4') faces.

Table 1. Calculational Worksheet
(Sheet 1 of 2)

(1) ISOTOPE	(2) WASTE STREAM MIX, Ci	(3) NORMALIZED MIX Ci/Ci	(4) Ci/CONTAINER Factor =	(5) Col (4) ÷ VOLUME	(6) CATEGORY 1 LIMIT Ci/m3	(7) CATEGORY 1 FRACTION (5)/(6)
14C					4.0 E-2	
60Co					7.7 E+1	
79Se					3.8 E-1	
94Nb					2.6 E-3	
90Sr					4.3 E-3	
99Tc					5.6 E-3	
129I					2.9 E-3	
137Cs					6.3 E-3	
154Eu					8.3 E-1	
235U					3.2 E-3	
238U					6.3 E-3	
237Np					1.9 E-4	
238Pu					9.1 E-3	
239Pu					3.6 E-3	
240Pu					3.6 E-3	
241Pu					7.7 E-2	
242Pu					3.8 E-3	
241Am					2.6 E-3	
243Cm					2.5 E-2	

Table 1. Calculational Worksheet
(Sheet 2 of 2)

(1) ISOTOPE	(2) WASTE STREAM MIX. Ci	(3) NORMALIZED MIX Ci/Ci	(4) Ci/CONTAINER Factor = _____	(5) Col (4) × VOLUME	(6) CATEGORY 1 LIMIT Ci/M3	(7) CATEGORY 1 FRACTION (5)/(6)
244Cm					2.3 E-1	
245Cm					2.1 E-3	
	Σ =	1.000				f =

Figure 1. Dose Rate to Curie Conversion Factor 55 Gal. Drum

Figure 2. Dose Rate to Curie Conversion Factor 85 Gal. Drum

Figure 3. Dose Rate to Curie Conversion Factor 3' x 3' x 6' Metal Box

Figure 4. Dose Rate to Curie Conversion Factor 2' x 2' x 6' Metal Box

Figure 5. Dose Rate to Curie Conversion Factor 5' x 5' x 9' Metal Box

Figure 6. Dose Rate to Curie Conversion Factor 5' x 5' x 6' Metal Box (LMB III)

Figure 7. Dose Rate to Curie Conversion Factor 4' x 4' x 8' Wood box

Figure 8. Dose Rate to Curie Conversion Factor 4' x 4' x 7.5' Metal Box

Figure 9. Dose Rate to Curie Conversion Factor 4' x 4' x 8' Wood Box

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APPENDIX B
CURVE DATA

The curves of Appendix A are given below in tabular form.

a. 4'x4'x8' Wood Box			14H	14P
mass	H6	P6		
(kg)	curies	Cs-137	per R/hr	
200.	2.7119	2.2872	2.74788	2.75529
600.	3.2410	2.790	3.25933	3.49382
1000.	3.8826	3.548	3.92306	4.50067
1400.	4.6276	4.7398	4.71094	6.50798
1600.	5.4481	6.5505	5.40301	9.42129
2200.	6.3172	9.0308	6.38805	13.8321

b. 2'x2'x6' Metal Box

50.	1.0591	.67415
100.	1.1387	.72174
200.	1.3141	.83094
300.	1.5170	.97078
400.	1.7336	1.1899
500.	1.9919	1.4248

c. 3'x3'x6' Metal Box

100.	1.6216	1.3112
200.	1.7689	1.4378
300.	1.9251	1.6000
400.	2.1077	1.7730
500.	2.2738	2.0045
600.	2.4850	2.2588
700.	2.6818	2.6146

d. 5'x5'x6' Metal Box

500.	3.3401	3.3404
1000.	4.2186	4.6362
2000.	6.4888	11.3791
3000.	9.0519	30.5265
4000.	11.734	91.3122
4500.	13.136	155.558

e. 5'x5'x9' Metal Box

200.	3.8326	3.2070
500.	4.2612	3.5585
1000.	5.0704	4.3882
1500.	5.9971	5.3545
2000.	7.1407	7.1907
2500.	8.2883	9.9511

f. 4'x4'x7.5' Metal Box

200.	2.6873	2.2186
------	--------	--------

500.	3.1306	2.6307
1000.	4.0295	3.7243
1500.	5.1725	5.7823
2000.	6.3640	8.8880
2500.	7.7235	14.436

g. 55 Gallon Drum

10.	4.72573e-1	4.84584e-1
45.	5.25268e-1	5.56471e-1
90.	6.11092e-1	6.85095e-1
135.	7.10047e-1	8.68627e-1
180.	8.19025e-1	1.14727e+0
226.	9.43994e-1	1.56209e+0
408.	1.48363e+0	5.88022e+0

h. 85 Gallon Drum

100.	7.40921e-1	8.23907e-1
200.	9.51925e-1	1.22112e+0
300.	1.21126e+0	1.97773e+0
400.	1.48191e+0	3.43433e+0
500.	1.78062e+0	5.85571e+0
600.	2.07687e+0	1.07479e+1

APPENDIX C
FILE LISTING

All computer files associated with this work reside on the Hanford Scientific and Engineering Computer Center UNIX network in the directory /home_area/w80502/projects/doseconv. A complete listing of files is given in Appendix C.

contents of:

/home_area/w80502/projects/doseconv

55gal.drm	5metal.box	7metal.box	8metal.box	mcnp-sg.wpBK!
55gb.200	6mb.200	85gal.drm	9mb.200	memol.wp
55gp.200	6mbp.200	85gb.200	9mbp.200	memol.wpBK!
5mb.200	6metal.box	85gp.200	9metal.box	wb.200
5mb.50	7mb.500	8mb.200	files	wbp.200
5mbp.200	7mbp.500	8mbp.200	mcnp-sg.wp	wood.box

/home_area/w80502/projects/doseconv/55gal.drm

51b900.a	55b200.a	55gb22.p	55gp22.u	dbat40
51b900.p	55b200.p	55gb22.u	55p100.a	dbat41
51b900.u	55b200.u	55gp.100	55p100.p	dcinp
51gb.900	55gb.100	55gp.200	55p100.u	ddinp
51gp.900	55gb.200	55gp.22	55p200.a	flux2dose
51p900.a	55gb.22	55gp.300	55p200.p	inp
51p900.p	55gb.300	55gp.400	55p200.u	inpn
51p900.u	55gb.400	55gp.500	dbat10	inpn1
55b100.a	55gb.500	55gp.900	dbat11	outp
55b100.p	55gb.900	55gp22.a	dbat20	psource
55b100.u	55gb22.a	55gp22.p	dbat30	

/home_area/w80502/projects/doseconv/85gal.drm

85gb.100	85gb.500	85gp.300	dbat16	inp
85gb.200	85gb.600	85gp.400	dbat17	outp
85gb.300	85gp.100	85gp.500	dbat18	psource
85gb.400	85gp.200	85gp.600	flux2dose	

/home_area/w80502/projects/doseconv/5metal.box

5ab200.a	5ap200.o	5bp50.ta	5mbp.300	dbat3
5ab200.o	5ap200.p	5bp50.tp	5mbp.400	dbat4
5ab200.p	5ap300.a	5bp500.o	5mbp.50	dbat4a
5ab300.a	5ap300.o	5mb.100	5mbp.500	dbat5
5ab300.o	5ap300.p	5mb.200	5mbp50.o	dbat5a
5ab300.p	5b100.ta	5mb.300	5p100.ta	dcinp
5amb.100	5b100.tp	5mb.400	5p100.tp	ddinp
5amb.200	5b200.ta	5mb.50	5p200.ta	flux2dose
5amb.300	5b200.tp	5mb.500	5p200.tp	inp
5amb.400	5b300.ta	5mb100.o	5p300.ta	inpn
5amb.50	5b300.tp	5mb200.o	5p300.tp	inpn1
5amb.500	5b400.ta	5mb300.o	5p400.ta	lines
5amp.100	5b400.tp	5mb400.o	5p400.tp	lines1
5amp.200	5b500.ta	5mb50.o	5p500.ta	mbsource

5amp.300	5b500.tp	5mb50.ta	5p500.tp	outp
5amp.400	5bp100.o	5mb50.tp	aline	plot
5amp.50	5bp200.o	5mb500.o	bsource	psource
5amp.500	5bp300.o	5mbp.100	dbat1	
5ap200.a	5bp400.o	5mbp.200	dbat2	

/home_area/w80502/projects/doseconv/6metal.box

5mb.50	6b100.ta	6bp300.o	6mb600.o1	6p500.tp1
6ab400.a	6b100.tp	6bp400.o	6mb700.o	6p600.ta
6ab400.o	6b200.ta	6bp500.o	6mb700.o1	6p600.ta1
6ab400.p	6b200.tp	6bp500.o1	6mbp.100	6p600.tp
6ab500.a	6b300.ta	6bp600.o	6mbp.200	6p600.tp1
6ab500.o	6b300.tp	6bp600.o1	6mbp.300	6p700.ta
6ab500.p	6b400.ta	6bp700.o	6mbp.400	6p700.ta1
6amb.300	6b400.tp	6bp700.o1	6mbp.500	6p700.tp
6amb.400	6b500.ta	6mb.100	6mbp.600	6p700.tp1
6amb.500	6b500.ta1	6mb.200	6mbp.700	dbat5
6amp.300	6b500.tp	6mb.300	6mbsource	dbat6
6amp.400	6b500.tp1	6mb.400	6p100.ta	dbat7
6amp.500	6b600.ta	6mb.500	6p100.tp	dbat8
6ap300.a	6b600.ta1	6mb.600	6p200.ta	dbat8a
6ap300.o	6b600.tp	6mb.700	6p200.tp	dbat8b
6ap300.p	6b600.tp1	6mb100.o	6p300.ta	dbat9
6ap400.a	6b700.ta	6mb200.o	6p300.tp	dbat9a
6ap400.o	6b700.ta1	6mb300.o	6p400.ta	dbat9b
6ap400.p	6b700.tp	6mb400.o	6p400.tp	inp
6ap500.a	6b700.tp1	6mb500.o	6p500.ta	mbsource
6ap500.o	6bp100.o	6mb500.o1	6p500.ta1	outp
6ap500.p	6bp200.o	6mb600.o	6p500.tp	psource

/home_area/w80502/projects/doseconv/7metal.box

7b1000.a	7b4000.p	7mb.500	7p1000.p	7p4500.o
7b1000.o	7b4500.a	7mb500.o	7p2000.a	7p4500.p
7b1000.p	7b4500.o	7mbp.500	7p2000.o	7p500.ta
7b2000.a	7b4500.p	7mp.1000	7p2000.p	7p500.tp
7b2000.o	7b500.ta	7mp.2000	7p3000.a	bsource
7b2000.p	7b500.tp	7mp.3000	7p3000.o	dbat11
7b3000.a	7mb.1000	7mp.4000	7p3000.p	dbat12
7b3000.o	7mb.2000	7mp.4500	7p4000.a	inp
7b3000.p	7mb.3000	7mp500.o	7p4000.o	lines
7b4000.a	7mb.4000	7p1000.a	7p4000.p	outp
7b4000.o	7mb.4500	7p1000.o	7p4500.a	psource

/home_area/w80502/projects/doseconv/8metal.box

8b1000.a	8b2500.o	8mbp.200	8p1500.o	bsource
8b1000.o	8b2500.p	8mbp.500	8p1500.p	dbat13
8b1000.p	8b500.ta	8mp.1000	8p200.ta	dbat14
8b1500.a	8b500.tp	8mp.1500	8p200.tp	inp
8b1500.o	8mb.1000	8mp.2000	8p2000.a	li15

8b1500.p	8mb.1500	8mp.2500	8p2000.o	lines
8b200.ta	8mb.200	8mp200.o	8p2000.p	outp
8b200.tp	8mb.2000	8mp500.o	8p2500.a	psource
8b2000.a	8mb.2500	8p1000.a	8p2500.o	
8b2000.o	8mb.500	8p1000.o	8p2500.p	
8b2000.p	8mb200.o	8p1000.p	8p500.ta	
8b2500.a	8mb500.o	8p1500.a	8p500.tp	

/home_area/w80502/projects/doseconv/9metal.box

9b1000.a	9b2500.o	9mbp.200	9p1500.o	bsource
9b1000.o	9b2500.p	9mbp.500	9p1500.p	dbat21
9b1000.p	9b500.ta	9mp.1000	9p200.ta	dbat22
9b1500.a	9b500.tp	9mp.1500	9p200.tp	dbat23
9b1500.o	9mb.1000	9mp.2000	9p2000.a	dcinp
9b1500.p	9mb.1500	9mp.2500	9p2000.o	ddinp
9b200.ta	9mb.200	9mp200.o	9p2000.p	inp
9b200.tp	9mb.2000	9mp500.o	9p2500.a	inpn
9b2000.a	9mb.2500	9p1000.a	9p2500.o	inpn1
9b2000.o	9mb.500	9p1000.o	9p2500.p	lines
9b2000.p	9mb200.o	9p1000.p	9p500.ta	outp
9b2500.a	9mb500.o	9p1500.a	9p500.tp	psource

/home_area/w80502/projects/doseconv/wood.box

ab1000.a	dbat3a	w1400.tp	wap.1400	wb600.o
ab1000.o	dcinp	w1800.ta	wap.1800	wbc.2200
ab1000.p	ddinp	w1800.tp	wap.200	wbp.1000
ab1400.a	inp	w200.ta1	wap.2200	wbp.1400
ab1400.o	inpn	w200.tpe	wap.600	wbp.1800
ab1400.p	inpn1	w2200.ta	wap200.a	wbp.200
aline	outp	w2200.tp	wap200.o	wbp.2200
ap1000.a	p1000.ta	w600.ta1	wap200.p	wbp.600
ap1000.o	p1000.tp	w600.tpe	wap600.a	wbp200.o
ap1000.p	p1400.ta	wab.1000	wap600.o	wbp600.o
ap1400.a	p1400.tp	wab.1400	wap600.p	wp1000.o
ap1400.o	p1800.ta	wab.1800	wb.1000	wp1400.o
ap1400.p	p1800.tp	wab.200	wb.1400	wp1800.o
bline	p2200.ta	wab.2200	wb.1800	wp200.ta
blines	p2200.tp	wab.600	wb.200	wp200.tp
bsource	plot	wab200.a	wb.2200	wp2200.o
dbat1	psource	wab200.o	wb.600	wp600.ta
dbat1a	runli	wab200.p	wb1000.o	wp600.tp
dbat2	runline	wab600.a	wb1400.o	
dbat2a	w1000.ta	wab600.o	wb1800.o	
dbat2b	w1000.tp	wab600.p	wb200.o	
dbat3	w1400.ta	wap.1000	wb2200.o	

CHECKLIST FOR INDEPENDENT TECHNICAL REVIEW

DOCUMENT REVIEWED Basis for Dose Rate to Curie Assay Method
 AUTHOR(s) S. R. Gedeon

I. Method(s) of Review

- (✓) Input data checked for accuracy
- (✓) Independent calculation performed
 - () Hand calculation
 - (✓) Alternate computer code: ISOSHAD
- () Comparison to experiment or previous results
- () Alternate method (define) _____

II. Checklist (either check or enter NA if not applied)

- (✓) Task completely defined
- (✓) Activity consistent with task specification
- (✓) Necessary assumptions explicitly stated and supported
- (✓) Resources properly identified and referenced
- (✓) Resource documentation appropriate for this application
- (✓) Input data explicitly stated
- (✓) Input data verified to be consistent with original source
- (✓) Geometric model adequate representation of actual geometry
- (✓) Material properties appropriate and reasonable
- (NA) Mathematical derivations checked including dimensional consistency
- (NA) Hand calculations checked for errors
- (✓) Assumptions explicitly stated and justified
- (✓) Computer software appropriate for task and used within range of validity
- (NA) Use of resource outside range of established validity is justified
- (✓) Software runstreams correct and consistent with results
- (✓) Software output consistent with input
- (NA) Results consistent with applicable previous experimental or analytical findings
- (✓) Results and conclusions address all points and are consistent with task requirements and/or established limits or criteria
- (✓) Conclusions consistent with analytical results and established limits
- (✓) Uncertainty assesment appropriate and reasonable
- () Other (define) _____

III. Comments:

IV. REVIEWER: J V Nelson DATE: 10/28/96

DISTRIBUTION SHEET

To	From	Page 1 of 1			
Distribution	Criticality and Shielding	Date October 4, 1996			
Project Title/Work Order		EDT No. 619214			
Basis for Dose Rate to Curie Assay Method		ECN No.			
Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only

P. A. Gagnon	S6-31	X
S. R. Gedeon	H0-35	X
J. Greenborg	H0-35	X
D. C. Hetzer	S6-31	X
Central Files (1 + Original)	A3-88	X