# Screening Excavated Soils for Spent Fuel Fragments Using a Compton to Cs-137 Photopeak Ratio Methodology - 9525

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## ABSTRACT

Washington Closure Hanford LLC, working with Chesapeake Nuclear Services (ChesNuc), undertook a study to evaluate radiation detection instrumentation and possible methods that could be used for identifying the presence of Spent Nuclear Fuel (SNF) fragments during the excavation of the reactor burial trenches at the Hanford Reservation. The focus of the study was for a real-time capability with radiation detectors located on or around an excavator (and bucket), providing indication to an operator of radiation levels and potential for presence of a SNF fragment during the actual excavation process. The result was the development of an innovative gamma measurement and spectral analytical methodology to screen soils for potential spent fuel fragments. The screening methodology is based on the principle that for a specific radiation source (in this case a spent fuel fragment) as the depth (soil shielding) increases, the Compton scatter component of the spectra increases in ratio to the unattenuated photopeak intensity. Consequently, by examining spectral characteristics using gamma spectroscopy instrumentation and evaluating the Compton scatter component with the Cs-137 photopeak intensity, a determination can be made as to the potential for the presence of a spent fuel fragment. The methodology developed does not require knowledge of the depth of the spent fuel fragment in the soil column (i.e., excavator bucket).

## INTRODUCTION

The remediation of the reactor burial trenches at the Hanford Reservation is a significant element of the overall Hanford clean-up activities. Buried in the trenches that are located adjacent the reactor sites are various rubble, components and miscellaneous materials that resulted from the decommissioning of the reactors. The significant, gamma-emitting radionuclides present in the reactor burial trenches are Co-60, an activation product mainly associated with reactor components, and Cs-137, a fission product and main constituent for a spent nuclear fuel (SNF) fragment.[1] The remediation activities require that spent fuel fragments be segregated and processed separately from the other remediated materials. Therefore, a method is needed for identifying these fuel fragments, which have been characterized as material containing greater than 1.1 Ci of Cs-137 from other Co-60 contaminated materials. The varying Co-60 radioactive component in the trenches renders the use of gross radiation measurements alone incapable of distinguishing between elevated levels associated with a potential SNF fragment versus that arising from increased Co-60 contamination. However, distinctions can be made by examining the gamma spectra characteristics associated with the Cs-137 (SNF fragment) and those for Co-60.

Field measurements were collected with several different type detectors with gamma spectral capabilities for an actual fuel fragment located at varying depths in a typical excavator bucket. Based on the results of this study, it was determined that NaI detectors provided sufficient spectral capabilities and were best suited for the burial trench excavation environmental conditions. Initial field testing of a prototype system was conducted in early 2008. In September 2008, additional field acceptance testing was conducted at the 100-D complex using an actual SNF fragment attached to the bottom of an excavator bucket that had been modified with the bucket depth limited to 76 cm (30 inches) to be consistent with the bounds of the modeling and detection of a SNF fragment.

Based on the results of the study and subsequent field testing, an innovative gamma measurement and spectral analytical methodology was developed to screen soils for potential spent fuel fragments. The screening

[1] It has been approximately 30 years since the disposal of radioactively contaminated materials in the subject burial trenches. Therefore, through radioactive decay, most activation and fission products are no longer present. For gamma-emitting radionuclides, there is a relatively minor presence of Eu-152 with its 13.6 year half-life; but is insignificant compared with the presence of Cs-137 in a SNF fragment.

methodology is based on the principle that for a specific radiation source (in this case a spent fuel fragment with greater than 4.1E+10 Bq (1.1 Ci) of Cs-137) as the depth (soil shielding) increases, the Compton scatter component of the spectra increases in ratio to the unattenuated photopeak intensity. Consequently, by examining spectral characteristics using gamma spectroscopy instrumentation and evaluating the Compton scatter component with the Cs-137 photopeak intensity, a determination can be made as to the potential for the presence of a spent fuel fragment. The methodology developed does not require knowledge of the depth of the spent fuel fragment in the soil column (i.e., excavator bucket). This same methodology can also be applied for the screening for high dose rate items, such as a Co-60 source, that could pose a DOT transportation concern.

The result of this effort was the development of a specialized radiation detection system called ***CRATER™*** (Compton Ratio Analysis for Testing Environmental Radioactivity) and its proprietary software application ***CoRE*** (Compton-Ratio Evaluation) for screening excavator bucket soil content for presence of a spent fuel fragment. The screening methodology is based on conservatively established threshold conditions as a real-time means for clearing excavator bucket content. Application of the ***CRATER™*** for burial trench remediation activities will improve operations by providing a real-time screening of excavator buckets for SNF fragments and reduce personnel exposures by minimizing hands-on surveys of trench excavated materials.

## SYSTEM DESCRIPTION

***CRATER™*** is enclosed in an aluminum housing, which is affixed to the arm of an excavator boom. The outside dimensions can be described as a solid right triangle "wedge" with 41 cm (16 inches) sides and 36 cm (14 inches) width. It is positioned such that the bottoms of the detectors are a nominal 61 cm (24 inches) from the top of the bucket/soil. The detector housing is constructed primarily of 0.6 cm (0.25inches) aluminum with a detector window of reinforced low-Z material to provide an essentially open field of view for the detectors to the excavator bucket.

Within the housing are two NaI(Tl) detectors. One is a 1-inch diameter by 1-inch long crystal intended for low-range operation of less than 0.2 mSv/h (<20 mR/h). The other is a 0.25-inch diameter by 1-inch long crystal intended for high-range operation for greater than 0.2 mSv/h to 3.5 mSv/h (>0.2 mSv/h to <350 mR/h). Positioned between these two detectors is an energy-compensated "peanut" G-M tube, which provides the ambient gamma radiation exposure rate as used by the system for determining which detector to use for the screening. This G-M provides indication of radiation levels exceeding the established system operating limit). Also housed within the wedge are two modified multi-channel analyzers (one for each NaI(Tl) detector); a motorized assembly for placing a gain-stabilization source in proximity to the detectors and retracting it back to a shield; and a master controller board responsible for direct management of all functions within the wedge and communication with the external controlling device.

***CRATER™*** is controlled via a master controller board communicating via Bluetooth with a Trimble RECON (a ruggedized PDA running the Windows Mobile 6 operating system). The software application residing on this RECON provides the user interface for controlling system operations, such as to begin measurements, evaluate spectrum for potential fuel fragment (utilizing the application methodology). Other functions, such as daily source checks, backgrounds and save/retrieve/view past spectra, are also controlled via the RECON.

### Customized Multi-Channel Analyzer Description

The ***CRATER™*** contains two multichannel analyzers (MCA) for acquiring spectra from the two scintillation detectors. These MCAs are customized systems that have been specifically designed for the collection and analysis of the measurements as required for this project. They have been adapted to operate using raw excavator power (9 to 36 volts DC) and to minimize the heat generated by the electronics. Additionally, a specialized internal microcontroller has been included with expanded memory and processing capability to handle the real-time processing of spectral data on a continual basis. The microcontroller firmware has been adapted to support a more efficient data packet to ensure integrity of transmitted spectra, improved autonomous operation, high precision acquisition timing, and initialization without the intervention of an external controlling device. Hardware settings (high voltage, threshold, gain, and fine gain) are maintained in the non-volatile memory and the last-used settings are re-loaded on power-up. Regions of interest (ROIs) were established for analyzing the spectra. ROIs for the 0.667 MeV Cs-137 photopeak, the Cs-137 Compton continuum, and the 1.17 and 1.33 MeV Co-60 photopeaks, as described later.

## Computer Application Description

The computer software program for the ***CRATER™*** running on the RECON was written specifically for this application using embedded Visual C++ version 4.0. The application provides control signals to the system, retrieves data from the MCAs and other sensors, and performs the Compton-Ratio Evaluation (***CoRE***) proprietary software application for screening excavator bucket soil content for presence of a SNF fragment. Additionally, the application controls the operation of the gain stabilization routine, background measurements, and continual QA/QC checks for ensuring proper system operation. The automated fine gain adjustment initiates check source measurements for all three detectors (two NaI(Tl) scintillation detectors and one G-M detector). Spectra are acquired and, as required, the fine gain is automatically adjusted to align the 662 keV peak with MCA channel 110, which has been established as a standard design feature to support multiple systems operations, exchange, maintenance, and comparison. This operation also provides a source check for the detectors. As a QA measure, all three detectors are required to have background-subtracted total counts within 20% of that determined during calibration.

## Dose Rate Operating Bounds and Energy Shift

NaI(Tl) detectors are highly efficient at detecting gamma photons. This characteristic also limits the upper range of the detectors, since each pulse requires a finite amount of time for the MCA to process. As pulses (or count) exceed 30,000 per second, the ability of the MCA to differentiate between pulses becomes limited until such time as no useable pulse height data can be extracted. To address this limitation, the ***CRATER™System*** uses two detector/MCA systems – a 1X1 inch detector for low ambient dose rate conditions and a smaller 0.25X1 inch detector for higher ambient dose rate conditions.

Measurements were performed at RSA's calibration laboratory in Hebron, CT, for the purpose of evaluating performance for the 1X1 inch and 0.25X1 inch NaI(Tl) detectors. The detectors were subjected to a 3.7E+09 Bq (100 mCi) Cs-137 source with measurements taken at numerous distances for a variety of photon fluence rates and corresponding dose rates. Figures 1 and 2 present spectral measurements for the 1X1 and 0.25X1 inch detectors, respectively. As Figure 1 shows, the 0.36 and 0.32 mSv/h spectra show an uncharacteristic feature (spike) around 90 keV, while the 0.20 and 0.14 mSv/h spectra have the more typical spectra distribution. Likewise, Figure 2 shows that for the 0.25X1 inch detector, a saturation condition occurs for the 5.1 mSv/h spectrum, while the 3.6 mSv/h spectrum shows typical distribution.

Based on these measurements, the 1X1 inch NaI(Tl) detector provides a useful operating range up to about 0.20 mSv/h, which has been established as its maximum operable exposure rate for this application. The 0.25X1 inch NaI(Tl) detector has an upper operating limit around 3.5 mSv/h.

## Sodium Iodide Detector Temperature Induced Gain Shift

Thallium-activated sodium iodide (NaI(Tl)) scintillation detectors and the photomultiplier tubes to which they are coupled are subject to gain shift under changing temperatures and damage from mechanical shock.

The light output of NaI(Tl) in response to gamma energies varies with temperature. It is vital that the fine gain is adjusted, via the automated routine, to keep the 662 keV peak aligned with channel 110 of the MCA for both detectors. This alignment is maintained by the automated fine gain adjustment that is periodically performed by the Radiation Control Technician throughout the day. Upon measurement of a $2^{o}$ C temperature change (inside the *CRATER*™ box), the CoRE software application alerts the RCT to perform an auto fine gain adjust.

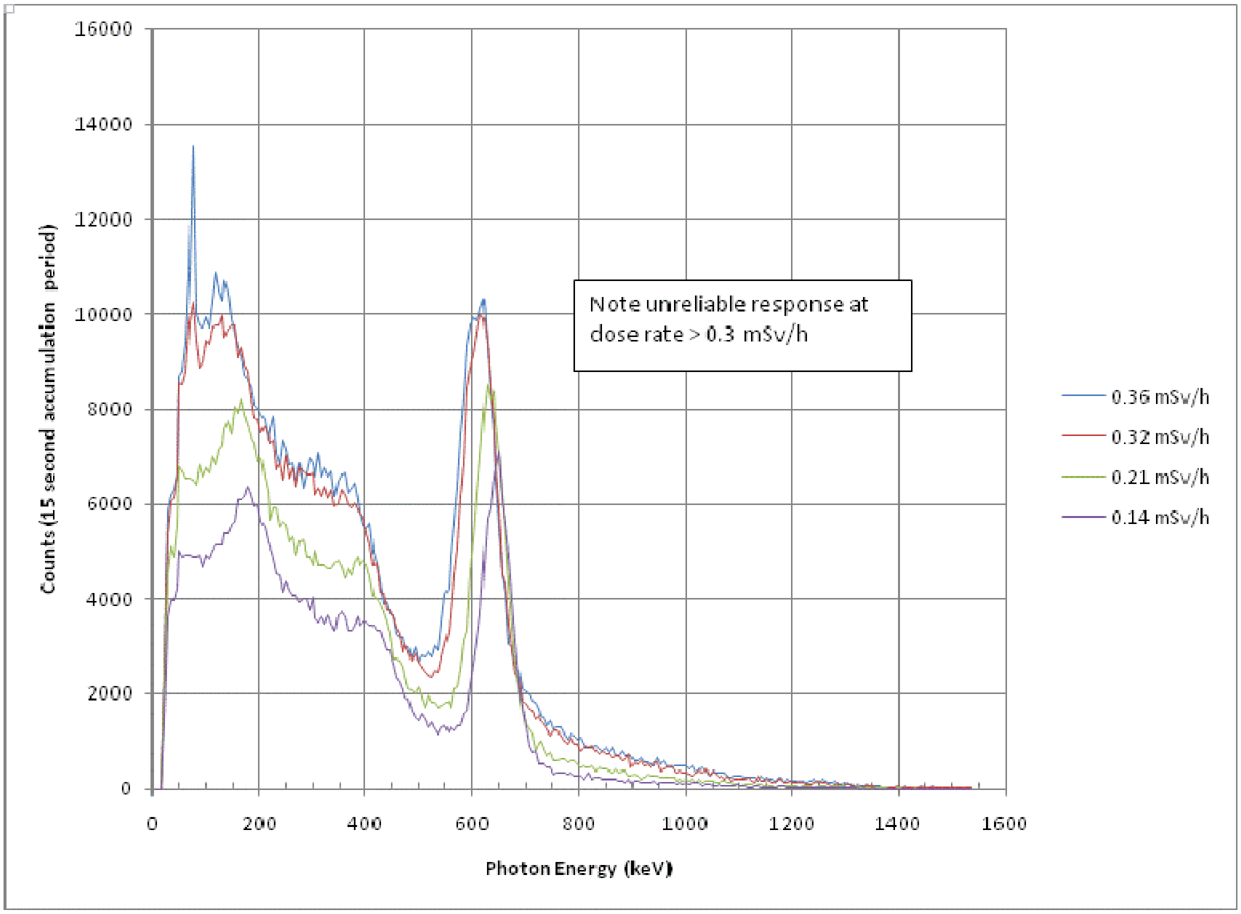


**Fig. 1. 1X1-Inch NaI(Tl) Detector Response as Function of Dose rate from a Cs-137 Source**

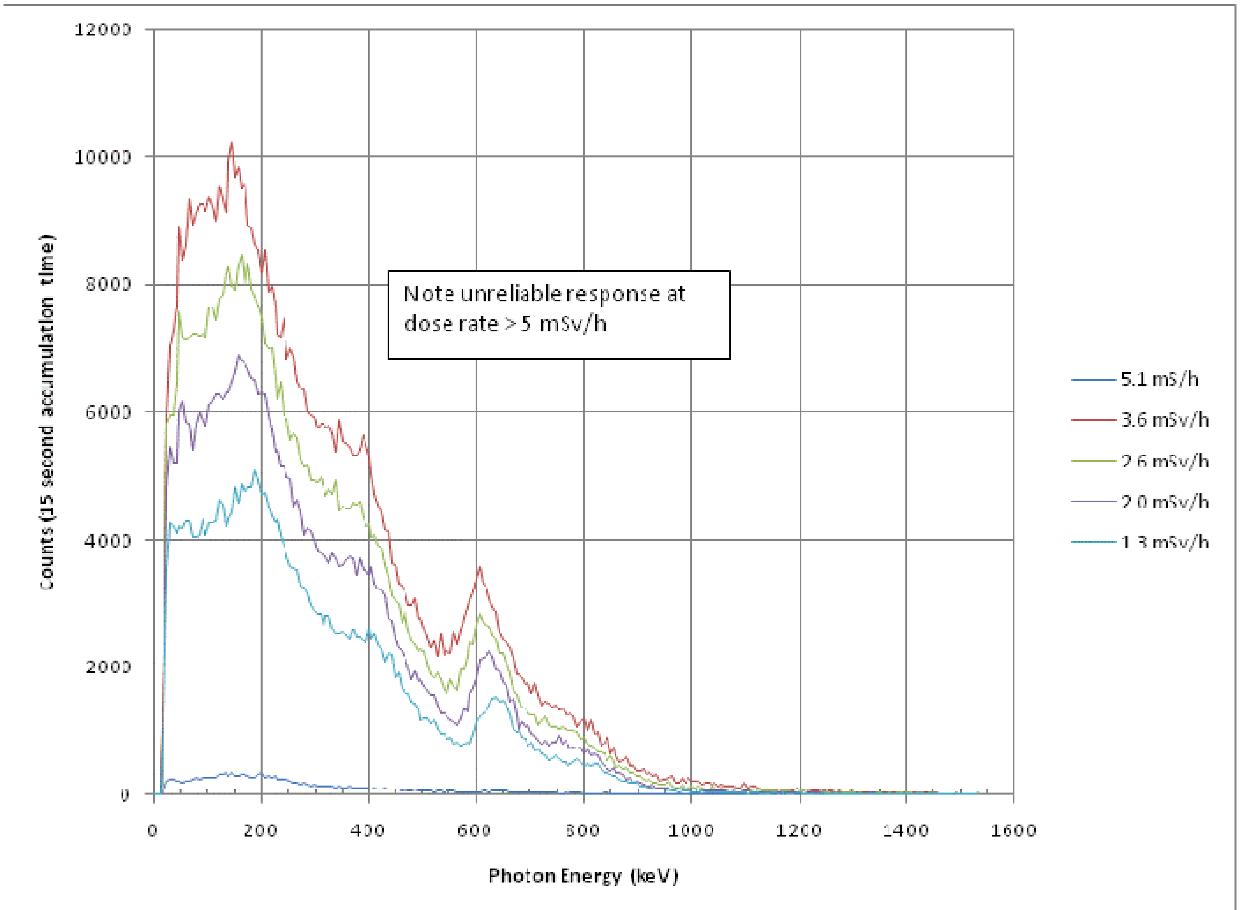


**Fig. 2. 0.25X1-Inch NaI(Tl) Detector Response as Function of Dose rate from a Cs-137 Source**

## Operability Determination

Due to the nature of the working environment (vibration and mechanical shock), it is important that the operability of the detectors be verified, essentially for each bucket measurement. This verification provides assurance that each bucket is appropriately screened. An operability evaluation is performed for each measurement by verifying that there is a minimum of 200 gross counts for the 1X1 inch NaI and 30 gross counts for the 0.25X1 inch NaI. Additionally, the 1st two channels for each MCA unit, by design, should have zero (0) counts, which is also verified. If both conditions are not met, the system returns the message, “Detector Malfunction – Contact Supervision.” Additional software checks and controls are provided to ensure functionality, such as 2-way software communication (positive acknowledgement) for commands functions and error checking (checksum) for complete and accurate data transmissions.

## RADIATION DETECTOR RESPONSE MODELING - FIELD TESTING AT 100-D COMPLEX

Field testing of the *CRATER*™ system was performed at the 100-D complex, using an actual SNF fragment having an activity of approximately 5.9E+10 Bq (1.6 Ci) Cs-137.[2] The actual field measurements with the SNF fragment positioned on the bottom of the modified excavator bucket (approximately 76 cm depth) provided data that was used in conjunction with MCNP modeling for deriving the screening methodology as discussed below. The following

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[2] A gamma spectral measurement was collected to verify presence of key gamma-emitting radionuclides (i.e., verifying Cs-137 and a SNF fragment) and dose rate measurements were used for quantifying activity based on radiation shielding calculations.

pictures show the *CRATER*™ attached to the excavator boom (Figure 3) and excavator bucket (modified to limit the depth to 76 cm) with the SNF fragment affixed to the bottom.


**Fig. 3. *CRATER*™ Attached to Excavator Boom**

Three days of testing were conducted. During day-1, testing was performed in a lay-back trench area, which was not expected to contain any SNF fragments. During the testing, a high Co-60 item was encountered, which produced a high Co-60 ROI.[3] Day-2 testing was with trench materials, more likely to contain an SNF fragment; however, no additional fragments were identified. Day-3 testing was with the SNF fragment removed and essentially background measurements collected in the same areas and materials as used during day-1 and day-2 testing. Additionally, during day-3, measurements were collected from the sorting cell. Measurements were collected with the SNF fragment affixed in the bucket and with the high Co-60 item that had been identified during the day one testing.

Measurements were also collected in the sorting cell with the high Co-60 item randomly positioned in the bucket and with the SNF fragment removed. These measurements provided data that was used for the deriving the Co-60 stripping algorithms as discussed later. The results of typical measurements collected during the testing are shown in Figure 4 for the 1X1 inch NaI(Tl) detector and Figure 5 for the 0.25X1 inch NaI(Tl) detector. The purpose of these measurements were to provide a data set for varying conditions, including measurements with and without an SNF fragment and some including a high dose rate Co-60 item.

For reasons to support modeling as discussed further below, Figure 4 shows the Compton ROI gross counts (15 second accumulation) versus the Cs-137 plus Co-60 ROI gross counts. Day-1, -2, and -3 data are all for measurements with the SNF fragment affixed in the bucket. The day-3 data with the SNF fragment removed is shown for comparison as well as typical background measurements collected on day-3 (i.e., measurements from areas/materials surveyed during day-1 and -2 areas but with SNF fragment removed). As the graphs illustrate, there is a clear distinction between the data for measurements with a SNF fragment from those representing background.

[3] The Co-60 source was identified as a thin wire reading approximately 5 mSv/h (500 mR/h) near contact. This Co-60 source was segregated to the sorting cell, where it was used for measurements during day-3 for purposes of establishing the stripping parameters (measurements without the SNF fragment) and for establishing a Compton ratio method that could be used to screen for high dose rate items, in addition to the SNF fragment screening.

Also, note that the day-3 data for the sorting cell without the SNF fragment represent measurements that included the Co-60 source identified during day-1.

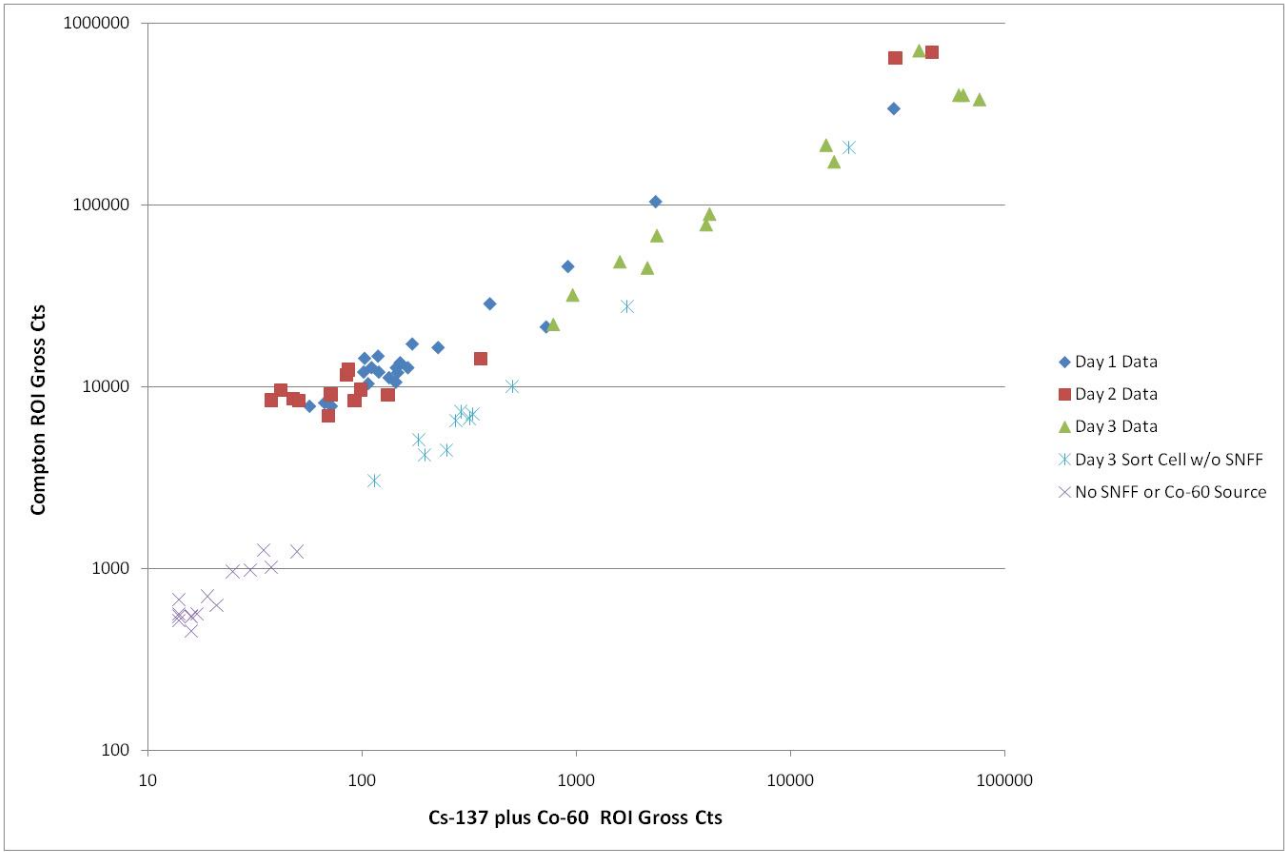


**Fig. 4. 1X1 Inch NaI(Tl) – Compton ROI versus Cs-137 plus Co-60 Gross Counts**

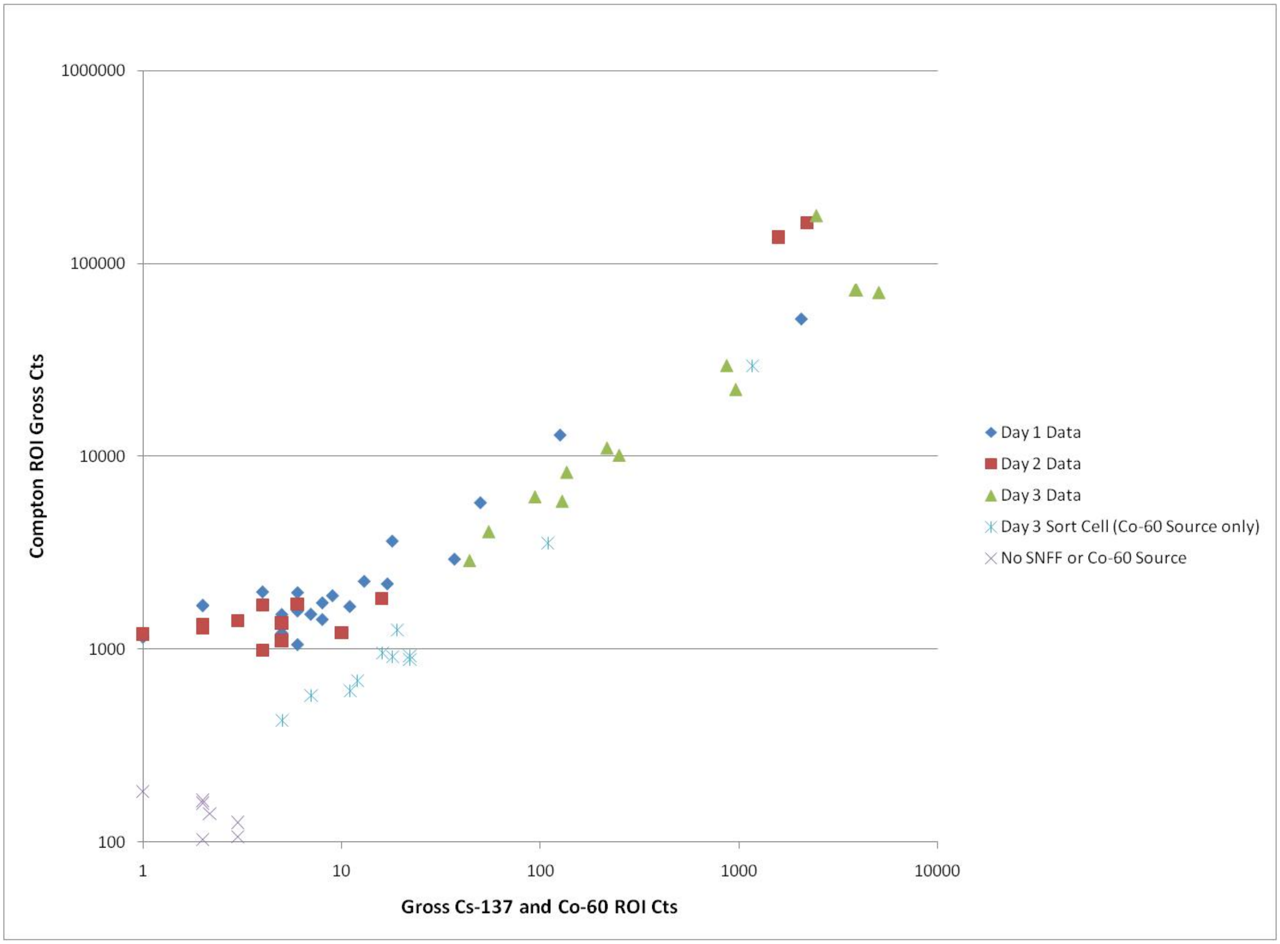


**Fig. 5. 0.25X1 Inch NaI(Tl) – Compton ROI versus Cs-137 plus Co-60 Gross Counts**

## SPENT FUEL FRAGMENT SCREENING METHODOLOGY

The methodology developed for screening the excavator buckets of soil for potential SNF fragments is based on the principle that as shielding (in this case soil depth in an excavator bucket) increases, the ratio of the total counts in the Compton continuum to that in the photopeak increases. For a given source activity, a measure of the source depth can be correlated to the ratio of Compton continuum to the photopeak area. This approach is discussed in more detail in [1] and was applied to the specifics for monitoring excavator buckets of soil considering the bucket-soil-detector(s) configuration. Considering the shape of the spectra as a function of depth (MCNP5 modeling), a methodology was developed based on a combination of a Co-60 spectral stripping technique for background subtraction and a Compton-to-photopeak ratio algorithm to quantitatively assess the total activity of Cs-137 present as an indication of a fuel fragment.

### Compton Pile-up and Cs-137 Photopeak Gamma Spectroscopy Windows

The application of the methodology to the gamma spectral analysis calls for establishing regions of interest (ROI), where the width of the region (i.e., energy window) appropriately set to capture the significant portion of the total spectral component of interest. Three particular ROIs are evaluated – Cs-137 photopeak, Co-60 photopeaks, and the Compton scatter.

The NaI(Tl) detectors have a nominal 7.7% full-width-half-maximum (FWHM) value. This 7.7% FWHM value for the 662 keV gamma from the Cs-137 (Ba-137M) decay corresponds to approximately 50 keV. Using standard statistical analysis, the total area under the FWHM corresponds to 2.35 sigma for the gamma energy distribution as recorded by the detector (system), which also corresponds to approximately 88% of the total for the photopeak, or a 1 σ value of 19 keV). Therefore, to ensure capture of essentially the full Cs-137 photopeak, an energy window from 600 keV to 720 keV is established (i.e., approximately ± 60 kev or 3 σ around the 662 keV Cs-137 gamma energy).

A similar approach is taken for establishing the Compton ROI. The interest is in establishing the ROI so as to capture the Compton scatter interactions as detected by the NaI(Tl) detector. As discussed in [1], multiple Compton interactions results in a pile-up of photons and a rather broad spectrum peak around 100 keV in soil. And, the upper energy value for a Compton interaction in the detector (i.e., measurement of the recoil electron in the detector from a single Compton interaction) is approximately 400 keV. Therefore, again taking into consideration the resolution of the detector, the ROI established for the Compton pile-up is 50 to 500 keV. (The lower energy cut-off is established to eliminate potential electronic noise in this lower region as well as recognizing that even the minimal shielding by the enclosure and detector covering will capture these low energy photons).

**Spectral Stripping**

A basic assumption is that the variation in the contribution from natural background radioactive components to the spectra (i.e., contribution to spectra from uranium and thorium decay series, K-40, and cosmic) will be negligible compared with the contribution from either a varying Co-60 component in the bucket or the Cs-137 activity (from a potential fuel fragment). This is a reasonable assumption, particularly when considering that the ambient dose rate from natural background is a few µSv/h compared with a upwards of 10 mSv/h from the Co-60 and/or Cs-137 components. Therefore, the spectral counts over the 15-second accumulation period in the established Cs-137 ROI for a spectral measurement would be attributable to that from the Cs-137 itself plus a contribution from any Co-60 present (i.e., Co-60 Compton scatter photons). Likewise, the Compton ROI will be comprised on these two components – a Cs-137 contribution and a Co-60 contribution. Under a varying Co-60 background, the relative contributions will also vary, making the distinction of the Cs-137 contribution alone difficult – without stripping the Co-60 contribution.

A spectral stripping technique as applied by Aage [2, 3] for identifying man-made radioactivity/sources in the environment has been applied. The technique involves determining the contribution to the region of interest from a background component -- in this case, the contribution from a varying Co-60 background to the Cs-137 photopeak and the continuum. A least-square fit of the spectral measurements taken of actual excavator bucket at 100-D during day-3 of the testing were used for developing stripping parameters for each detector. Measurements of excavator buckets of soil with identifiable Co-60 (and absent identifiable Cs-137) were used for deriving the stripping parameters for the Compton and Cs-137 ROIs for the 1X1 inch and the 0.25X1 inch NaI(Tl) detectors.

As discussed, the activities of interest are relatively high (compared with background level); and, therefore, there are no significant contributions to the NaI detector response in the energy region above 0.8 MeV, except for the Co-60 component. Therefore, a relatively wide ROI can be established for determining the Co-60 component, as required for stripping. An ROI of 1100 to 1400 keV was established, thereby including both Co-60 primary gamma photopeaks (1.17 and 1.33 MeV).

Spectral Stripping for 1X1 Inch NaI Detector

For the Cs-137 photopeak:

$$Net\ R_{Cs-137} = Gross\ R_{Cs-137} - 1.025 * Co60_{ROI\ window} \quad \text{(Eq. 1)}$$

Where: Net $R_{Cs-137}$ = net counts in Cs-137 ROI

Gross $R_{Cs-137}$ = gross counts in Cs-137 ROI

$Co60_{ROI\ window}$ = total gross counts in the Co-60 ROI

1.025 = stripping factor

For the Cs-137 component of the Compton ROI:

$$Net\ R_{Cs\ Compton\ ROI} = Gross\ R_{Comptio\ ROI} - 23.9 * Co60_{ROI\ window} \quad \text{(Eq. 2)}$$

Where: Net $R_{CsCompton\ ROI}$ = net counts in Compton ROI

Gross $R_{Compton\ ROI}$ = gross counts in Compton ROI

| | |
|---|---|
| $Co60_{ROI\ window}$ | = total gross counts in the Co-60 ROI |
| 23.9 | = stripping factor |

<u>Spectral Stripping for 0.25X1 Inch NaI Detector</u>

For the Cs-137 photopeak:

$$Net\ R_{Cs-137} = Gross\ R_{Cs-137} - 1.41 * Co60_{ROI\ window} \qquad \text{(Eq. 3)}$$

Where: 1.41 = applicable stripping factor

For the Cs-137 component of the Compton ROI:

$$Net\ R_{Cs\ Compton\ ROI} = Gross\ R_{Comptio\ ROI} - 60.8 * Co60_{ROI\ window} \qquad \text{(Eq. 4)}$$

Where: 60.8 = applicable stripping factor

**SNF Fragment Screening Methodology**

The methodology derived for screening excavator buckets of soil for SNF fragments is based on the field measurements with an actual SNF fragment as conducted at the 100-D complex with MCNP modeling [4] providing consistent results. The field measurements were with a fuel fragment affixed to the bottom of an excavator bucket that had been modified to a depth of 30 inches. During testing, several measurements were taken with the soil at less than 30 inch depth (covering the SNF fragment) to mimic measurements with the SNF fragment at varying depths in the bucket. The estimated 5.9E+10 Bq Cs-137 for the test fragment is greater than the 4.1E+10 Bq Cs-137 as established for the screening criterion. Since the emission (and consequently detection) is a linear function of activity (for the same geometry), the results from the field testing can be ratio to give equivalent results for use in deriving screening criteria based on a 4.1E+10 Bq Cs-137 SNF fragment.

Graphs illustrating the screening levels compared with field measurements (adjusted to an equivalent 1.1 Ci Cs-137) and the MCNP modeling are shown in Figures 6 and 7 for the 1X1 and 0.25X1 inch NaI(Tl) detectors, respectively. The following algorithms (as represented by the screening level curves) were derived to provide a screening level that would provide positive identification for all measurements presented.

<u>For 1X1 inch NaI(Tl) Detector:</u>

$$Low\ Screening\ Level = 7E+07 * Compton\ Ratio^{-4.14} + 13 \qquad \text{(Eq. 5)}$$

Where: Low Screening Level = the level for measurements with the 1X1 inch NaI(Tl) detector above which the potential for a SNF fragment exists

<u>For the 0.25X1 inch NaI(Tl) Detector:</u>

$$High\ Screening\ Level = 3E+07 * Compton\ Ratio^{-4.1} + 1 \qquad \text{(Eq. 6)}$$

Where: High Screening Level = the level for measurements with the 0.25X1 inch NaI(Tl) detector above which the potential for a SNF fragment exists

For the 1X1 inch NaI(Tl) detector, a low screening level for SNF fragment was established considering the field measurements collected with the identified SNF fragment in the excavator bucket. As shown in Figure 8, the minimum Compton ROI gross counts for the measurements with the SNF fragment was 6,968 counts during the 15 second acquisition time. Adjusting for 4.1E+10 Bq Cs-137, this value equates to 4,790 counts. Therefore, a lower cut-off level at 4600 gross counts in the Compton ROI has been established as a lower cut-off level, below which there is insufficient counts to be representative of a SNF.

Similarly, for the 0.25X1 inch NaI(Tl) detector, the minimum Compton ROI gross counts for the measurements with the SNF fragment was 993 counts during the 15 second acquisition time. Adjusting for 4.1E+10 Bq Cs-137, this value equates to 683 counts. Therefore, as shown in Figure 9, a value of 600 gross counts in the Compton ROI has been established as a lower cut-off level, below which there are insufficient counts to be representative of a SNF.

The screening using the 0.25X1 inch NaI(Tl) detector can only be used to verify a radiation level likely associated with a SNF fragment (or high dose rate item as discussed below). It cannot be used to exclusively clear a bucket since it does not have sufficient sensitivity for detecting a SNF fragment at low depths in the bucket (e.g., at the 61 – 76 cm depth). Therefore, if a high exposure rate bucket (i.e., greater than 0.2 mSv/h) is screened by the 0.25X1 inch detector and no SNF fragment or high dose rate item (discussed below) is identified, there is an "indeterminate" finding by the CoRE analysis; the bucket should be segregated (for follow evaluation) or returned to the excavation area where the material can be re-sampled (i.e., reposition of source leading to the high dose rate).

**High Co-60 Dose Rate Item Screening Methodology**

Using the field measurements collected on day-3 in the sorting cell with the 500 mR/h Co-60 wire source, a screening level for high dose rate items has also been derived. This screening is secondary to the SNF fragment screening but it does provide a check on the primary screening when a high dose rate item (i.e., high Co-60 contribution to the spectrum) could cause over stripping and a non-conservative SNF fragment screening. The method is similar to that used for the SNF fragment screening, where the combination of a lower cut-off level is established coupled with a correlation between the Co-60 plus Cs-137 ROIs are the Compton ROI.[4] This screening would only apply if the screening for a fuel fragment yielded negative results (i.e., no SNF fragment identified).

The lowest Compton ROI observed during the day-3 measurements (with the Co-60 wire and without the SNF fragment) was 3067 counts. Therefore, based on these field measurements for a 500 mR/h Co-60 wire source, a lower screening level for a high Co-60 source item can be established at 2500 gross counts in the established Compton ROI. For the 0.25X1 inch NaI(Tl) detector, the lower cut-off level is 400 counts in the Compton ROI. Similar to the method for identifying a SNF fragment, there is a direct correlation between the increase in Compton as a function of the Cs-137 plus Co-60 gross ROI. If the gross Compton exceeds the cut-off level, the algorithms for these correlations can be used for screening for elevated Co-60 items.

<u>For 1X1 inch NaI(Tl) detector</u>:

$$Low\,HDR\,Screening\,Level = 39.644*(\,^{137}Cs\,ROI + \,^{60}Co\,ROI\,)^{0.8271} \qquad \text{(Eq. 7)}$$

Where: Low HDR Screening Level = the level for measurements with the 1X1 inch NaI(Tl) detector above which the potential for a high dose rate item exists

<u>For 0.25X1 inch NaI(Tl) detector</u>:

$$High\,HDR\,Screening\,Level = 61.274*(\,^{137}Cs\,ROI + \,^{60}Co\,ROI\,)^{0.8148} \qquad \text{(Eq. 8)}$$

Where: High HDR Screening Level = the level for measurements with the 0.25X1 inch NaI(Tl) detector above which the potential for a high dose rate item exists

These screening levels and correlation for Compton increase as a function of the gross Cs-137 plus Co-60 ROI are illustrated in Figures 10 and 11.

**CRATER™ and CoRE Software Logic for SNF Fragment and High Dose Rate Item Evaluation**

The complete evaluation of the radioactive content for each excavator bucket includes, primarily, screening for a potential SNF fragment and, secondarily, for any high dose rate item. A logic flow diagram is presented as Figure 12 illustrating the sequence of evaluations that are performed.

[4] The combined Cs-137 plus Co-60 ROIs (gross counts) were used for this screening based on the fact that a high dose rate item could be either a Co-60 or Cs-137 source – or a combination thereof.

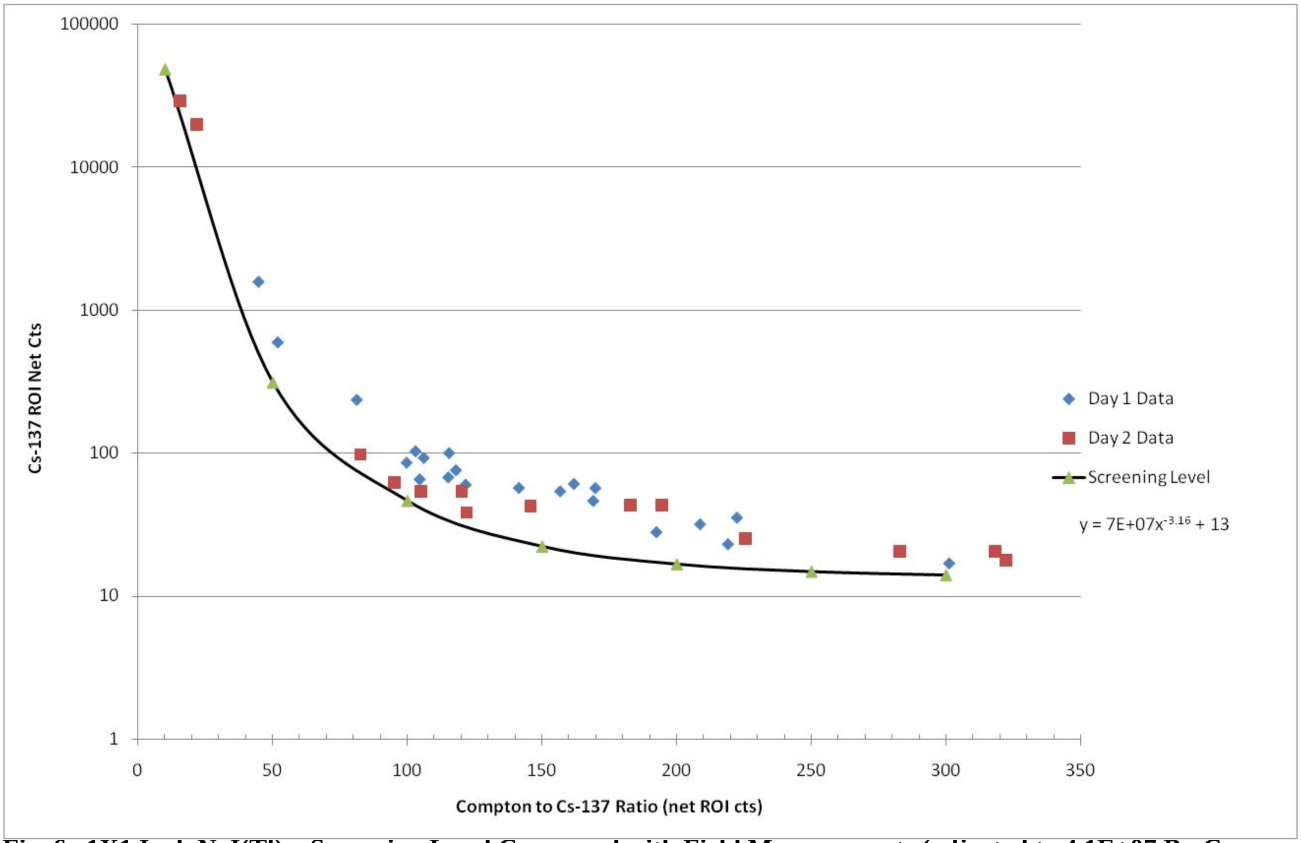


**Fig. 6. 1X1 Inch NaI(Tl) – Screening Level Compared with Field Measurements (adjusted to 4.1E+07 Bq Cs-137 SNF Fragment**

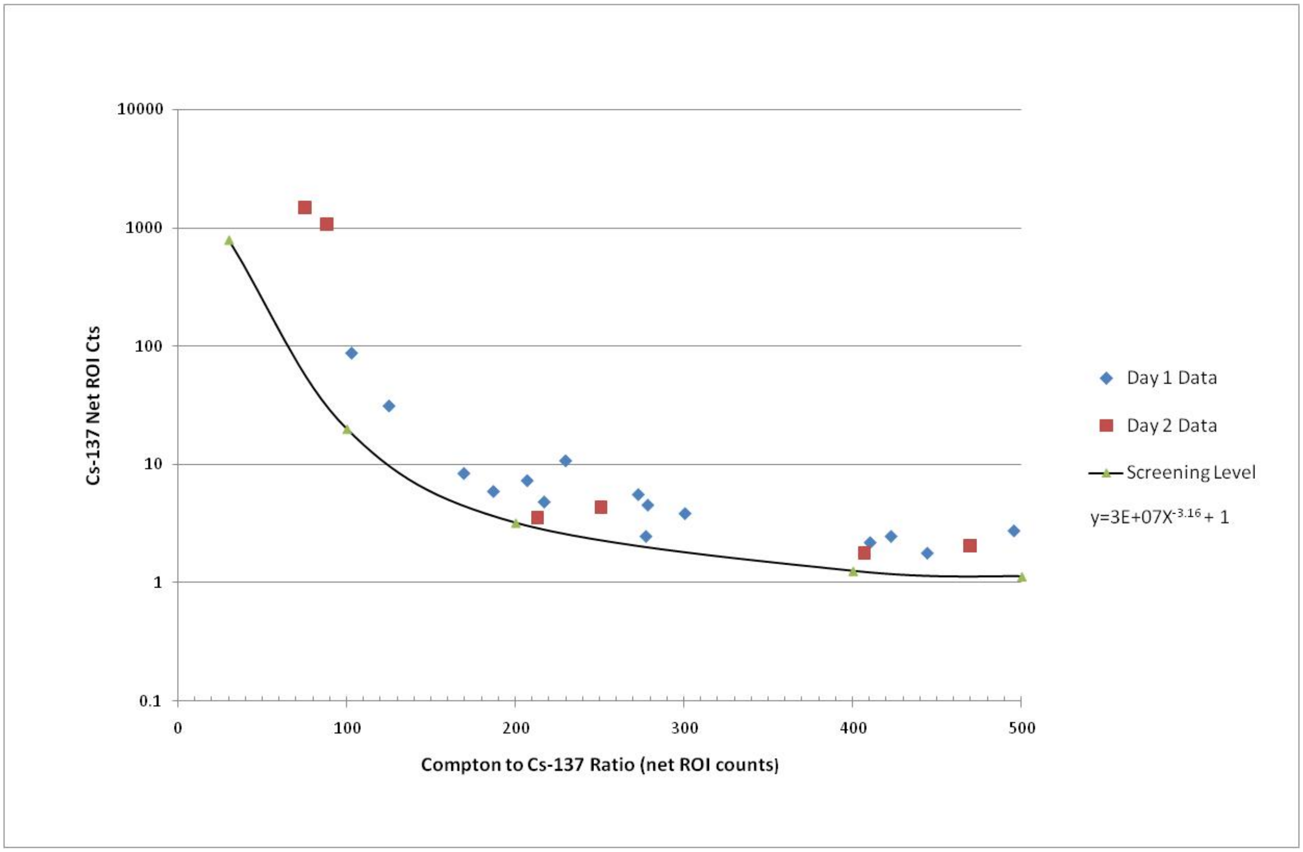


**Fig. 7. 0.25X1 Inch NaI(Tl) – Screening Level Compared with Field Measurements (adjusted to 4.1E+07 Bq Cs-137 SNF Fragment**

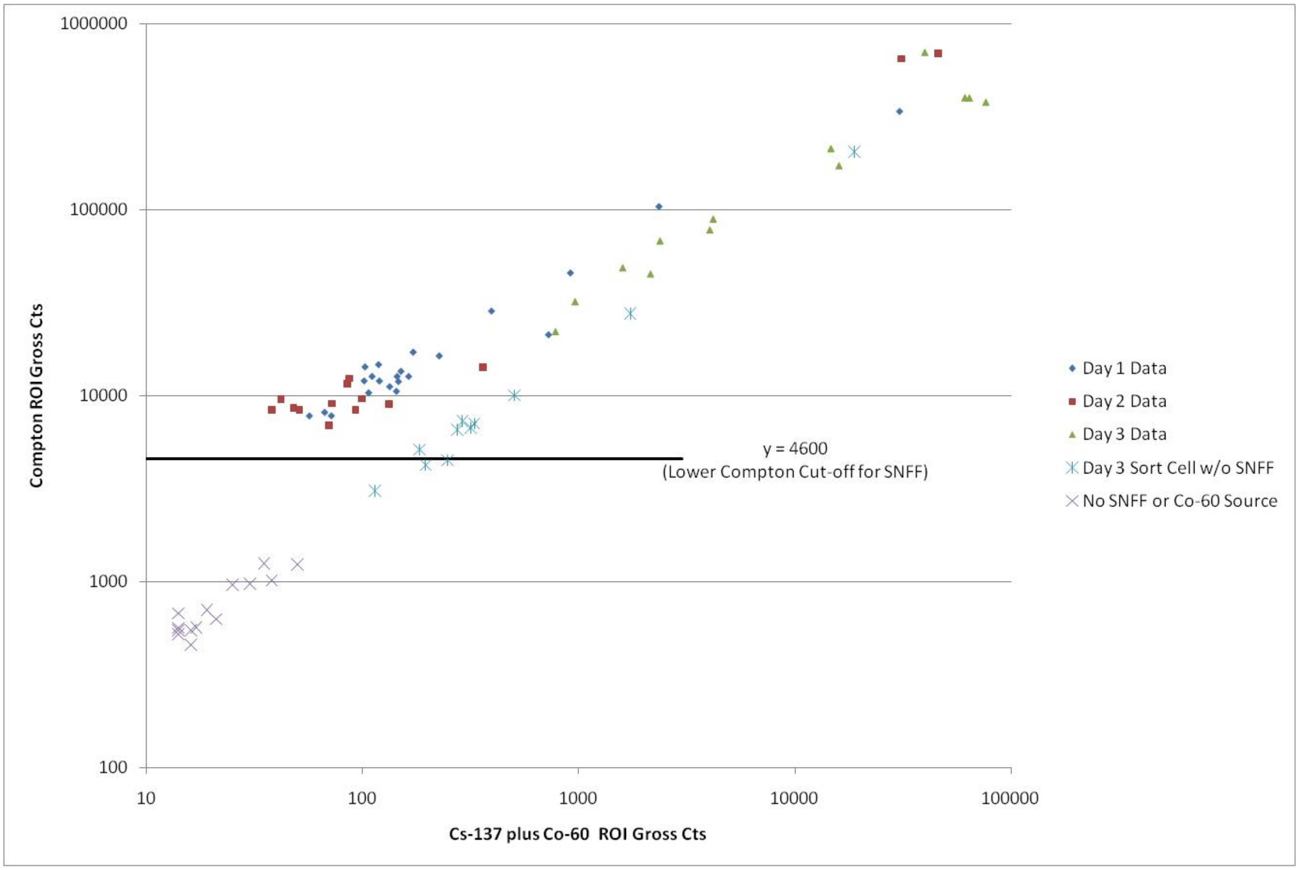


**Fig. 8. 1X1 Inch NaI(Tl) – Compton ROI versus Cs-137 + Co-60 ROI Gross Counts**

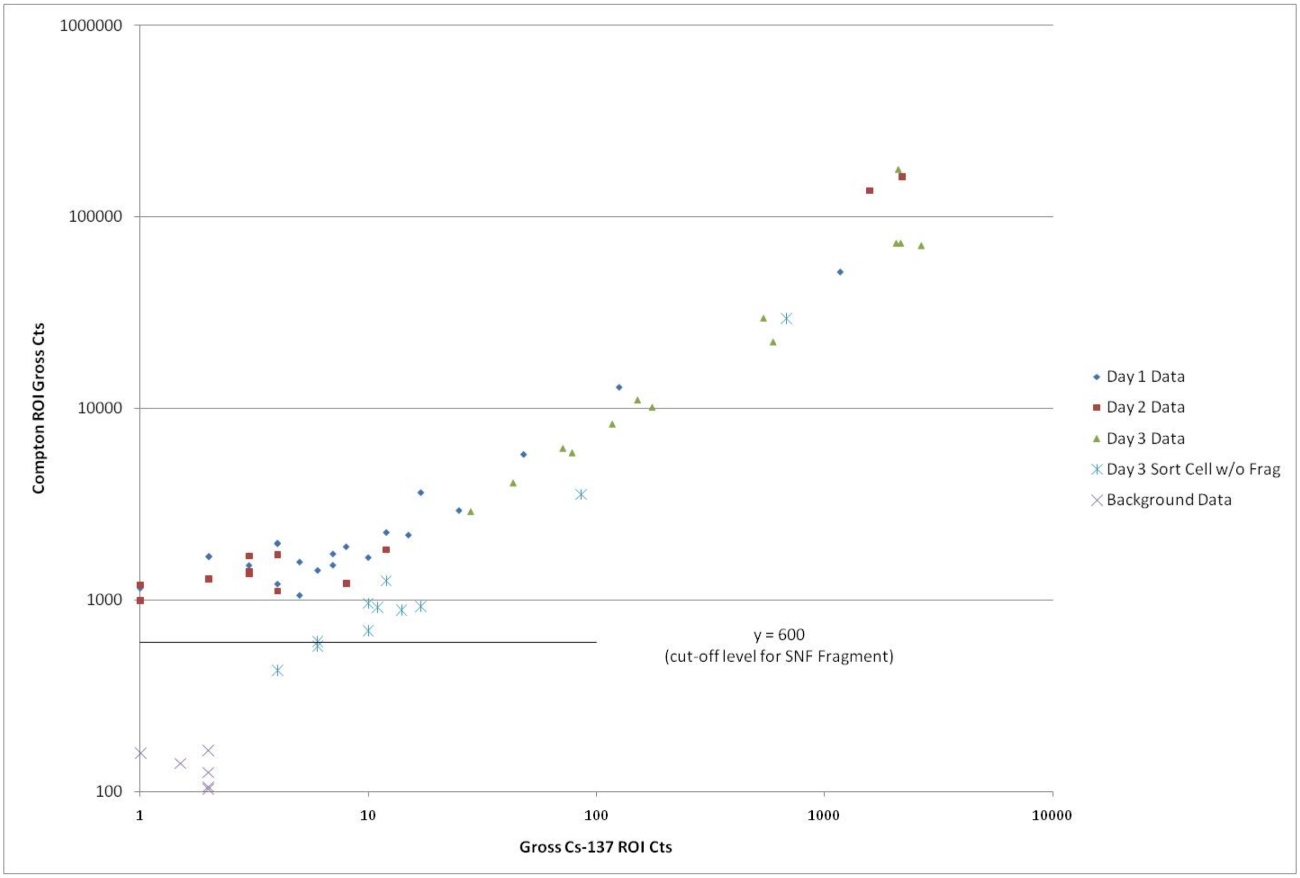


**Fig. 9. 0.25X1 Inch NaI(Tl) – Compton ROI versus Cs-137 + Co-60 ROI Gross Counts**

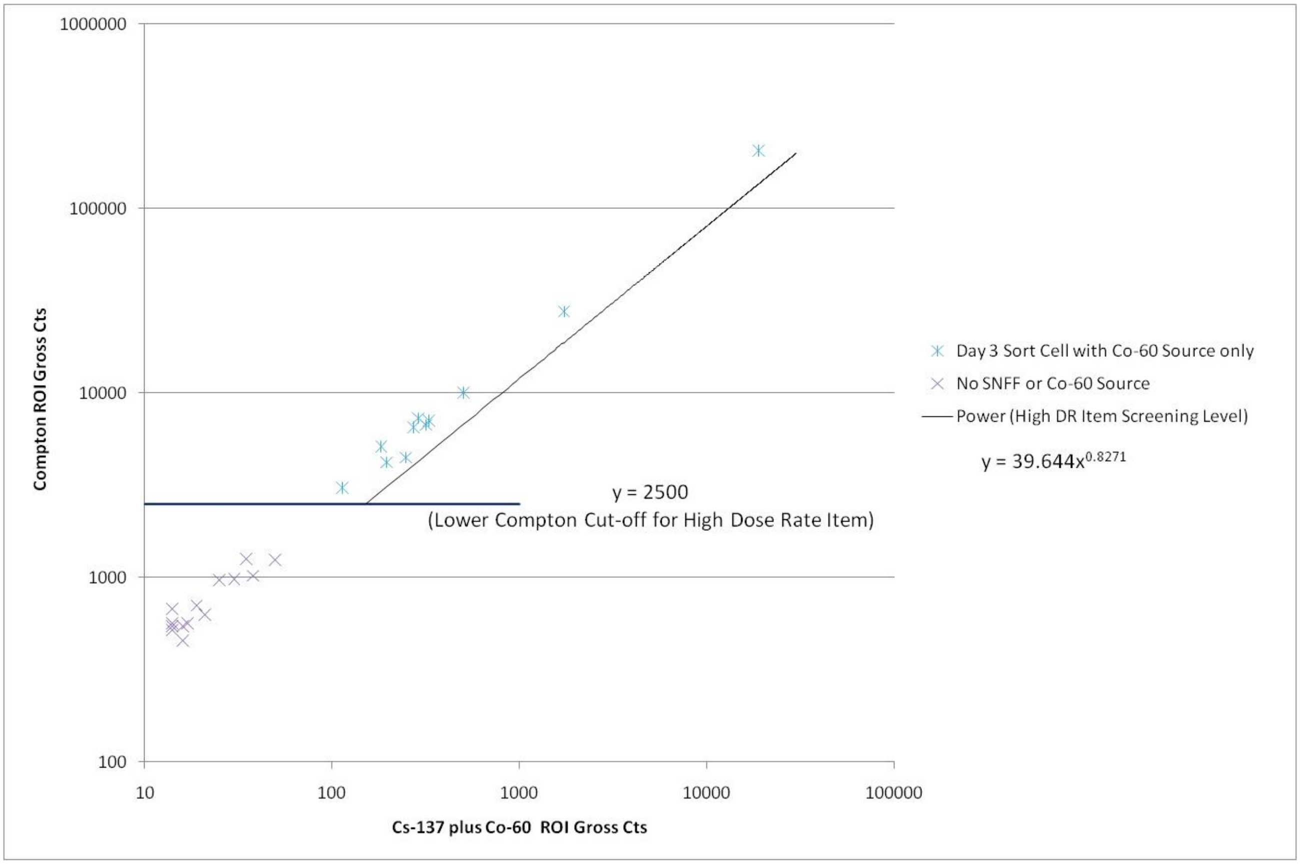


**Fig. 10. 1X1 Inch NaI(Tl) – Compton ROI versus Cs-137 + Co-60 ROI Gross Counts for Measurement with 5 mSv/h Co-60 Source in Excavator Bucket Compared with Bucket Measurements with no SNF Fragment or Co-60 Source**

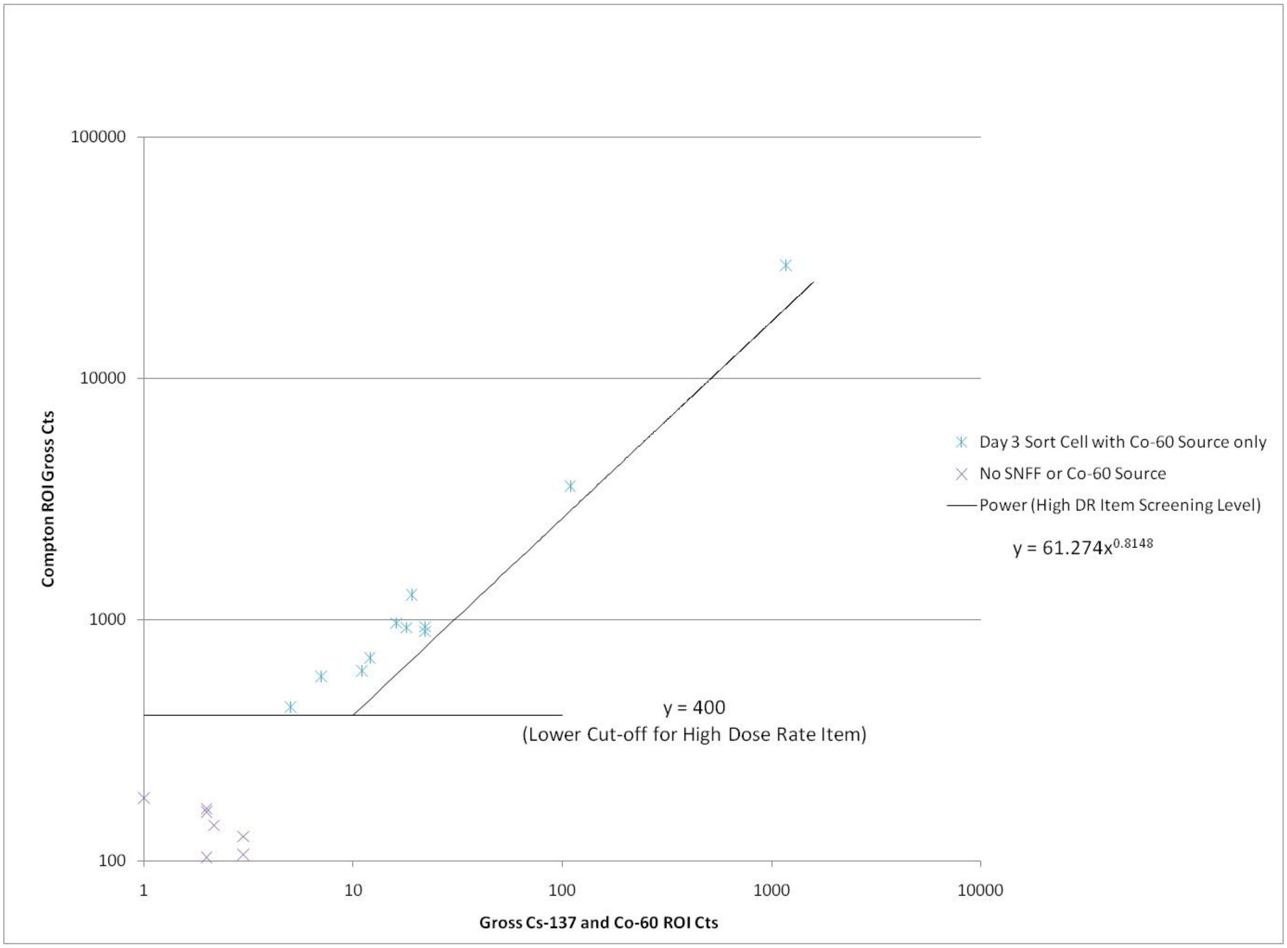


**Fig. 11. 0.25X1 Inch NaI(Tl) – Compton ROI versus Cs-137 + Co-60 ROI Gross Counts for Measurement with 5 mSv/h Co-60 Source in Excavator Bucket Compared with Bucket Measurements with no SNF Fragment or Co-60 Source**

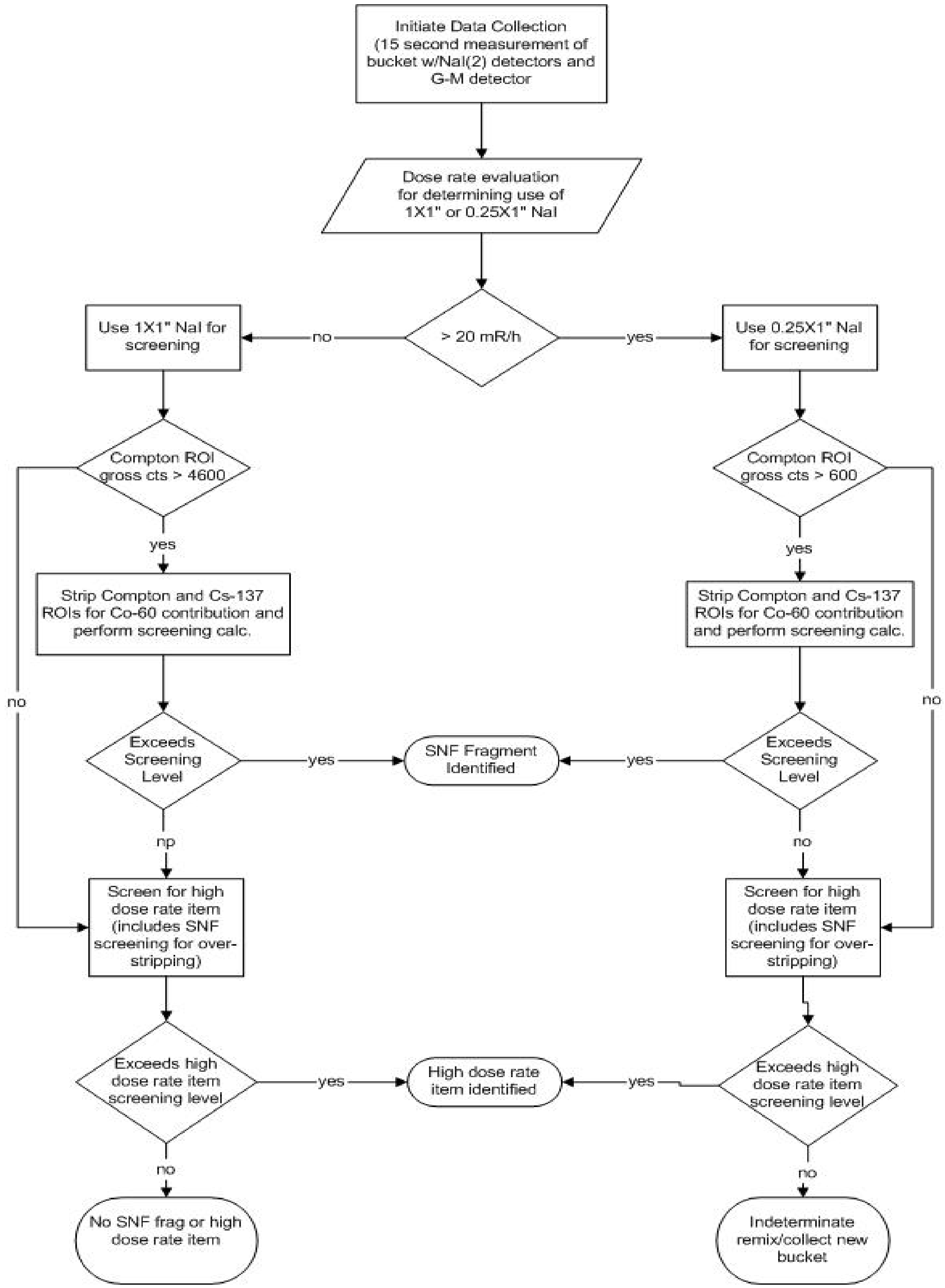


**Fig. 12. Screening Logic Diagram**

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