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MATRIX EFFECTS IN TRU ASSAYS USING THE SWEPP PAN ASSAY SYSTEM

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ABSTRACT

The Drum Assay System (DAS) at the Stored Waste Experimental Pilot Plant (SWEPP) is a second-generation active-passive neutron assay system of the type developed by Caldwell et al.¹ It has been used to assay over 5000 208-liter drums of transuranic waste from the Rocky Flats Plant (RFP). Data from these assays have been examined and compared with the assays performed at Rocky Flats, mainly utilize counting of ^{239}Pu gamma rays. For the most part the passive assays are in very good agreement with the Rocky Flats assays. The active assays are strongly correlated with the results of the other two methods, but require matrix-dependent correction factors beyond those provided by the system itself. A set of matrix-dependent correction factors has been developed from the study of the assay results.

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INTRODUCTION

More than 130,000 drums and 11,000 boxes of radioactive waste are stored at the Radiactive Waste Management Complex (RWMC) at the Idaho National Engineering Laboratory (INEL). Much of this waste will be transferred to the Waste Isolation Pilot Plant (WIPP) in New Mexico. Another portion will be classified as Low Level Waste (LLW) (less than 100 nCi/g), which can be buried under less stringent controls than those employed at WIPP. Some waste will be processed at the INEL to reduce its volume, before being classified as transuranic (TRU) waste to go to WIPP, or LLW to be buried in Nevada. To determine which route the waste will follow, each drum or crate must be examined and its TRU content certified. To make possible the assay of the huge backlog of waste drums, the assay procedure must be rapid and accurate.

DESCRIPTION OF THE ASSAY SYSTEM

The instrument selected to examine the waste is the Los Alamos second-generation Passive-Active Neutron (PAN) assay system developed by Caldwell et al.¹ Only a brief description of the PAN system is given here. For further details, see Reference 1.

The SWEPP installation is shown in Figure 1. It is basically a rectangular chamber in which the drum to be assayed is placed, surrounded by ³He detectors embedded in the polyethylene surrounding the chamber. Some of the detectors are shielded by cadmium, so they are not sensitive to thermal neutrons. Others are unshielded. Both types of detectors are included in the packages present in each of the six surfaces surrounding the chamber--the four walls plus the top and bottom of the chamber.

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Figure 1. SWEPP PAN assay system cross section.

The Active Assay System

This instrument has two assay modes, both of which depend upon the detection of neutrons from the contained TRU waste. The active mode is the more complex procedure. It utilizes the shielded detectors plus two flux monitors and a neutron generator. The neutron generator produces 14-MeV neutrons in pulses of 10^6 neutrons each. After each pulse the neutrons are thermalized through collisions in the graphite and polyethylene in the walls of the assay chamber. The flux dies away through absorption and escape of the neutrons. During the period of dieaway there is present in the chamber a more or less isotropic flux of interrogating thermal neutrons, which penetrates the drum being assayed. When the thermalized neutrons encounter fissile material within the waste matrix, they cause fissions. The resulting fission neutrons penetrate the cadmium covers surrounding the shielded detectors and are counted for a gated period of 380 microseconds during the dieaway time of the thermal flux. A later count for 1000 microseconds measures the background for the active assay. The detector response is normalized by dividing the background-corrected count by the count observed for the first flux monitor, which is a small bare ^3He tube mounted at the top of the rear wall of the assay chamber.

A second flux monitor is used to deduce the effects of the absorption of neutrons by the materials of the waste matrix. It is the presence of this monitor that makes the SWEPP system a "second generation" unit. The second monitor, or Barrel Flux Monitor (BFM) is mounted in a back corner of the assay chamber. It is a ^3He detector with a contoured cadmium shield that excludes thermal neutrons except for those scattered from the waste matrix in the drum. Highly absorptive matrices will scatter fewer neutrons to the BFM. The ratio of the neutrons counted by the two monitor detectors is an index of the neutron absorption by the matrix. The absorption correction appears to work well for very uniform matrices, such as sludges. It is less successful for inhomogeneous matrices, where regions of high neutron absorption cross section are interspersed with regions which readily pass neutrons. In such cases the

thermal neutrons can reach the BFM without properly sampling the absorption properties of the waste matrix.

It is found empirically that the active assay is also affected by the amount of moderating material in the waste matrix.¹ A moderator correction factor is applied to account for these effects. It is based upon the ratio of the shielded detector counts to the total detector counts in the passive assay mode. Since the shielded and unshielded detectors respond to neutrons of different energies, the ratio yields a rough indication of the shape of the neutron spectrum. Changes in the spectral shape are assumed to be primarily affected by the amount of moderator in the waste matrix. The overall correction factor is the product of the absorption and moderator correction factors.

The advantage of the active method is its good sensitivity to the presence of small quantities of fissile materials. Its disadvantage is its vulnerability to neutron absorption by the waste matrix, which is often a more complex problem than can be solved by the BFM alone.

The Passive Assay System

The passive assay system senses the presence of TRU materials in the waste through detection of neutrons from spontaneous fission, principally of ^{240}Pu . Neutrons from spontaneous fission are correlated in time, and the correlation is identified by looking for neutrons within the dieaway time following detection of a first neutron. There are actually two passive neutron systems. One utilizes only the shielded detectors, and has a short gated counting time, currently about 35 microseconds. The second uses the output of both the bare and the shielded detectors and has a relatively long gated time of 250 microseconds. The "short-gated" assay is selected if the total count rate exceeds 2000 counts per second. The amount of total Pu present is calculated using the known isotopic ratio of the Pu isotopes. This conversion is valid for RFP waste, for which the fraction of ^{240}Pu is reasonably constant at about 0.059.

The passive assay is much less affected by absorption of neutrons by the waste matrix than is the active assay. This is because the passive mode requires only that the fast neutrons escape from the waste matrix, while the active mode requires that first the thermal neutrons penetrate the matrix, and secondly that the fast neutrons escape. Therefore the passive assay is preferred, provided that spontaneously fissioning material is indeed present, and that the statistical precision for the passive counting is adequate to yield good results. Statistical precision suffers if the counting rate is either too low or too high. At low rates there are simply not enough counts to obtain good statistics. At high rates the assay is essentially an attempt to measure a small difference between two very large numbers. High counting rates often indicate the presence of a large neutron background due to (α, n) neutrons. These are neutrons produced by nuclear reactions between α -particles emitted by the TRU materials and various materials of the medium in which they are located. Some RFP drums contain substantial amounts of fluorine, magnesium, chlorine, aluminum, or even beryllium, for which the (α, n) production rates are very high.

The decision tree of the SWEPP assay procedures calls for the active assay to be accepted if it indicated a Pu content of 20 grams or less. Above that value the passive assay is accepted, provided that the calculated statistical error of the passive assay is less than 40 g Pu. A larger statistical error indicates that the neutron rates are either too low or too high to yield a reliable assay. A number of drums have been encountered for which the (α, n) content led to assays for which both the assay values and their attendant errors reached values of several hundred grams of Pu. Assays with such large errors are useless. Under these conditions the decision tree branches back to a corrected value of the active assay. The correction factor applied depends upon the matrix material in the drum. The matrix correction factors currently in use are those installed on 7 September 1989, and are shown in Table 1. This report describes a study which revealed the need for such matrix-dependent correction factors, and the method developed for determining their magnitude. The actual values chosen represent the results of discussions with John Caldwell, and a compromise in points of view.

TABLE 1. Active Assay Correction Factors

<u>Content Code</u>	<u>Active Mass Correction*</u>
292	Act Mass = $FTRUM * (1 + 0.0358 * FTRUM)$
300 & 303	Act Mass = $FTRUM * (1 + 0.015 * FTRUM)$
320	Act Mass = $2.50 * FTRUM * (1 + 0.02 * FTRUM)$
339	Act Mass = $2.6 * FTRUM$
376	Act Mass = $2.54 * FTRUM$
393	Act Mass = $2.82 * FTRUM$
409	Act Mass = $10.8 * FTRUM / CF$
411	Act Mass = $13.0 * FTRUM / CF$
480	Act Mass = $2.9 * FTRUM$
All other Codes	Act Mass = $FTRUM * (1 + 0.015 * FTRUM)$

* FTRUM is the active mass before application of the matrix correction factor.

CF is the correction factor generated by the assay algorithm.

EXAMINATION OF ASSAY DATA

In the present study we examined the results of assays of approximately 5000 drums by the SWEPP PAN system. This is a large enough sample to make it possible to examine the data for evidence of systematic effects. The PAN produces two estimates of the plutonium content of a drum: the active and the passive assay. An additional estimate is given by the Rocky Flats value,

which for all but the sludges is based on gamma-ray counting. With three estimates of the Pu content available, it becomes possible to form judgments concerning the relative validity of the three methods. If all three are in good agreement, it is assumed that they give a particularly reliable estimate of the Pu content of the drum. If two agree but the third differs markedly, it is assumed that the two in agreement are reasonably correct, and that a search should be made for a source of error in the third assay.

The general procedure followed in comparing assay results is to plot one set of results against another. The resulting display shows graphically the degree of agreement or disagreement between the assay systems. If the measurements are well correlated, the points will be concentrated in the vicinity of a line. If a proportionality exists, the line will be straight, and if the assays are generally equal the slope of the line will be unity. Usually the slope of the line is somewhat different from unity. In that case the slope of the line represents a correction factor that could be systematically applied to one set of data to force agreement with the other set.

For the data fitting we chose the linear regression procedure of Lotus 1-2-3. We chose the "zero intercept" option in order to establish the correction factor between the data sets as a fixed multiplier. A non-zero intercept could be interpreted as indicating a bias in one of the assay methods. However, such an indication would more likely be merely an artifact of the broad data scatter, and not significant. Therefore all of the data fitting done in this study utilized the "zero intercept" option.

The assays were compared two by two. For each content code we made plots of the passive assay vs the active assay, Rocky Flats values vs the active assay, and passive vs RFP. Because of the resulting large number of plots, we have placed them in the Appendix of this report.

Where there is a suggestion of curvature in the relation between data sets, consideration must be given to the question of whether the curvature is real and whether there are identifiable systematic effects causing the

nonlinearity. One possible source of nonlinearity is self-protection in thick deposits of plutonium. For increasingly thick Pu deposits the interrogating thermal neutron flux may be depressed, leading to progressively low active assay values. On the other hand, if an increment of Pu occurs in a part of the drum distant from the first deposit, the flux depression may be minimal. Care must be taken in applying nonlinear correction factors, because effects other than self-protection may be involved.

In this connection it should be noted that there has been a continuing dialogue between John Caldwell and ourselves as to whether a curvature, representing self-protection, should be part of the code-dependent matrix correction factor. We prefer strictly linear correction factors. Although self-protection does become a severe problem with increasing deposit thickness, this should be considered to be an effect in individual drums, and not necessarily uniform over the whole array of drums of the same content code. The current algorithms represent a compromise between the two points of view. Some of the matrix correction factors include curvature, but only as a small contribution in the second degree. Exponential correction factors have been eliminated.

On the whole the passive and the RFP assays tend to agree with one another, with the active assay falling lower, sometimes by large factors. That is before the application of matrix correction factors resulting from the present study. The principal cause of the depression of active assay values is inhomogeneity in the matrix. The problem is that the BFM is required to sample the whole matrix in the drum in order properly to assess the absorption of the interrogating neutrons. That is possible only if the drum is completely filled with material of uniform neutron absorption properties. If it is possible for the thermal neutrons to reach the BFM without passing through the absorptive material of the waste matrix, the BFM cannot see the effects of absorption where the Pu is located. Despite the disagreement in terms of absolute values, for many content codes the active assay data are strongly correlated with the results of the other two methods, differing only by a constant factor. This suggests that it is possible to derive a code-dependent correction factor that will correct for the matrix absorption

and bring the active assay into general agreement with one or both of the other methods. There would be no point in making such corrections for cases where the passive assay is valid. However, such correction factors provide a technique for resolving the problems presented by those drums for which the high (α, n) content invalidates the passive assay. For such codes a matrix correction factor is derived by fitting a straight line to the plot of the passive vs the active data, using only those passive data points for which the (α, n) contribution is not too large. Empirically it is noticed that the calculated passive assay error is a good measure of the prominence of the (α, n) component. In this study an indicated error of 30 grams of Pu was arbitrarily set as the limit of acceptability of the passive assay for the data comparisons. When the operating algorithms were selected, the limit of passive assay acceptability was expanded to a 40 gram error.

Consideration of Individual Content Codes

Following the above-outlined general procedure, code-dependent correction factors have been derived for many of the content codes. These cases are individually considered in the following paragraphs. Typically, each comparison incorporate three plots: Passive vs active, Rocky Flats vs active, and passive vs Rocky Flats. Because of their great number, these plots are relegated to the Appendix.

RFP Sludges: Content Codes 001, 003, 004, and 007

Sludges comprise the largest single classification of waste received by SWEPP from Rocky Flats. At Rocky Flats the sludges are assayed by counting α -particles from thin sources prepared from grab samples of sludge. This procedure cannot be repeated once the drum is sealed. The sludges were perceived originally to be the most difficult type of matrix to assay with the PAN system, because of their high macroscopic cross sections for scattering and absorption. As it turns out, these sludges meet the requirements for effective operation of the BFM better than any other waste matrix type examined thus far. They uniformly fill the drum, and apparently are reasonably homogeneous within a given drum. The homogeneity may not be

complete, but for application of the assay algorithms it is sufficient to assume that the waste is piecewise homogeneous. That is, each horizontal slice that could be cut from the drum is assumed to be homogeneous in Pu content.

Of the four sludge types, Codes 003 and 007 normally contain too little Pu to allow adequate statistical precision in the passive assay. Code 001 includes some drums for which passive assay is feasible, but for the most part either the Pu content is too small or the Am content is high enough to produce too many (α, n) neutrons for effective passive assay. Therefore most of the comparisons of assays of sludges are between the Rocky Flats values and the active assays.

Code 001 and Code 007 sludges are assayed at RFP by alpha counting of samples prepared from grab samples from a large batch. The TRU value obtained for the batch is apportioned equally to all drums filled from that batch. It might therefore be expected that if a correlation exists between assay values, it would be on a batch basis rather than an individual drum basis. Batch averages were compared for both of these matrix types.

Code 001 Sludge. A comparison of the active assay and RFP values for Code 001 sludge for individual drums is shown in Figure A-1. There is no obvious correlation between the two types of assay. An improved picture can be gained by comparing the average of the SWEPP active assay values for a given batch with the RFP value for the same batch. To identify a batch, it was assumed that drums belonging to the same batch would have the same RFP Pu content and be consecutively numbered. Among 1324 Code 1 drums there were 92 such groups, containing from four to 33 drums each. Figure A-2 is a plot of the RFP assays versus the group averages of the active assays for the grouped data. Compared to Figure A-1, Figure A-2 shows a marked improvement in correlation. While the point scatter appears rather large, there is a relatively high density of points near the regression line. A linear fit, with the line forced to go through the origin or coordinates, shows a slope of 1.03. This is an indication of a broad overall agreement between the RFP and active assays, although the fitting parameter R^2 is only 0.48. A further

evidence of agreement is found in a comparison of the total plutonium represented by all of the assays represented in Figure A-2. The sum of the active assays is 5.11 kg, and for the RFP assays the sum is 5.04 kg. This agreement is better than had been hoped.

Another view of the comparison is provided by Figures A-3 and A-4, representing frequency distributions of the active and RFP assays, respectively. Each bar represents the number of drums for which the assay value fell within the range of the group represented on the abscissa. The frequency distributions are very similar, confirming the impression that the active assay sees Code 001 sludge very much the same as the Rocky Flats assays do.

The total neutron output of a drum can be used to deduce the total α activity if the number of (α, n) neutrons produced per unit α activity is known. Caldwell² has devised a scheme for deducing this value from the assay data for the single case of Code 001 sludge. From basic nuclear data it is calculated that each gram of typical RFP plutonium emits 61.4 spontaneous fission neutrons per second. A neutron emission rate observed in excess of the Pu assay value times 61.4 is assumed to be due to (α, n) activity. The α activity is calculated from the Pu assay, using the activity value of 72.3 mCi/g Pu, and the Rocky Flats inventory Am value, using the Am activity value of 3432 mCi/g Am. No correction was made for growth of Am between the Rocky Flats determination and the SWEPP assays, but time delays for the drums studied were less than three years. Dividing the calculated (α, n) neutron rate by the calculated α rate yields the neutron production factor in n/s·mCi. This value was calculated for all Code 001 drums. The frequency distribution is shown in Figure A-5, with the lower yield portion expanded in Figure A-6. The distribution of values is very broad. The average value is 13.9 n/s·mCi for Code 001 sludge, which is a reasonable value for a matrix consisting of magnesium and iron oxides.

The inverse of the above procedure allows the Am content of a drum to be calculated from the excess of neutrons over those expected from ²⁴⁰Pu fissions if the neutron yield per mCi is known. The assay algorithms now contain a

calculation of the americium content of Code 001 drums using this procedure and the neutron yield value of 13.9 n/s·mCi. The calculated value is no better than the value coming from Rocky Flats, but it is based on the assay value for the individual drum, and not a batch average.

Figure A-7 shows the observed distribution of the moderator parameter MOD for Code 001. The average value is 0.64, which is characteristic of a moderately wet medium. Figure A-8 shows the frequency distribution of the overall correction factor CF, whose average value is 4.6.

Code 007 Sludge. We next discuss Code 007, "Building 374 Sludge", because it is similar to Code 001 sludge in number of drums assayed to date at SWEPP. The method of assay at Rocky Flats Plant is similar to that for Code 001, except that the batches over which averages are taken cover a week's time instead of a single tank load. It is therefore a little disconcerting that no real correlation appears between the RFP and active assays, even when batch assays are considered. The drum-by-drum comparisons are shown in Figure A-9, and the batch-average comparison is shown in Figure A-10. In neither is the correlation very good. The active assay values tend to be consistently higher than the RFP values. For 1743 assays the average active assay is 3.27 grams Pu, compared with the average RFP value of 0.326 grams. The sum of all active assays is 5733 grams Pu, a factor of 10 higher than the corresponding RFP value of 571 grams. This is a surprisingly large difference, although the impact upon waste screening is minimal because of the low quantities of Pu involved.

Figures A-11 and A-12 compare the frequency distributions of active and RFP assays, respectively, for Code 007 sludge. In contrast with Code 001, the Code 007 distributions are markedly different.

Figure A-13 shows the frequency distribution of the (α ,n) neutron production factor, calculated as was done for Code 001. The excess neutrons present in this material are very low, as are all assay values.

Figure A-14 shows the distribution of the moderator index, MOD for Code 007.

The MOD distribution is distorted because MOD was set to zero if the system totals counting rate is less than 10 counts per second in the assays studied here. In addition, any values of MOD calculated as greater than 0.9 were set back to 0.9. Therefore, the assays from which a valid average for MOD can be determined are comparatively few in number. A value of 0.714 has been adopted for MOD for Code 007. The values calculated for individual drums are ignored.

The distribution of values of the total correction factor, CF, is shown in Figure A-15. The average correction factor for all Code 007 drums is 6.1. It might be suspected that this correction factor artificially makes the assays higher than the Rocky Flats values. However, if the correction factor were reset to unity, the active assays would still be greater than the RFP values.

Code 003 Sludge. Code 003, "Organic Setups", consists of an organic sludge. In assay it behaves very much like the Code 007 sludge, in that it contains very small amounts of plutonium, and there is no discernable correlation between the results of the separate assays. Figure A-16 shows a comparison of RFP results with active assay values. A least-square fit to the data produced the line shown in Figure A-16, but the fit is not impressive.

Figures A-17 and A-18 show the frequency distributions of the moderator parameter MOD and the total correction factor CF. The average value of MOD is 0.39, but this average is biased by the many zeroes generated. In the current algorithm a fixed value of 0.45 is used for the MOD parameter. The average value of CF is 6.3.

Code 004 Sludge. Code 004, "Special Setups", consists of liquids absorbed in a cement mixture. Again the Rocky Flats and active assay values are not well correlated, as can be seen from Figure A-19. The drums of Code 004 are not grouped into batches, so no batch-average comparison can be made. A comparison of average assay values shows that the active assay is, on the average, about four times as large as the Rocky Flats value. The amounts of plutonium present in the Code 004 drums are on the average larger than they are for the other sludge classifications, and a comparison with the passive-assay values is possible. Figure A-20 shows the passive values

passive-assay values is possible. Figure A-20 shows the passive values plotted against the active values. The error bars represent the calculated passive statistical errors. A clear correlation is evident. The slope of the fitted line indicates that, on the average, the passive assay values are about 30% lower than the active assays. This is in contrast to the usual observation in these comparisons, which normally show the active assay lower than the passive. Figure A-21 compares the passive and Rocky Flats assays of Code 004 sludge. The distributions of MOD and CF are shown in Figures A-22 and A-23, respectively. A MOD value of 0.51 has now been adopted for Code 004 sludge.

Table 1 compares the average values of assays for the sludges. Passive assay values are included, although the selection algorithm uses no passive results for the sludges. It is a bit puzzling that there should be such excellent agreement on Code 001 between active and Rocky Flats assays, and such poor agreement on Codes 004 and 007. The Rocky Flats sampling procedures and preparation of α -counting sources are said to be the same for all of these sludge codes. The sludges represent the only examples encountered in which the active assay values are, on the average, higher than the Rocky Flats values. Were it not for the good agreement between the active and passive assays on Code 004, and the fact that the Rocky Flats values are higher than the active assay values for Code 003, it might be suspected that the matrix correction factors for the active assays are overestimated. The total correction factors range from 4.55 for Code 001 to 6.15 for Code 007. The range of these values is too small to explain the assay differences. The agreement between the active and passive assays for Code 004, coupled with the agreement between active and RFP values for Code 001, leads to the conclusion that the conservative decision is to select the active assay as the best estimate of Pu content for the sludge codes 001 through 007.

TABLE 2. Average Values For Assays Of Sludges

<u>Content Code</u>	Active Assay	Passive Assay	RFP Assay
	<u>(g Pu)</u>	<u>(g Pu)</u>	<u>(g Pu)</u>
001	4.2	13.5	4.1
003	1.0	2.0	3.1
004	16.9	12.1	4.4
007	3.3	9.4	0.3

Cemented Sludge, Code 292. Code 292 sludge comes from the recovery building filter plenums, pumps, and incinerator off-gas system. Portland cement is added to absorb free liquid. This material should be similar to the other sludges in its interactions with neutrons. However, the active assays are systematically a factor of two lower than are the passive assays and the RFP values. Both the absorption and the moderator correction factors are substantially smaller for Code 292 than for the other sludges. Code 292 sludge represents one case for which the BFM cannot properly sample the absorption of the waste matrix. Whereas the waste material uniformly fills the drum for the other sludges, Code 292 sludge is packaged in 3.8-liter polyethylene bottles. The spacing between bottles, plus the fact that the bottles may not be completely filled, leaves channels through which thermal neutrons may reach the BFM without properly indicating the absorption of the sludge within the bottles. Consequently the active assays tend to be underestimates of the TRU content of the drum.

Figure A-24 shows the comparison of the passive and active assays for Code 292. A linear fit to the data shows a slope of 1.94, meaning that on the whole the passive assay yields values about 1.94 times the active assay. There is an indication of curvature in the data that the linear fit does not reproduce. The dashed line represents the parabolic correction factor that is now used in the SWEPP algorithms. Figure A-25 shows a plot of the Rocky Flats assays against the active assays. The slope of the fitted curve is 2.51, slightly higher than the slope of Figure A-24. There is less suggestion of curvature, leading to the question of whether the nonlinearity shown in Figure A-24 is in the active or the passive data. Figure A-26 compares the passive assay data with the Rocky Flats values for Code 292. They are in reasonable agreement, but the passive values are about 30% lower. In all but three cases the passive assay met the criteria in the algorithm and was the selected assay value. The corrected active assay value was chosen for only three low-content drums.

Graphite matrices, Codes 300 and 303. On the whole, these matrices are among the most benign of all the waste forms examined thus far. Graphite has a high neutron scattering cross section and a low neutron absorption cross section. Therefore the matrix effects for neutron assays, both active and passive, can be expected to be minimal. This expectation is realized in practice. Figures A-27 through A-29 show the intercomparison of the three methods of assay. For both the passive and the RFP assays the fit vs the active assay values has a slope near 1.50, the passive-active slope being 1.49 and the RFP-active slope being 1.53. The dashed curves in Figures A-27 and A-28 represent the current correction factor for the active assay values. It represents a compromise correction for self-protection. The lone assay near 100 g indicates that the curved line may grossly overpredict the Pu content in the higher assay range. In any event, there will be very few times that the decision tree will defer to the corrected active assay, as the (α ,n) activity is usually very small in these matrices. The passive assay value is nearly always chosen.

Code 320: Tantalum Crucibles. This was the first waste type for which the inhomogeneous matrix effect was noticed. It very early became clear that the active assay values for Code 320 waste were about one-fourth of the values indicated by the passive and RFP assays, which usually agreed within 20%. The Rocky Flats Plant has used two types of tantalum crucibles, one being generally cylindrical in shape and the other in the general form of a flat rectangular box. All of the Code 320 drums for which the Real-Time Radiography (RTR) images have been checked have contained crucibles of the rectangular style, except for two drums that evidently were misclassified. Those appeared to be actually Code 480 drums, as they showed pipes and valves. The rectangular crucibles are stacked in a single column in the middle of the drum, with lighter weight packing material surrounding them to hold them in place. Tantalum has a neutron absorption cross section of 21.7 barns, which is a comparatively large cross section for a waste matrix. The residual plutonium, being plated on the interior surfaces of the crucibles, is well shielded from the interrogating neutron flux. Nevertheless, the absorption correction factor derived by the assay system is seldom different from 1.00, meaning that the second flux monitor has failed to detect that this is a highly absorptive matrix. The reason for this failure is that there is a lot of room around the tantalum column for neutrons to stream past and reach the BFM. The scattered flux appears to the BFM to be unaffected by the absorption in tantalum, and an unrealistic correction factor is generated.

Figures A-30 through A-32 show the comparison of the three assay methods for Code 320 waste. In Figure A-30 the solid line represents a linear fit to the plot of passive vs active assays. The slope is 4.23. The processing code now uses the quadratic correction represented by the dashed line of Figure A-30. Both curves fit the available data adequately. The data are still a bit sparse to make a final judgment between the two fits. This relationship will be reexamined as additional data become available. The passive and RFP values are in good agreement. The comparison in Figure A-32 shows that they differ on the whole by only 11%.

Code 330: Dry Paper and Rags. Code 330 data are quite sparse in the current data set. This should be one of the most benign of all matrices. Nevertheless both the RFP data and the passive assays indicate that the active assay requires a correction factor of about 2. Figures A-33 to A-35 show the comparisons of the three types of assays. Linear fits are represented by solid lines. The current algorithm assigns the active assays a generic correction grouped with "all other" codes that have not had individual corrections assigned. The correction is represented by dashed lines in Figures A-33 and A-34. The picture is clouded by the presence of one passive assay with a relatively high value. Additional data will be required to clarify the issue.

Code 335: Absolute Filters. This is another matrix type that has few examples to examine and has not previously been treated individually. Like Code 330, Code 335 has the correction factor intended for "all other" codes. Despite the sparse data, it is evident that the active assay requires a correction closer to the linear fit value of about 1.7, rather than the generic correction. The passive and RFP assays are usually within about 11% agreement. Data comparisons are shown in Figures A-36 to A-38. These drums contain relatively small amounts of Pu, and the passive value will be used in most cases, so the details of the active assay correction are of minimal consequence.

Code 336: Moist Paper and Rags. Figures A-39 through A-41 show the assay comparisons for Code 336. Correlation is best for the RFP-active assay comparison, although a correction factor of 2.89 is indicated. The generic correction factor falls far short. The passive assay values are comparatively widely scattered.

Code 337: Plastics, Teflon, PVC. Most plastics contain hydrogen, a moderator. Teflon contains no hydrogen, but is composed of fluorine and carbon, both having very low thermal neutron absorption cross sections. PVC contains both hydrogen and chlorine, the latter being a strong neutron absorber. Therefore Code 337 could be a somewhat schizophrenic matrix. Assays of drums included in the present sample appear to be dominated by

neutron-absorbing PVC. Figure A-42, displaying the relation between the passive and active assays, shows essentially a linear behavior with a correction factor of about 2.5 required for the active assays. Figure A-43 shows the RFP-active assay relationship, with a slope in good agreement with that of Figure A-42. Two surprisingly high RFP values appear. These points are missing from the RFP-passive comparison in Figure A-44, because the corresponding passive assay values have error estimates exceeding 30 g Pu. The "all other" correction, in which classification Code 337 falls, undercorrects the active assays. A constant correction factor of about 2.5 should be used for active assays of this matrix type.

Code 339: Leaded Gloves. The Rocky Flats Plant uses leaded gloves for personnel protection in all plutonium areas. The gloves range in thickness from 30 to 90 mils. Lead has a fairly low thermal neutron absorption cross section, 0.17 b, so it might be expected that the absorption correction factor for this code might be rather small. The assay data show that, on the contrary, this is one of the more highly absorptive matrices. The fit of passive vs active assay data, Figure A-45, shows that a correction factor of about 2.7 is required to force the active assay to agree with the passive. This is in addition to a correction factor of 2.6 produced internally from the BFM response. Comparison of the active assay data with the RFP results, Figure A-46, indicates a systematic factor of 3.4 between these two methods. Figure A-47 compares the passive and the Rocky Flats assays for Code 339 waste. Another comparison between assay techniques for this matrix is available. Rocky Flats made a mockup of a drum containing known amounts of Pu in a leaded-glove matrix.³ They found that a correction factor of 1.85 had to be applied to the passive assay to force agreement with the known Pu content. This was in good agreement with the factor of 2.1 that was observed earlier between passive assays at SWEPP and the Rocky Flats gamma assay values for a small sample of assays, but is in not quite so good agreement with the present 27% difference. The lesson to be learned here is that care must be taken in basing conclusions on small bodies of data. As the data base increases in size, it is necessary to reexamine the data and update the correction factors as necessary.

In Figure A-46 three curves are shown. The solid line represents the least-squares fit to the data shown, while the dashed line represents the generic correction factor included in the SWEPP algorithms. The dotted line represents the fit to the passive data shown in Figure A-45. The latter curve appears to represent better a large subgroup of Rocky Flats assays than does the solid line, which is influenced by the three relatively high Rocky Flats points. The algorithm for this matrix type should be changed to use a constant correction factor of 2.65 for the active assays.

Code 371: Firebrick. Firebrick is largely a neutron scattering medium, so Code 371 would not be expected to show a large absorption correction. Indeed, the BFM/monitor ratio leads to an absorption correction factor of 1.0. However, comparison with the passive assay, Figure A-48, suggests a correction factor of 2.1, while the comparison with the RFP assay, Figure A-49, indicates a factor of 1.9 is needed for the active assays. Code 371 does not have a unique correction factor. It is grouped with the "all other" classification, which uses the correction factor represented by the dashed lines in Figures A-48 and A-49. Code 371 assays appear to be adequately served by the generic correction factor. Figure A-50 compares the passive and Rocky Flats assays. This one of the few cases for which the passive assay is overall greater than the RFP assay. The fitted line in Figure A-50 indicates that on the average the passive assays are about 3% greater than the RFP assays.

Code 374: Blacktop, Concrete, Dirt, and Sand. This is a code of very low Pu content, and most assay values fall near zero. There are not enough assays with substantial Pu values to make a consistent comparison. The comparisons are shown in Figures A-51 through A-53. The solid lines represent the fitted curves, but the fits are not significant. Code 374 is grouped with the "all other" codes. This treatment is adequate within the uncertainties.

Code 376: Cemented Insulation and Filter Media. Code 376 is one of the truly pathological matrices encountered in RFP waste. The RTR images show filters, boxes, and miscellaneous items randomly loaded into the drum. The result is an inhomogeneous matrix that is porous to thermal neutrons and does

not allow the BFM to assess the absorptive properties of the waste adequately in the active assay. An additional problem is that many of the drums contain fluorides. As a consequence, these drums tend to have high outputs of (α,n) neutrons, which in many cases overload the coincidence circuitry and invalidate the passive assay. However, there are enough drums with low numbers of (α,n) neutrons to allow a comparison between the active and passive assays, and normalization of the active to the passive response. Of a data base of 795 drums, 557 show passive assay errors between 0 and 30 g Pu, and therefore are acceptable assays. Figure A-54 shows the acceptable passive assay values plotted against the uncorrected active assay values. A linear fit yields a slope of 2.54, as represented by the solid line. The current matrix correction algorithm uses the constant correction factor 2.54 for active assays of Code 376 waste.

Close examination of Figure A-54 reveals that there are a great many points falling below the fitted line at low Pu contents. For these drums the passive and active assays are approximately equal. At higher Pu contents there are more points above than below the line. The question arises as to whether a curvilinear correction factor should be used. We do not favor curvilinear correction factors because they may lead to gross overestimates of the Pu content in the regions of higher Pu content, particularly if extrapolated beyond the region of fit. Figure A-55 compares the Rocky Flats assays with the active assays. All assays are represented, not just those for which the passive assays are acceptable. There are a great many low-content assays represented, but the effect is not as pronounced as in the case of the passive assays. Figure A-56 shows a comparison of Rocky Flats assays with the (uncorrected) active assays for the 238 drums for which the passive assay errors fall outside of the acceptable range 0-30 g Pu. These are the drums for which the passive assay is not reliable, and the algorithm switches to the corrected active assay. The relationship appears linear, and there is no sign of the lower, heavily populated group. As the drums in this figure represent the only cases for which the algorithm would branch back to the active assay, it is clear that a linear correction factor is quite appropriate.

Figure A-57 shows a comparison of the passive assays with the Rocky Flats assays for Code 376. The slope of the fit is 0.72, indicating that the two methods agree with each other within 28%.

Code 393: Sand, Slag, and Crucibles. Code 393 waste consists of the residue from processing magnesium oxide sand, slag, and crucibles. The waste is packaged in 1.9- and 3.8-liter polyethylene bottles. Rocky Flats assays of individual bottles are performed on what they call their can counter, which uses a NaI detector. This procedure has the advantage that the assayed samples are small, well-defined, and uniform. Another advantage of the Rocky Flats assay is that this and similar codes have been the subject of an inventory verification program, which compared the assays by the can counter with assays by a calorimeter.

Approximately 15-20 bottles are loaded into one 208-liter drum. Since magnesium is a prolific source of (α ,n) neutrons, the drums have high neutron source strengths. Very few drums of this matrix type can be assayed by the passive system. Therefore a relationship between the passive and active assays cannot be established. Comparison of the active assays with the RFP assays (Figure A-58) indicates a correction factor of about 2.8 for the active data to achieve general agreement with the RFP assays. Currently Code 393 is included in the "all other" classification, and the matrix correction follows the dashed line in Figure A-58. The corrected assay is therefore underpredicted by about 50 g Pu over most of the range shown in the figure.

Codes 409 and 411: Molten Salts. These materials are chloride salts of magnesium, potassium, sodium, and calcium, and are used in plutonium recovery operations. At Rocky Flats the salts to be discarded are packaged in #303 produce cans. The cans are individually assayed by segmented gamma scanning before being placed in the 208-liter drums. The non-destructive assay of molten salts has been the subject of a series of studies under the Continuous Inventory Verification Plan at Rocky Flats Plant. The SGS assays were compared with values obtained from calorimetric measurements, with the latter being corrected for contributions from ^{241}Am using isotopic information gained from gamma spectroscopy of the samples. Overall these studies show

agreement between the two methods of from 3% to 5%. This excellent agreement indicates that the Rocky Flats assays of molten salts are very reliable. For a drum containing cans of molten salt waste the Rocky Flats assay should be correct within 10% unless an error has been made in counting the cans loaded into the drum.

The components of the salts are all moderately high producers of (α, n) neutrons, so the intimate mixture of Pu and Am with these materials makes a formidable source of uncorrelated neutrons. It is a rare drum of this salt that can be successfully assayed by the passive neutron method. Therefore no meaningful comparisons between the passive and active assays can be made. The active assay is itself limited by the neutron absorption in chlorine, which has a 33.5 b thermal absorption cross section. As for deriving an absorption correction from the BFM response, the molten salts are a worse case than Code 320. Some drums contain only two or three cans of salt, and these lie on the bottom of the drum where they have no effect upon the neutron flux seen by the BFM. Therefore the assay system derives a correction factor of 1.00 where the true correction factor would have to be near 10.

The only way the SWEPP assay system can be used on molten salt matrices is to calibrate the active assays in terms of the Rocky Flats assay values. Figure A-59 shows the Rocky Flats assay values for Code 409 waste plotted against the active assay results. The relationship is linear, and the fitted curve shows a slope of 10.87, which is the correction factor that must be applied to the active assay to derive the corrected assay value. Figure A-60 shows the corresponding data and fit for Code 411. The correction factor for Code 411 is 13.7. There is considerable scatter in the data, and the standard deviation of Y upon X is 35 g Pu for Code 409 and 43 g Pu for 411. Some of the scatter may be due to the variations in effective positioning of the waste within the drum.

Many drums have a very few containers lying on the bottom, while others are filled more than half full. In the latter case it is possible for the system to derive a correction factor greater than 1.00. Since the fit to the RFP data is dominated by assays for which the system-generated correction factor

is 1.00, any higher correction factor will produce an over-estimate of the Pu content of the drum. Therefore the proper treatment of assay data for Codes 409 and 411 is to delete the BFM-generated correction factor completely, using only the assigned matrix correction factor. This procedure is followed in the current version of the assay algorithms.

Measurement of the Matrix Correction Factor for Salt Matrices. Such large correction factors as those derived for the molten salts are not readily accepted without additional confirmation. To obtain such confirmation an experiment was performed to determine a generic correction factor for rock salt. Rock salt was chosen for the mockup because it is readily available and because it is a chloride. Chlorine is the principal neutron absorber in rock salt, just as it is in the molten salts.

In the experiment an empty drum was prepared with sample tubes, as shown in Figure 2. The test drum was patterned after the units used by Caldwell et al.¹ in the original calibration of the system. The sample tubes are installed at radii 0 cm, 10 cm, and 20 cm from the center of the drum. Rock salt was added to the drum in successive 13-cm layers. For each level of rock salt, assays were performed with a metal plutonium sample placed at different positions down the outer sample tube shown in Figure 2. This is the radial position that the original Los Alamos studies¹ identified as the effective average position for a sample to simulate uniform loading of the drum. The Pu sample was a group of nine one-gram metal foils. Because of self-protection, the effective active assay value of the sample was about two grams in the empty drum. The passive assays averaged about 7 grams, indicating perhaps

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Figure 2. Test drum for salt matrix.

that the plutonium of the foils had slightly less ^{240}Pu than standard Rocky Flats plutonium.

The results of the experiment are summarized in Figure 3. The observed counts from the two flux monitors are plotted logarithmically according to the scale on the left side of the figure. The matrix correction factor derived from the ratio of the two monitor counts is plotted linearly to the scale on the right side of the figure. Although both monitors respond almost immediately to the absorption of neutrons by added salt, the derived correction factor does not depart from unity until the drum contains about 25 cm of salt. Then the salt comes into the effective vision angle of the second flux monitor, and the correction factor rapidly rises to an approximately constant value near 10. The correction factor actually tails off as more salt is added, evidently due to the continued decrease in the counting rate of the first flux monitor. The "plateau" value of 10 is approximately the same as the correction factors deduced for the molten salts from comparisons with the Rocky Flats assays. The matrix correction factors derived from the assay comparisons are therefore quite credible.

The question presents itself as to whether we really gain anything from assaying the molten salts at SWEPP, when these assays must be normalized to the Rocky Flats results anyway. It should be kept in mind that the normalization to the Rocky Flats data is a comparison to the general trend of assays, and not to individual drum values. There are two reasons for continuing the SWEPP assays. They give a double check on the "as-loaded" condition of the drum, guarding against a possible inventory error in filling the drum with individually-assayed packages. Also, it may be necessary to rely more heavily on the SWEPP assays when older waste is encountered. In such cases the active assay, with its normalization refined with experience in assaying many drums, may provide the most reliable estimate of the TRU content of the drum.

SWEPP ASSAY SYSTEM TESTS NAD Foils in Salt Matrix

Figure 3. Results of tests with salt matrix. The counts for the flux monitor (triangles) and BFM (circles) should be read from the left hand scale. The derived correction factors CF (squares) should be read from the right hand scale.

Code 422: Soot. Of the 5000 drums included in the data base used in the present study, only four are of Code 422. It is difficult to draw conclusions from such a sparse data set, but it appears that the active and passive assays are in good general agreement. The "all other" correction factor suits the active assay well, in comparison to the passive assays. The Rocky Flats assays are about double the values of the other two methods. The assays of Code 422 are shown in Figures A-61 through A-63.

Code 432: Resin, Leached and Cemented. The assays for Code 432 are represented in Figures A-64 through A-66. The "all other" correction factor is adequate for the active assays. The passive and Rocky Flats assays agree within about 25%.

Codes 440 and 442, Glass Matrices. These two codes are similar in that they are both glasses. They differ in that Code 440 contains ordinary borosilicate laboratory glassware, while Code 442 contains Raschig rings, a special high-boron glass used as a neutron absorber. At present the SWEPP algorithms do not include unique correction factors for these two codes, which are grouped in the "all other" classification. This correction factor underpredicts the active assays, in comparison to the other two assay methods. The passive assay values are consistently lower than the RFP value, by a factor of about two. To obtain agreement between the active assay and the Rocky Flats assay, correction factors of 4.0 for Code 440 and 11.6 for Code 442 would be required. Assay comparisons for Code 440 are shown in Figures A-67 to A-69, and for Code 442 in Figures A-70 through A-72.

Codes 480 and 481: Non-SS Scrap Metals. These codes represent principally iron and steel scrap materials. The difference between them is that for Code 481 waste an attempt has been made to leach out the Pu contamination, while Code 480 waste is unleached. Most of the drums in these categories on hand at INEL were assayed at Rocky Flats using the South Drum Counter, a gamma assay instrument using a NaI detector. Since 23 March 1987 these drums have been assayed by SGS. For an interim period a software restriction prevented the SGS system from performing an assay if the

transmission source showed a transmission less than 0.5%. Such drums had to be taken back to the South Drum Counter.

For Codes 480 and 481 the passive assays and Rocky Flats assays are in excellent agreement, in the main. However, a large proportion of the Code 480 drums contain strong (α, n) sources, and the passive assays are rendered unreliable. When comparisons are restricted to those passive assays showing error estimates smaller than 30 grams Pu, however, a clear correlation appears, as can be seen in Figure A-73. The slope of the curve indicates a correction factor of 2.58. Figure A-74 shows the corresponding comparison between the RFP and active assays. The slope of the fitted curve is 2.90. Because the matrices are essentially identical, a correction factor of 2.90 has been adopted for both Code 480 and Code 481 active assays. Figure A-75, comparing the passive and Rocky Flats assays, shows that these are in generally good agreement.

Code 490: Filters, CWS. Figures A-76 through A-78 compare the assays for Code 490 drums. The assays cover a limited range, and no clear correlation pattern is evident. The active assays use the "all other" correction factor, but in most cases the passive assay value will be accepted for Code 490.

Miscellaneous Codes. Some of the codes in the data set studied included only one or two drums. For such codes too little data exist to make meaningful comparisons among the assay techniques. Until additional data become available, the miscellaneous codes will be grouped in the "all other" category of the algorithm decision tree.

CONCLUSIONS

The Passive-Active Neutron Assay System is very versatile, yielding good results in the assay of nuclear waste of a wide variety of compositions. The comparisons with the Rocky Flats assays show overall good agreement. Each mode of assay has its limitations. The passive assay technique requires that

the neutron coincidence rates yield adequate statistical precision, but that the (α ,n) neutron rate be restricted to rates within the capacity of the system to identify true coincidences. Matrix effects are minimal with the passive system. The active assay technique is very sensitive to small amounts of plutonium and yields excellent statistical precision, but is highly susceptible to matrix effects. These matrix effects are due to absorption of the interrogating thermal neutrons by the materials of the waste. To make effective use of the active assay technique it is essential that the composition of the waste matrix be known. The Rocky Flats assays, except for the sludges, utilize gamma-ray counting techniques, which are subject to their own large matrix effects. Development of correction factors for a wide variety of waste matrices has been refined over a period of many years at Rocky Flats. These efforts have evidently been very successful. We have gained new respect for the overall effectiveness of the Rocky Flats assay techniques through the assay comparisons of the present study. The comparisons of active assays with the passive assay results and the Rocky Flats values has made it possible to derive matrix correction factors that allow the active assay to yield acceptable results where the passive assay technique fails.

Table 3 summarizes the results of the various linear fits that were used to compare the results of the three methods of assay, and to derive matrix correction factors for the active assays. The matrix correction factors derived from the fits are the slopes of the fits of passive assay vs uncorrected active assay for the most part. Fits of the Rocky Flats measurements vs the active assays were used in some cases, notably the molten salts. The actual correction factors adopted are those shown in Table 1. Some compromises were made in arriving at the adopted values, notably the acceptance of a parabolic fit to simulate the possible effects of self-protection in some matrices.

The standard deviations of Y upon X listed in Table 4 represent a measure of the precision of the assays. Some of the values look remarkably small in view of the amount of point scatter shown in the various figures. This is notably true for Code 376 waste. The standard deviation is dominated by the many

assays falling close to the fitted line. Figure 4 shows the frequency distribution of the residuals in the RFP-active assay fit of Figure A-55. These residuals do not represent errors in the active assays alone, but represent a convolution of the error distributions of the active and the Rocky Flats assays. The distribution is dominated by a large, narrow central peak, indicating that most residuals are small. The curve represents the shape of the normal distribution. There are many points having residuals greater than would be expected if the residuals followed a normal distribution. This situation illustrates the difficulty of assigning error estimates to assays of nuclear waste. Whatever reasonable estimate is used for the error, there will be some assays for which the errors are dramatically greater. A reliable system of error estimation will require an intensive study of the systematics of the waste assay procedures.

TABLE 3. Fitted Parameters

Code	Passive vs Active		RFP vs Active		Passive vs RFP	
	Slope	$\sigma_{y,x}$	Slope	$\sigma_{y,x}$	Slope	$\sigma_{y,x}$
001	3.12	14.03	1.03	2.69	2.30	17.02
003	1.56	3.57	0.74	3.53	0.40	0.05
004	0.69	5.92	0.18	4.32	1.80	11.67
007	1.74	11.85	0.08	0.64	5.46	14.08
292	1.94	8.96	2.51	6.59	0.69	14.12
300 & 303	1.49	13.58	1.54	11.30	0.96	10.61
320	4.23	15.22	4.52	16.82	0.89	15.70
330	2.36	59.68	1.97	9.36	1.32	56.57
335	1.69	2.48	1.77	0.78	0.89	2.82
336	1.94	22.24	2.89	20.79	0.48	23.36
337	2.51	8.97	2.36	38.88	0.86	33.88
339	2.65	16.28	3.40	21.39	0.73	13.52
371	2.13	19.84	1.89	15.81	1.03	32.17
374	0.57	11.92	0.66	1.57	1.37	11.73
376	2.54	21.47	2.67	29.01	0.72	24.72
393	....	....	2.56	40.69	....	....
409	....	....	10.87	34.63	....	....
411	....	....	13.68	43.11	....	....
422	1.02	7.98	2.72	12.03	0.37	6.80
432	1.45	3.49	1.82	8.22	0.74	6.63
440	1.66	1.78	3.35	6.32	0.60	4.61
442	7.06	5.50	11.90	5.01	0.64	5.68
480 & 481	2.58	14.80	2.90	28.14	1.00	24.51
490	2.25	10.92	2.94	9.77	0.78	7.47
Averages	2.25	13.36	3.37	15.48	1.14	16.03
Std Dev	1.38	12.22	3.57	13.52	1.09	13.12

SWEPP CODE 376 ASSAYS

Figure 4. Frequency distribution of residuals in the fit of Rocky Flats assays to active assays for Code 376. The curve represents a normal distribution.

REFERENCES

1. J. T. Caldwell et al., The Los Alamos Second-Generation System for Passive and Active Neutron Assays of Drum-Size Containers, LA-10774-MS, September 1986.
2. J. T. Caldwell, Private Communication.
3. R. A. Harlan, Private Communication

APPENDIX

The plots in this Appendix represent the assay comparisons and data fitting upon which are based the derivation of matrix correction factors for the active assays. The solid lines represent the linear fit to the data. The dashed lines represent the matrix corrections used in the current algorithms, when these are different from the linear fits.

SWEPP CODE 001 ASSAYS

Figure A-1. Code 001 sludge: Comparison of Rocky Flats and active assays by individual drums.

SWEPP CODE 001 ASSAYS Group-Averaged Data

Figure A-2. Code 001 sludge: Comparison of Rocky Flats and active assays by batch average.

SWEPP CODE 001 ASSAYS Frequency Distribution of Active Assays

Figure A-3. Code 001 sludge: Frequency distribution of active assays.

SWEPP CODE 001 ASSAYS Frequency Distribution of RFP Assays

Figure A-4. Code 001 sludge: Frequency distribution of Rocky Flats assays.

SWEPP CODE 001 ASSAYS Frequency Distribution of (N/S)/MCI

Figure A-5. Code 001 sludge: Frequency distribution of (α, n) neutron production, high range.

SWEPP CODE 001 ASSAYS
Frequency Distribution of (N/S)/MCI

Figure A-6. Code 001 sludge: Frequency distribution of (α, n) neutron production, low range.

SWEPP CODE 001 ASSAYS
Frequency Distribution of MOD

Figure A-7. Code 001 sludge: Frequency distribution of the moderator parameter MOD.

SWEPP CODE 001 ASSAYS

Figure A-8. Code 001 sludge: Frequency distribution of the total correction factor CF.

SWEPP CODE 007 ASSAYS

Figure A-9. Code 007 sludge: Comparison of Rocky Flats and active assays by individual drums.

SWEPP CODE 007 ASSAYS Group-Averaged Values

Figure A-10. Code 007 sludge: Comparison of Rocky Flats and active assays by batch averages.

SWEPP CODE 007 ASSAYS Frequency Dist. of Active Assays

Figure A-11. Code 007 sludge: Frequency distribution of active assays.

SWEPP CODE 007 ASSAYS Frequency Dist. of RFP Assays

Figure A-12. Code 007 sludge: Frequency distribution of Rocky Flats assays.

SWEPP CODE 007 ASSAYS
Freq. Dist. of N/S-mCi

Figure A-13. Code 007 sludge: Frequency distribution of (α, n) neutron production.

SWEPP CODE 007 ASSAYS

Freq. Dist. of MOD

Figure A-14. Code 007 sludge: Frequency distribution of the moderator parameter MOD.

SWEPP CODE 007 ASSAYS

Figure A-15. Code 007 sludge: Frequency distribution of the total correction factor CF.

SWEPP CODE 003 ASSAYS

Figure A-16. Code 003 sludge: Comparison of Rocky Flats and active assays.

SWEPP CODE 003 ASSAYS

Figure A-17. Code 003 sludge: Frequency distribution of the moderator parameter MOD.

SWEPP CODE 003 ASSAYS

Figure A-18. Code 003 sludge: Frequency distribution of the total correction factor CF.

SWEPP CODE 004 ASSAYS

Figure A-19. Code 004 sludge: Comparison of Rocky Flats and active assays.

SWEPP CODE 004 ASSAYS

Figure A-20. Code 004 sludge: Comparison of passive and active assays.

SWEPP CODE 004 ASSAYS

Figure A-21. Code 004 sludge: Comparison of passive and Rocky Flats assays.

SWEPP CODE 004 ASSAYS

Figure A-22. Code 004 sludge: Frequency distribution of the moderator parameter MOD.

SWEPP CODE 004 ASSAYS

Figure A-23. Code 004 sludge: Frequency distribution of the total correction factor CF.

SWEPP CODE 292 ASSAYS

Figure A-24. Code 292 (bottled sludge): Comparison of passive and active assays.

SWEPP CODE 292 ASSAYS

Figure A-25. Code 292 (bottled sludge): Comparison of Rocky Flats and active assays.

SWEPP CODE 292 ASSAYS

Figure A-26. Code 292 (bottled sludge): Comparison of passive and Rocky Flats assays.

SWEPP CODES 300 AND 303

Figure A-27. Codes 300 and 303 (graphite): Comparison of passive and active assays.

SWEPP CODES 300 AND 303

Figure A-28. Codes 300 and 303 (graphite): Comparison of Rocky Flats and active assays.

SWEPP CODES 300 AND 303

Figure A-29. Codes 300 and 303 (graphite): Comparison of passive and Rocky Flats assays.

SWEPP CODE 320 ASSAYS

Figure A-30. Code 320 (tantalum): Comparison of passive and active assays.

SWEPP CODE 320 ASSAYS

Figure A-31. Code 320 (tantalum): Comparison of Rocky Flats and active assays.

SWEPP CODE 320 ASSAYS

Figure A-32. Code 320 (tantalum): Comparison of passive and Rocky Flats assays.

SWEPP CODE 330 ASSAYS

Figure A-33. Code 330 (dry paper and rags): Comparison of passive and active assays.

SWEPP CODE 330 ASSAYS

Figure A-24. Code 330 (dry paper and rags): Comparison of Rocky Flats and active assays.

SWEPP CODE 330 ASSAYS

Figure A-35. Code 330 (dry paper and rags): Comparison of passive and Rocky Flats assays.

SWEPP CODE 335 ASSAYS

Figure A-36. Code 335 (absolute filters): Comparison of passive and active assays.

SWEPP CODE 335 ASSAYS

Figure A-37. Code 335 (absolute filters): Comparison of Rocky Flats and active assays.

SWEPP CODE 335 ASSAYS

Figure A-38. Code 335 (absolute filters): Comparison of passive and Rocky Flats Assays.

SWEPP CODE 336 ASSAYS

Figure A-39. Code 336 (moist paper and rags): Comparison of passive and active assays.

SWEPP CODE 336 ASSAYS

Figure A-40. Code 336 (moist paper and rags): Comparison of Rocky Flats and active assays.

SWEPF CODE 336 ASSAYS

Figure A-41. Code 336 (moist paper and rags): Comparison of passive and Rocky Flats assays.

SWEPP CODE 337 ASSAYS

Figure A-42. Code 337 (plastics, teflon, PVC): Comparison of passive and active assays.

SWEPP CODE 337 ASSAYS

Figure A-43. Code 337 (plastics, teflon, PVC): Comparison of Rocky Flats and active assays.

SWEPP CODE 337 ASSAYS

Figure A-44. Code 337 (plastics, teflon, PVC): Comparison of passive and Rocky Flats assays.

SWEPP CODE 339 ASSAYS

Figure A-45. Code 339 (lead gloves): Comparison of passive and active assays.

SWEPP CODE 339 ASSAYS

Figure A-46. Code 339 (lead gloves): Comparison of Rocky Flats and active assays.

SWEPP CODE 339 ASSAYS

Figure A-47. Code 339 (lead gloves): Comparison of passive and Rocky Flats assays.

SWEPP CODE 371 ASSAYS

Figure A-48. Code 371 (firebrick): Comparison of passive and active assays.

SWEPP CODE 371 ASSAYS

Figure A-49. Code 371 (firebrick): Comparison of Rocky Flats and active assays.

SWEPP CODE 371 ASSAYS

Figure A-50. Code 371 (firebrick): Comparison of passive and Rocky Flats assays.

SWEPP CODE 374 ASSAYS

Figure A-51. Code 374 (blacktop, etc.): Comparison of passive and active assays.

SWEPP CODE 374 ASSAYS

Figure A-52. Code 374 (blacktop, etc.): Comparison of Rocky Flats and active assays.

SWEPP CODE 374 ASSAYS

Figure A-53. Code 374 (blacktop, etc.): Comparison of passive and Rocky Flats assays.

SWEPP CODE 376 ASSAYS

Figure A-54. Code 376 (cemented insulation and filter media): Comparison of passive and active assays.

SWEPP CODE 376 ASSAYS

Figure A-55. Code 376 (cemented insulation and filter media): Comparison of Rocky Flats and active assays, for all drums.

SWEPP CODE 376 ASSAYS

Figure A-56. Code 376 (cemented insulation and filter media): Comparison of Rocky Flats and active assays. for drums for which passive assay failed.

SWEPP CODE 376 ASSAYS

Figure A-57. Code 376 (cemented insulation and filter media): Comparison of passive and Rocky Flats assays.

SWEPP CODE 393 ASSAYS

Figure A-58. Code 393 (sand, slag, crucibles): Comparison of Rocky Flats and active assays.

SWEPP CODE 409 ASSAYS

SWEPP CODE 411 ASSAYS

Figure A-60. Code 411 (molten salts): Comparison of Rocky Flats and active assays.

SWEPP CODE 422 ASSAYS

Figure A-61. Code 442 (soot): Comparison of passive and active assays.

SWEPP CODE 422 ASSAYS

Figure A-62. Code 422 (soot): Comparison of Rocky Flats and active assays.

SWEPP CODE 422 ASSAYS

Figure A-63. Code 422 (soot): Comparison of passive and Rocky Flats assays.

SWEPP CODE 432 ASSAYS

Figure A-64. Code 432 (resin, leached and cemented): Comparison of passive and active assays.

SWEPP CODE 432 ASSAYS

Figure A-65. Code 432 (resin, leached and cemented): Comparison of Rocky Flats and active assays.

SWEPP CODE 432 ASSAYS

Figure A-66. Code 432 (resin, leached and cemented): Comparison of passive and Rocky Flats assays.

SWEPP CODE 440 ASSAYS

Figure A-67. Code 440 (glass): Comparison of passive and active assays.

SWEPP CODE 440 ASSAYS

Figure A-68. Code 440 (glass): Comparison of Rocky Flats and active assays.

SWEPP CODE 440 ASSAYS

Figure A-69. Code 440 (glass): Comparison of passive and Rocky Flats assays.

SWEPP CODE 442 ASSAYS

Figure A-70. Code 442 (Raschig rings): Comparison of passive and active assays.

SWEPP CODE 442 ASSAYS

Figure A-71. Code 442 (Rashig rings): Comparison of Rocky Flats and active assays.

SWEPP CODE 442 ASSAYS

Figure A-72. Code 442 (Rashig rings): Comparison of passive and Rocky Flats assays.

SWEPP CODE 480-481 ASSAYS

Figure A-73. Codes 480 and 481 (scrap metal): Comparison of passive and active assays.

SWEPP CODE 480-481 ASSAYS

Figure A-74. Codes 480 and 481 (scrap metal): Comparison of Rocky Flats and active assays.

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SWEPP CODE 490 ASSAYS

Figure A-76. Code 490 (CWS filters): Comparison of passive and active assays.

SWEPP CODE 490 ASSAYS

Figure A-77. Code 490 (CWS filters): Comparison of Rocky Flats and active assays.

SWEPP CODE 490 ASSAYS

Figure A-78. Code 490 (CWS filters): Comparison of passive and Rocky Flats assays.

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