TRU Waste Assay Methodology with the Combined Thermal Epithermal Neutron (CTEN) System

John M. Veilleux and Jane A Enter
Los Alamos National Laboratory, Los Alamos, NM 87545
January 2, 2003

Abstract

The CTEN assay system is designed to measure plutonium bearing 208-L waste drums and make the transuranic versus low-level waste determination. The system was certified for Waste Isolation Pilot Plant operations and the Environmental Protection Agency approved the CTEN in 2002. It is the only system capable of making the transuranic/low-level waste (TRU/LLW) determination since it can routinely assay below 100 nCi/g. The system conducts a measurement by using either (or both) an active 14 MeV neutron pulse to induce fission in $^{239}$Pu and $^{241}$Pu or measures the spontaneous fission properties of $^{238}$Pu, $^{240}$Pu and $^{242}$Pu. When the coincidence neutron signal is combined with mass fraction data from a gamma system, the result is the total plutonium mass. The system’s lower limit of detection is as low as 2 mg of weapons grade plutonium, making it an ideal platform to make the TRU/LLW determination. Analysis of an assay is made with visual basic application driven subroutines and Microsoft Excel spreadsheets. Input values and calculations include: the raw neutron scaler and coincidence counts; mass fraction information; plutonium mass; alpha, total and TRU activity; thermal power, $^{239}$Pu Equivalent Curies; fissile gram equivalent mass; decay heat; and uncertainties associated with each parameter. A general diagnostic analysis is performed for each assay to facilitate a technical review of the results. The results of analysis from 372 waste drums are summarized. The results indicate that modifying current operating procedures involving the use of acceptable knowledge isotope data and use of the lower detection limit could increase the number of certifiable assays from 38% to 66%.

INTRODUCTION

The CTEN assay system is designed to measure plutonium bearing 208-L waste drums and make the transuranic (TRU) versus low-level waste (LLW) determination. A description of the system may be found at reference 1. The system was certified for Waste Isolation Pilot Plant (WIPP) operations and the Environmental Protection Agency (EPA) approved the CTEN in 2002. CTEN is one of the few systems capable of making a transuranic/low-level waste (TRU/LLW) determination because its lower limit of detection (LLD) is as low as 2 mg, which is often below the 100-nCi/g TRU limit for plutonium. The system performs a measurement by actively inducing fission in $^{239}$Pu and $^{241}$Pu or by passively measuring the spontaneous fission emissions from $^{238}$Pu, $^{240}$Pu and $^{242}$Pu. When the neutron signal is combined with isotopic data from a gamma system and corrected for matrix effects, the result is the total plutonium mass.

In the period 8/15/2001 through 10/9/2002, the CTEN performed 372 active and passive assays of waste drums. This total does not include assays for calibration, total measurement uncertainty and verification to meet the WIPP shipping requirements. A typical waste assay begins after the daily background (blank) measurement, a daily system check, and a weekly matrix performance check have been conducted and evaluated. Data acquisition is controlled with a software program, WIN-CTEN (2). A 20,000 14 MeV active neutron pulse lasting 200 seconds is first taken and followed by a passive neutron five-minute assay. At the conclusion of each active and passive assay, WIN-CTEN generates an ASCII and binary assay files containing the raw neutron counts and neutron arrival times. For passive data, the neutron arrival times contained in the binary files must first be processed by an ancillary program, CTEN-FIT (3), to generate the neutron coincidence data before these can be processed by the assay spreadsheet. The overall process flow is shown in Figure 1. A visual basic application (VBA) driven Excel assay spreadsheet, CTEN02D.xls (4), is used to process the data and derive the plutonium mass. This paper describes the methodology of the CTEN02D assay spreadsheet and the results of the waste assays.
Figure 1. CTEN Process Flow

CTEN02D ASSAY SPREADSHEET AND REGIONS

The CTEN02D assay summary sheet is shown in Figure 2 and divided into five regions for ease of description. The regions and their function are summarized in Table 1. The RadioAssay Data Sheet is automatically generated from the summary sheet. Detailed MathCAD (5) application documentation is incorporated in the quality assurance development testing conducted for the applications, as described at reference 4.

Table 1. CTEN02D Summary Radioassay Data Sheet

<table>
<thead>
<tr>
<th>Region</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The Assay Data Region. Region A is generated by reading the WIN-CTEN generated ASCII files. The data include the assay and background file names, the waste drum and matrix weight, the analysis method, background data, and neutron count data. Values are determined for both active and passive modes. For passive data, the CTEN-FIT program must first be run to develop the coincidence (doubles) neutron counts.</td>
</tr>
<tr>
<td>B</td>
<td>The Gamma System Isotopic Region. Region B is driven by a visual basic application that read the gamma system isotopic results and determines if the isotope is to be reported based on detection limits.</td>
</tr>
<tr>
<td>C</td>
<td>Effective and Total Plutonium Mass Region. Region C contains calculations to determine the plutonium mass and uncertainties. The data combines the results from regions A and B.</td>
</tr>
<tr>
<td>D</td>
<td>Isotopic Assay Results Region. Region D contains calculations to determine the isotopic mass, activity, fissile gram equivalent, thermal power, and plutonium equivalent activity results for all reportable isotopes.</td>
</tr>
<tr>
<td>E</td>
<td>General Assay Results and Diagnostic Tests Region. Region E summarizes the main assay results and incorporates diagnostics tests. The total measurement uncertainty is calculated in this region.</td>
</tr>
</tbody>
</table>
CTEN Assay Overview

Figure 2. The CTEN Assay Spreadsheet
Region A: The Assay Data Region

The data in region A is generated from the WIN-CTEN ASCII files and operator input. The data include the assay and background file names, the waste drum and matrix weight, the analysis method, background data, and neutron count data. Values are determined for both active and passive modes. For passive data, the CTEN-FIT program must first be run to develop the coincidence counts. The cells are populated by VBA macros developed for this purpose. The drum ID, net weight, and assay method are input by the operator when the “Read Assay Data” button is activated. The background method is operator selectable and options include automatic file selection (typical), operator entered value, or an empirical function. The VBA macros read the raw data files generated by WIN-CTEN and/or CTEN-FIT, extract the raw neutron counts from the appropriate time windows, and populate the cells. Cells contain appropriate formulae to calculate the net response, transmission and flux correction factors, self-shielding factors, and calibration factors. The appendix summarizes the equations and purpose of the cells.

Region B: The Gamma System Isotopic Region

The data in region B is obtained from the FRAM gamma system assay data that calculates isotopic mass ratios. The data is populated by a VBA macro initiated by the operator via the “Read FRAM Data” button on this sheet. Isotopes listed are those that are either specified by WIPP or that may be in the LANL waste stream. This data is in the form of weight % for the Pu isotopes, in parts per million for $^{241}$Am, and in mass fractions for all the other isotopes. The Pu and $^{241}$Am uncertainties are all one standard deviation and in the same units as reported for the isotope. For the remaining isotopes (i.e., the secondary isotopes), the uncertainties are one standard deviation relative fractions.

The Pu isotopes and $^{241}$A are always reported but the secondary isotopes are reported only if they are detected. Detection is defined as a relative mass fraction exceeding the Currie (6) detection limit by a factor of 4.65 (or 21.5%). When this occurs, the column “Report on RDS” for isotopes $^{243}$Am through $^{232}$Th are reported with a “Y”. If the isotope is reported as undetected (a “N”), the mass of that isotope is zeroed in region D.

Region C: Effective and Total Plutonium Mass

The effective and total plutonium mass is calculated by combining the neutron counts (region A) with the isotopic information in region B. The preferred assay mode is made based on either operator selection or automatic selection. The automatic selection requires that both the effective $^{239}$Pu and $^{240}$Pu equal or exceed the lower calibration range of the instrument, that alpha (ratio of singles to doubles) be greater than 1000, that the passive error be less than 100%, and that the passive error be less than the active error. The automatic selection is used only in a passive mode and can be overridden by the operator. The appendix summarizes the equations and purpose of the cells.

Region D: Isotopic Assay Results

Region D summarizes the assay for each isotope. If the isotope was not detected, as indicated by “N” in region B, “Report on RDS”, it is zeroed. All values are determined from the plutonium mass and total measurement uncertainty (TMU) calculated in region E. The isotope masses are first determined and then the isotopic activity, FGE, thermal power, and PE curies are calculated from the isotopic mass and nuclear data (7,8) for specific activity, FGE, thermal power, and PE curies. The appendix summarizes the equations and purpose of the cells.

Region E: General Assay Results and Diagnostic Tests

Region E of the spreadsheet summarizes the assay results, includes the calculation for the total measurement uncertainty (TMU), and provides a set of diagnostic tests for a technical review of the data. The appendix summarizes the equations and the diagnostic tests.

The general assay results include the FGE mass, the total and total alpha activity, the TRU activity relative to the matrix weight, the decay heat and the PE curies. The value is obtained by summing the isotopic data in region D while the uncertainty is obtained as the sum squared of the isotopes.

The Assay Results and General Diagnostics summarize the key points of the assay and are intended for the technical reviewer. The questions are answered with a “yes” or “no”, except where a specific value is needed. The analysis method identifies the selected assay mode, either “Active” or “Passive”. Checks for transportation
and activity limits are made for FGE, PE, and TRU activities. The Pu mass is transferred from region C and the total measurement uncertainty (TMU) is calculated. The TMU takes into account the total bias of the instrument and the counting statistic results from region C. The minimum detectable concentration (MDC) mass or equivalently the LLD is calculated and its determination is based on 5% error limits for detection (see ref. 6).

The “General Diagnostics” checks the drum ID obtained from the ASCII file with the drum ID entered by the operator. The FRAM ID provides a similar check. The MDC is compared to the background uncertainty to verify that the lower limit of detection criteria is met. Other checks are performed to verify that the limits are met for the certified assay range, that the assay on both CTEN and FRAM were made within 1.5 years (to minimize assay errors), that the number of pulses and count time reflect the certification parameters, that there is no significant interference from $^{233}\text{U}$ or $^{235}\text{U}$ in the active mode, that the cosmic ray interference is minimal for both the assay and the background, that the MDC ratio is above one, and that the matrix correction factor is within certified limits. The appendix summarizes the equations and purpose of the cells.

RESULTS OF ASSAYS

Assays of 208-L drums of plutonium waste using the CTEN were conducted from August 15, 2001 during which time 372 waste drums were assayed through October 9, 2002. The purpose of this section is to characterize these assays in terms of the number that were WIPP certifiable, and the additional number that could be certified using other criteria, such as acceptable knowledge of the waste stream. Table 2 summarizes the CTEN assay results for the period indicated.

The WIPP certifiable assays were those that were determined to be transuranic (TRU) waste, that had a certifiable gamma spectroscopic assay using FRAM, and that the criteria identified in region E of the assay spreadsheet were met or otherwise qualified. A total of 140 drums (37.6%) met these criteria.

For 59 additional waste drums, although CTEN obtained a signal above its MDC, the FRAM gamma spectroscopic assay did not result in a certifiable assay because the plutonium mass was too weak to produce an adequate spectrum after one hour of counting (15 hours in some cases). However, these wastes came from streams with acceptable knowledge (AK) that provide estimates of the isotopic mass fractions. The AK isotopic values were decay corrected by an arbitrary 9 years for MT52, 54, 55, and 83 and by 5 years for MT42 and 53 to improve the assay results. Using the AK isotopic data with the CTEN signal would produce an otherwise certifiable assay, increasing the percentage of WIPP shippable drums from 37.6% to 53.5%.

For 94 waste drums, the CTEN signal was below its MDC and, in all but two cases, the FRAM spectroscopic assay did not result in a certifiable assay because the plutonium mass was too weak to produce an adequate spectrum after one hour of counting (15 hours in some cases). If the TRU/LLW determination were made at the MDC mass and decay corrected AK data were used for the isotopic mass fraction, an additional 48 (12.9%) waste drums could be certified for WIPP shipment with the remainder assaying as LLW.

For 18 waste drums, other assay problems were noted including assays with too high a uranium content, assays with high ($\alpha$, n) reactions, assays outside the CTEN range certification limits, assays with corrupted WIN-CTEN data files, etc. These account for 4.8% of the waste drums.

Of the assays, 102 drums were assayed below the TRU limit of 100 nCi/g; these drums are low-level waste by definition. This total includes drums that were otherwise certifiable or that were determined to be LLW based on AK or were determined to be LLW at the CTEN’s MDC mass.

Most assays were made using the active neutron interrogation mode (92.7%) and the remainder using the passive assay mode (7.3%). The passive assay is typically used when the mass loading in the matrix exceeds three grams of Pu up to 201.5 g of weapons grade Pu. The active assay can be used from the MDC (as low as 2 milligrams of weapons grade Pu) to 8.96 g of weapons grade Pu.
Table 2. Assays on CTEN from August 15, 2001 through October 9, 2002

<table>
<thead>
<tr>
<th>Description</th>
<th>Number</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Assays</td>
<td>372</td>
<td>100.0</td>
</tr>
<tr>
<td>Number of WIPP Certifiable Assays</td>
<td>140</td>
<td>37.6</td>
</tr>
<tr>
<td>Number of Additional Assays with AK Isotopic Data</td>
<td>59</td>
<td>15.9</td>
</tr>
<tr>
<td>Number of Additional Assays with MDC Determination</td>
<td>48</td>
<td>12.9</td>
</tr>
<tr>
<td>Number of Additional Assays with Other Problems</td>
<td>18</td>
<td>4.8</td>
</tr>
<tr>
<td>Number of LLW Drums</td>
<td>102</td>
<td>27.4</td>
</tr>
<tr>
<td>Number of Active Assays</td>
<td>345</td>
<td>92.7</td>
</tr>
<tr>
<td>Number of Passive Assays</td>
<td>27</td>
<td>7.3</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This paper summarizes the CTEN assay methodology and presents the assay results from 372 waste drums that were assayed Aug 15, 2001 through Oct 9, 2002. Of these drums, 140 (37.6%) were certifiable for shipment to the Waste Isolation Pilot Plant. An additional 28.8% (107 drums) could also be shipped by changing operating procedures to utilize acceptable knowledge of the isotopic waste stream and/or evaluating the transuranic/low-level waste criteria at the lower detection limit. Of the waste drums assayed, 27.4% (102 drums) could be reclassified as low-level waste rather than transuranic waste.

REFERENCES

7. Los Alamos National Laboratory Transuranic Waste Certification Plan (Cert Plan), TWCP-PLAN-0.2.4-001, R.5), LA-UR-02-3724
Appendix

The assay descriptions listed below are summarized by region of the assay spreadsheet as described in the main text.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region A—The Assay Data Region</strong></td>
<td></td>
</tr>
<tr>
<td>Drum ID</td>
<td>The drum identification name read from the ASCII file</td>
</tr>
<tr>
<td>Net Weight (g)</td>
<td>The drum net weight as input by the operator in the VBA form, Assay_Form</td>
</tr>
<tr>
<td>Assay Method</td>
<td>An operator selected input method in the VBA form, Assay_Info</td>
</tr>
<tr>
<td>Active Win CTEN Version</td>
<td>The version number as read from the ASCII file</td>
</tr>
<tr>
<td>Active File &amp; Date</td>
<td>Active file name as input by the operator in the VBA form, Assay_Form</td>
</tr>
<tr>
<td>Bkg File &amp; Date</td>
<td>The blank drum file name and date as read from the blank drum ID ASCII file name for the assay date specified. If file is unavailable, the macro requests where to find the file or to specify the background response and uncertainty.</td>
</tr>
<tr>
<td>Bkg Response</td>
<td>Same as Background, R_0 (see below). The actual background response values and uncertainties used from one of the following sources: the blank drum file, the operator selected values, or an empirical function for the background.</td>
</tr>
<tr>
<td>File</td>
<td>File name read from the ASCII file</td>
</tr>
<tr>
<td>Pulses</td>
<td>Number of pulses fired as read from the ASCII file</td>
</tr>
<tr>
<td>Thermal Cnts, C_4</td>
<td>C_4 is the total number of neutron counts from the thermal window, scaler 4, all angles, excluding the total counts from scaler 4 external flux monitor, detector A16. The thermal window is from 800 to 2800µs. [ \sigma_{C_4} = \sqrt{C_4} ]</td>
</tr>
<tr>
<td>Backgnd Cnts, C_5</td>
<td>C_5 is the total number of neutron counts from the background window, scaler 5, all angles, excluding the total counts from scaler 4 external flux monitor, detector A16. The background window is from 5600 to 9600µs. [ \sigma_{C_5} = \sqrt{C_5} ]</td>
</tr>
<tr>
<td>ExtFlux, F</td>
<td>F is the number of neutron counts from the external flux monitor (detector A16) during the first 50 microsecond of the neutron burst, all angles, all scalers. This value is available but not used for an assay. [ \sigma_F = \sqrt{C_F} ]</td>
</tr>
<tr>
<td>DFM4</td>
<td>DFM4 is the number of neutron counts from the bare flux monitors in the thermal window, scaler 4, from detectors B13, B14, and B15. [ \sigma_{DFM4} = \sqrt{C_{DFM4}} ]</td>
</tr>
<tr>
<td>DFM3</td>
<td>DFM3 is the number of neutron counts from detectors B13, B14, and B15 in the third epithermal window, scaler 3, for all angles. This value is available but not used for an assay. [ \sigma_{DFM3} = \sqrt{C_{DFM3}} ]</td>
</tr>
<tr>
<td>BFM4</td>
<td>BFM4 is the number of neutron counts from the thermal window, scaler 4, for all angles, from the bare flux monitor, detector B12. [ \sigma_{BFM4} = \sqrt{C_{BFM4}} ]</td>
</tr>
</tbody>
</table>
BFMS

BFMS is the number of neutron counts from the epithermal and thermal windows, scalers 1 through 4, all angles, detector B12, the bare flux monitor.

$$\sigma_{BFMS} = \sqrt{C_{BFMS}}$$

SFM

SFM is the number of neutron counts from the shielded flux monitor in the epithermal region, scalers 1 through 3, all angles, detector B16, the shielded flux monitor.

$$\sigma_{SFM} = \sqrt{C_{SFM}}$$

Background, R₀

The term (0) indicates the blank drum.

$$R_0 = \frac{C_4 - g C_3}{DFM 4(0)}$$

$$\sigma_{R_0} = \frac{1}{DFM 4(0)} \sqrt{C_4(0) + g^2 C_3(0) + R_0^2 \cdot DFM 4(0)}$$

Net Response, R

$$R = \frac{C_4 - g C_3}{DFM 4} - R_0$$

$$\sigma_R = \sqrt{\left(\frac{\sigma_{C_4}}{DFM 4}\right)^2 + \left(\frac{g \sigma_{C_3}}{DFM 4}\right)^2 + \left[(R + R_0) \sigma_{DFM 4}\right]^2 + \sigma_{R_0}^2}$$

transCf

The transmission correction factor. An empirical function relating ratios of chamber flux monitors.

fluxCf

The flux correction factor. An empirical function relating ratios of bare and shielded drum flux monitors.

ActiveCal, K and $$\sigma_K$$

0.54 ± 0.0700 grams of Pu239 effective per unit net response. Active calibration factor was determined using NIST traceable standards.

MatrixCF, MATₐ

$$MAT_a = transCf \times fluxCf$$

$$\sigma_{MAT_a} = MAT_a \sqrt{\epsilon_{transCf}^2 + \epsilon_{fluxCf}^2}$$

This is the active matrix correction factor.

Self-Shielding, SSF

$$SSF = ae^{-br}$$

$$\sigma_{SSF} = SSF \sqrt{\epsilon_a^2 + \left(Rb\right)^2 \left(e_b^2 + e_r^2\right)}$$

SSF is an empirical function relating SSF to the assayed active mass. Separate values are used for waste and for calibration and verification sources.

Cosmic Rate

The count rate attributed to cosmic rays. Value is determined in CTEN_FIT.

Cnt Time (s)

The passive assay count time, in seconds

Net Sgls Rate, S

The net singles rate of neutrons after subtracted from the background. Value is determined in CTEN_FIT. Uncertainty based on Poisson counting statistics only. This is the total neutron counts irrespective of source, and includes coincidence neutrons as well as interactive neutrons (e.g, alpha particle interactions with nuclides to produce neutrons)

Net Dbls Rate, D and $$\sigma_D$$

The net neutron doubles rate after subtraction for background. Value is determined in CTEN-FIT. Uncertainty based on Poisson counting statistics only.

Bkg Dbls Rate, D₀

The background doubles rate of coincidences in the blank drum, normally an empty drum. Uncertainty based on Poisson counting statistics only.

SinglesCal, Kₛ & $$\sigma_{K_s}$$

0.0032 ± 0.0001 g Pu240Effective/Net Singles Rate. The singles neutron calibration constant and uncertainty. Calibration based on use of shielded detectors only.
### SglsMatCF, MAT₅

MAT₅ = \( transCf \)

\[ \sigma_{\text{MAT}_5} = \sqrt{\text{transCf}} \]

This is the passive single neutron matrix correction factor and uncertainty.

### DoublesCal, K_D

0.1239 ± 0.0121 g Pu240Effective/Net Doubles Rate

The neutron coincidence (doubles) calibration factor and uncertainty. Calibration based on use of shielded detectors only.

### PasMatCF, MAT_D

\[ \text{MAT}_D = (\text{transCf})^2 \]

\[ \sigma_{\text{MAT}_D} = 2 \times \text{transCf} \times \sigma_{\text{transCf}} \]

### Alpha, α

\[ \alpha = \frac{K_S \times \text{MAT}_S}{K_D \times D \times \text{MAT}_D} \]

### gate, g

The gate fraction, typically ½. The gate fraction is the time of the thermal window to the time of the background window.

### Region C: Effective and Total Plutonium Mass

#### Pu239Eff

\[ m_{\text{Pu239Eff}} = \frac{K \times R \times \text{MAT}_D}{\text{SSF}} \]

\[ \sigma_{m_{\text{Pu239Eff}}} = m_{\text{Pu239Eff}} \times \sqrt{\epsilon^2_R + \epsilon^2_{\text{K}_S} + \epsilon^2_{\text{MAT}_D} + \epsilon^2_{\text{SSF}} + 2bR\epsilon^2_R} \]

#### Pu240Eff

\[ m_{\text{Pu240Eff}} = K_D \times D \times \text{MAT}_D \]

\[ \sigma_{m_{\text{Pu240Eff}}} = m_{\text{Pu240Eff}} \times \sqrt{\epsilon^2_D + \epsilon^2_{K_D} + \epsilon^2_{\text{MAT}_D}} \]

#### Active Pu Mass, m_Pu

\[ F_{239} = 9.013 \pm 0.97 \]

\[ F_{241} = 12.582\pm0.303 \]

These values are proportional to the thermal cross sections of Pu239 or Pu241 and the neutron emissions per collision, and inversely proportional to the molecular weight.

ICF is a factor to account for the Pu241 contribution.

#### ICF

\[ ICF = \frac{F_{241}f_{\text{Pu241}}}{F_{239}f_{\text{Pu239}}} \]

\[ \sigma_{\text{ICF}} = \frac{\sqrt{2.52f_{\text{Pu238}}} + 1.0f_{\text{Pu240}} + 1.68f_{\text{Pu242}}}{f_{\text{Pu239}}} \]

#### Passive Pu Mass, m_Pu

\[ m_{\text{Pu}} = \frac{m_{\text{Pu239Eff}}}{f_{\text{Pu239}}} \times \text{ICF} \]

\[ \sigma_{m_{\text{Pu}}} = m_{\text{Pu}} \times \sqrt{\epsilon^2_{f_{\text{Pu239}}} + \epsilon^2_{m_{\text{Pu239Eff}}} + \epsilon^2_{\text{ICF}}} \]

\[ f_{\text{Pu240Eff}} = 2.52f_{\text{Pu238}} + 1.0f_{\text{Pu240}} + 1.68f_{\text{Pu242}} \]

\[ \sigma_{f_{\text{Pu240Eff}}} = \sqrt{(2.52\sigma_{f_{\text{Pu238}}})^2 + \sigma_{f_{\text{Pu240}}}^2 + (1.68\sigma_{f_{\text{Pu242}}})^2} \]

### Region D—Isotopic Assay Results

#### Isotope Mass, m_j

\[ m_j = m_{\text{Pu}} \times f_j \]

\[ \sigma_{m_j} = \sqrt{(\sigma_{m_{\text{Pu}}} f_j)^2 + (m_{\text{Pu}} \sigma_{f_j})^2} \]
Alpha activity, FGE, thermal Power, total activity where X is the parameter and j is the isotope.

\[ X_j = m_j S_{X_j} \]
\[ \sigma_{X_j} = \sigma_{m_j} S_{X_j} \]

S is the specific value per gram of Pu.

PE Ci

\[ PE_j = A_j S_{PE_j} \]

\[ A_j \] is the total activity of isotope j. \( S_{PE_j} \) is the inverse of the weighing factor for isotope j.

### Region E--General Assay Results and Diagnostic Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
</table>
| FGE, Total Activity (A), Total Alpha Activity (A\(_\alpha\)), Decay Heat (W), and PE Curies (PE). The value X represents an of the above parameters. | \[ X = \sum X_j \]
|                           | \[ \sigma_X = \sqrt{\sum (\sigma_{X_j})^2} \]                           |
|                           | While the sum is over all isotopes, those isotopes that don’t contribute to FGE have been zeroed in region D. |

#### TRU Activity (nCi/g)

\[ k = \text{Pu238, Pu239, Pu240, Pu242, Am241, Am243, NP237}. \text{ Net Weight is the matrix weight (g) and is assumed to be error free.} \]

\[ TRU = \frac{10^9 \sum A_{ak}}{NetWeight} \]
\[ \sigma_{TRU} = \frac{10^9 \sqrt{\sum (A_{ak})^2}}{NetWeight} \]

#### FGE Test

\[ FGE + 2\sigma_{FGE} < 200 \]

#### PE Test

\[ PE < 80 \]

#### TRU Test

\[ TRU > 100 \text{ nCi/g} \]

#### Pu Mass (g)

The Pu mass for the selected method

#### Pu 1\( \sigma \) (TMU)

\[ TMU = \sqrt{\left(\sigma_A^2 + \text{MAX}\left(\sigma_p, \sigma_{m_Pu}\right)^2\right)} \]

Subscript A represents the accuracy component of bias, P represents the precision component of bias, and \( m_{Pu} \) represents the counting statistics portion of the plutonium mass.

#### MDC

Active, MDC\(_A\), Passive, MDC\(_D\)

\[ MDC_A = \frac{4.65\sigma_{R_a} K_A \ast \text{MAT}_A \ast \text{ICF}}{SSF \ast f_{Pu239}} \]
\[ MDC_D = \frac{4.65\sigma_{D_a} K_D \ast \text{MAT}_D}{f_{Pu240Eff}} \]

Minimum detectable concentration is equivalent to the lower limit of detection.

#### MDC OK?

\[ R \geq 4.65\sigma_{R_a} \ast \text{Active mode} \]
\[ D \geq 4.65\sigma_{D_a} \ast \text{Passive mode} \]

#### Active Range OK

\[ m_{Pu239Eff} + 2\sigma_{Pu239Eff} \geq \frac{4.65\sigma_{R_a} K_A \ast \text{MAT}_A}{SSF} \]
\[ m_{Pu239Eff} - 2\sigma_{Pu239Eff} \leq 8.46 \]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
</table>
| Passive Range OK                | \[ m_{\text{Pu}240\text{Eff}} + 2\sigma_{\text{Pu}240\text{Eff}} \geq 4.65\sigma_{D_0} K_D \times MAT^*_D \]  
\[ m_{\text{Pu}240\text{Eff}} + 2\sigma_{\text{Pu}240\text{Eff}} \geq 0.1845 \]  
\[ m_{\text{Pu}240\text{Eff}} - 2\sigma_{\text{Pu}240\text{Eff}} \leq 12.0913 \]                                                   |
| Decay Correction OK             | Requires that the CTEN assay date and the FRAM assay date be within 1.5 years of each other.                                                        |
| Pulse or Time OK                | Requires that the number of active pulses be greater than 19,900 pulses or that the passive count time be at least 300 seconds.                    |
| U-235 OK                       | Checks that the mass fractions of both U233 and U235 are zero or not detected. Not detected is defined as the mass fraction being less than 21.5% (the Currie limit). Applies to active mode only. If response is NO, technical supervisor may certify based on other criteria. |
| Cosmic Ray OK                  | Checks that both the cosmic rate for the assay and for the blank are less than 0.75. Applies to passive mode only.                               |
| MDC Ratio                      | Active Ratio = \( \frac{R}{4.65\sigma_{R_0}} \)  
Passive Ratio = \( \frac{D}{4.65\sigma_{D_0}} \)                                                                 |
| Active Matrix OK?              | \( MAT^*_A \leq 1.6 \)  
Effectively limits waste to combustible and metal waste matrices.                                                                              |
| Passive Matrix OK?             | \( 3 \leq MAT^*_D \leq 15 \)  
\( m_{\text{Pu}} \geq 0.1822 \)                                                                                                                  |