Methods to Determine Corrective Action Boundaries at Aerially-Dispersed Radiological Release Sites – 10334

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ABSTRACT

Determining the corrective action boundary of radiological contamination from atmospheric radiological releases can be costly and problematic due to the relatively large areas involved, the different types of releases, the amount of nuclear yield that occurred during detonation of the device, the different inherent properties of the radionuclides released, and the local variability of radionuclides present. Types of releases studied as part of the Soils Sub-Project at the Nevada Test Site include atmospheric tests, shallow underground tests that were designed to displace surface material, and deep underground or tunnel tests that vented to the surface. The amount of nuclear yield relative to the amount of nuclear material in the device is an important variable as most of the nuclear source material in efficient devices reacts during detonation whereas inefficient devices destroyed using conventional explosives result in dispersal of the nuclear source material. Different mixtures of radionuclides may be present at release sites based on the composition of the nuclear source materials used in the test devices. Also observed in the investigation of Soils Sub-Project release sites is the variation of radionuclide mixtures within individual sites due to differential fallout patterns. Regardless of the source type, location of release, efficiency of detonation, and fallout pattern, each release site was characterized for the annual total effective dose (TED) that would be received by the most exposed individual that could be present at the site. The approaches used to establish TED at each site were based on the type of each release and the configuration of each site. Individual measurements of TED within each release site were made over an area of 100 m^2 (i.e., a 10 × 10 m sample plot). Sample plots were located at each release site based on the results of radiological surveys. The estimates of TED at the various sample plots involved adding independent estimates of internal and external doses. For each release site, the calculated TEDs from each sample plot location were compared to isopleths of radiological survey values generated from various radiological survey techniques. These isopleths provided valuable information on the shape of the radioactive contaminant plumes and the spatial distribution of radiological contaminants. The radiation survey values at each of the sample plot locations were correlated to the estimates of TED to determine a relationship between TED and survey values. The radiation survey isopleth equal to the TED action level was used to establish the corrective action boundary. Determining corrective action boundaries at sites where nuclear materials have been deposited through an atmospheric release can be accomplished efficiently by using the appropriate method (based on the type of radionuclides present, the nature of the release, and site properties).

INTRODUCTION

Defining the appropriate environmental decision framework, identifying supporting data needs, and designing appropriate investigation methods are required to comprehensively address environmental issues related to the release of nuclear material and to define corrective action boundaries. The conceptual site model (CSM) is a key element in the data quality objective (DQO) process [1]. It describes the most probable scenario for current conditions at the site and defines the assumptions that are the basis for identifying the future land use, contaminant sources, release mechanisms, migration pathways, exposure points, and exposure routes. The CSM is used to develop appropriate sampling strategies and data collection methods. The CSM is developed using information from the physical setting, potential contaminant sources, release information, historical background information, knowledge from similar sites, and physical and chemical properties of the potentially affected media and potential contaminants. If evidence of contamination that is not consistent with the presented CSM is identified, the environmental decisions may not be valid. If the CSM is not correct, the situation must be reviewed, the CSM revised, the DQOs reassessed, and the stakeholders must agree on the information needed to make the environmental decisions (and the methods used to collect the information) before the investigation can continue and before environmental decisions are made.

Examples of different CSM elements for nuclear releases at Soils Project sites include:

- The release occurred at or above the soil surface resulting in atmospheric deposition of radioactive contamination onto surface soils from fallout of activated soil, fission fragments, and unfissioned fuel; activation of nearby soil and steel-containing materials; and radioactive molten material (trinity glass) on soil, rock, and structural surfaces.
- The release occurred at or below the soil surface resulting in prompt injection of radionuclides and activated material into the soil below and around the detonation site (see Figure 1).
- The release occurred deep below the soil surface and radionuclides were released with venting gasses escaping through surface fissures in the geologic formation.
- The release resulted in a significant displacement of soil and debris where a crater was formed and contamination is buried under the ejected soil and materials (ejecta) (see Figure 1).

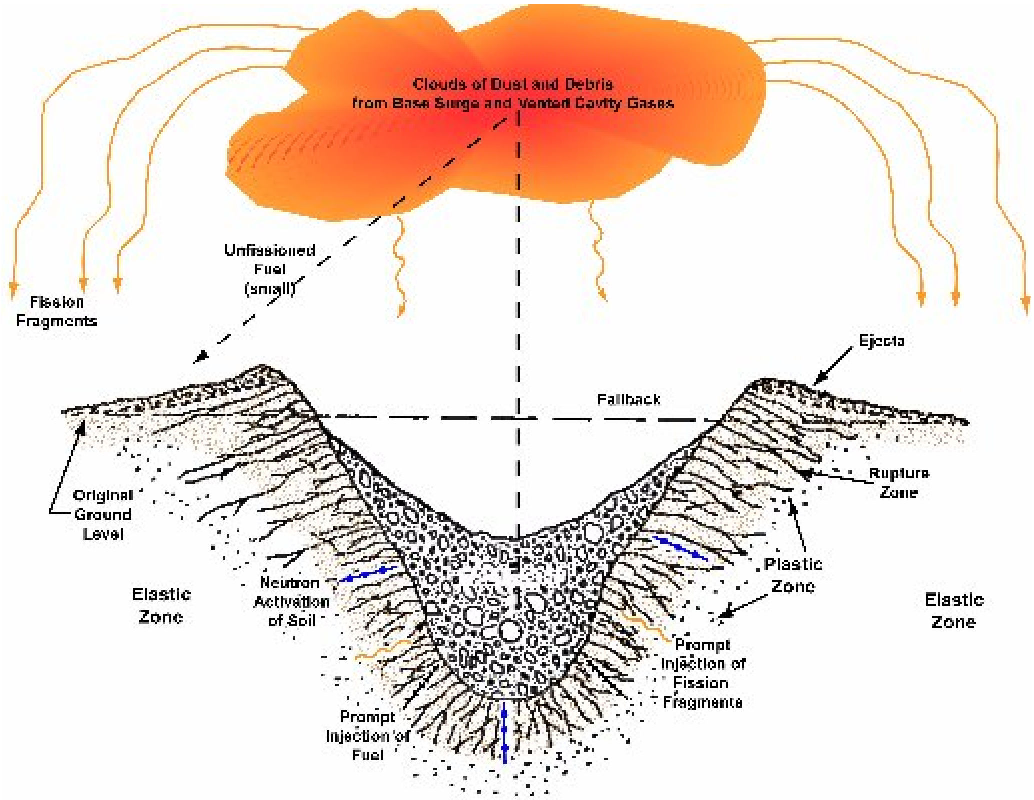

Fig. 1. Conceptual release from near-surface nuclear detonation.

- The nuclear device had little or no yield resulting in the release and distribution of the source nuclear material. The resulting contamination has a significant alpha component and, therefore, internal dose is expected to be the major component of the total effective dose (TED).
- The nuclear device was efficient in converting the source nuclear material into fission products. The resulting contamination is composed primarily of gamma-emitting radionuclides and, therefore, external dose is expected to be the major component of TED.

The first environmental decision for any Soils Project site is to determine if contamination exceeding the final action level (FAL) exists at the site. The FAL that has been agreed to by stakeholders for use at Soils Project sites is a dose of 25 mrem per year (using the appropriate exposure scenario) [2]. If contamination exceeding the FAL exists at the site, the next environmental decision is to determine the extent of material that exceeds the FAL (i.e., the corrective action boundary). The data needed for this determination is a measurement of the TED at specific locations that will support the environmental decision. For example, an environmental decision that TED does not exceed the FAL would require that the TED be measured at the location(s) most likely to present the maximum dose.

As the measurement of TED can be affected by individual radioactive particles and these particles may not be homogeneously distributed across any particular area, point measurements of TED may indicate a much higher variability of dose than that actually received by a receptor that is not limited to one particular point (whose received dose is essentially an integration of point doses over the area of exposure). The U.S. Environmental Protection Agency (EPA) has addressed this issue by issuing guidance to average the exposure concentrations over an area of exposure [3]. The EPA guidance states:

> An exposure point (also called an exposure area or exposure unit) is a location within which an exposed receptor may reasonably be assumed to move at random and where contact with an environmental medium (e.g., soil) is equally likely at all sub-locations…. An exposure point concentration (EPC) is an estimate of the true arithmetic mean concentration of a chemical in a medium at an exposure point.

The EPA's Human Health Evaluation Manual [4] states:

> In some cases, contamination may be unevenly distributed across a site, resulting in hot spots (areas of high contamination relative to other areas of the site)…. The area over which the activity is expected to occur should be considered when averaging the monitoring data for a hot spot. For example, averaging soil data over an area the size of a residential backyard (e.g., an eighth of an acre) may be most appropriate for evaluating residential soil pathways.

While the use of an exposure area (or point dose measurements) would not produce a realistic estimate of total dose received by a receptor (that may result in a false positive decision error), use of an exposure area that is too large may unrealistically underestimate the total dose received (and may result in a false negative decision error). To control both of these types of errors, the Soils Project used an exposure area of 100 m^2 (i.e., a 10 × 10 m sample plot). While this area is much smaller than the area where a receptor may reasonably be assumed to move during normal work activities (resulting in a conservative estimate of TED), it is large enough to integrate the effects on TED of small particles of high specific activity.

The TED at each sample plot is established as the combination of separate measurements of internal dose and external dose. External dose is measured using thermoluminescent dosimeters (TLDs) placed at a height of 1 m above the soil to integrate external dose over the sample plot area. Internal dose variability is also managed by collecting composite soil samples from nine random locations within the sample plot.

CLOSURE STRATEGY

The basic strategy for determining corrective action boundaries at Soils Project sites is based on the assumption that the spatial distribution of TED over the entire release area is correlated to the spatial distribution of radiation survey values (using an appropriate radiation survey that is determined by the radionuclides present at the site and sensitivity of the instrument). The distribution of radiation survey values can be more readily established as these values can be collected in a relatively short period of time (as compared to intensive soil sampling, analysis, and dose calculations). Therefore, many measurements can be made over a large area. Figure 2 shows the results of an aerial gamma survey. The radiological survey measurements guide the location of the sample plots where TED is measured and correlated to corresponding radiation survey values. If an acceptable correlation exists, the survey value equivalent to the FAL can be determined and used to establish an initial corrective action boundary. Although initial corrective action boundaries at Soils Project sites have been determined using aerial gamma radiation survey results, other types of radiation surveys (aerial americium or various ground-based detectors) are planned for use at other Soils Project release sites. Additional sample plots are then established at locations where non-gamma-emitting radionuclides (e.g., plutonium) may be present outside the initial corrective action boundary (may be based on the detection of americium-241 [Am-241] in a radiation survey or via an appropriate hand-held instrument). If the TED exceeds the FAL at these locations, the correlation of TED to radiation survey values can be established and the corrective action boundary expanded to include the areas where it is estimated that plutonium contamination exceeds the FAL. The corrective action boundary can also be expanded to include any areas where TED exceeds the FAL based on the migration or translocation of contamination subsequent to the release. Migration or translocation of contaminants includes the erosion of contaminated soil in stormwater runoff and the subsequent movement of contaminated soil or materials (from initial mitigation measures or construction activities such as clearing a path to the detonation point).

Measurement of TED

The TED at each location (i.e., sample plot) was determined by summing the internal and external dose components. Internal dose was calculated from soil sample results for individual radionuclides using the RESRAD computer code [5]. The internal dose for each sample plot was established as the average of the dose calculated from four composite soil samples. External dose was determined by collecting in situ measurements using TLDs. The external dose for each sample plot was established as the average of the dose readings from the three TLD elements (see Calculation of Initial Corrective Action Boundary).

Sample Plot Location Selection

A judgmental sampling design was implemented for determining sampling plot locations. This selection was based on radiological surveys and applicable prior sampling results. These data included aerial radiological surveys, Global Positioning System (GPS)-assisted gamma walkover surveys, or other available survey data. Sample plots were established on each of three or four vectors (depending upon the size of the contaminated area) that are approximately normal to the radiation survey isopleths with the constraint that, on each vector, at least one sample plot will present a TED greater than the FAL and at least one sample plot will present a TED less than the FAL. To meet this constraint, it was necessary to determine a preliminary estimate of the locations where TED is equal to the FAL. Based on results from previously investigated Soils Project sites, it was determined that the Bicron micro-rem-per-hour meter is not sensitive enough to distinguish differences in dose at a level equivalent to 25 mrem per year for an industrial worker exposure scenario (25 millirem per Industrial Access year [mrem/IA-yr]) (see External Dose Measurement). The PRM-470B plastic scintillator (used for gamma walkover surveys) is more sensitive to gamma radiation but does not produce results in terms of external dose (mrem). However, the PRM-470B can be used to estimate external dose if the readings can be correlated to external dose measurements (e.g., TLD results) from the site. This was accomplished at Soils Project sites by plotting the correlation of Nevada Test Site (NTS) environmental monitoring TLD external dose measurements [6] to the radiological readings collected with the PRM-470 radiation meter. At one site, it was estimated that external dose would exceed the FAL when PRM-470B readings exceeded 470 counts per second (cps). Therefore, the first sample plots on each vector were located where PRM-470B readings were greater than 470 cps. The approximate proposed sampling vectors and sample plots for one Soils Project site are shown in Figure 2.

Internal Dose Measurement

Statistical methods that generate site characteristics were used for establishing TED values that represent the sample plot as a whole. Composite samples were collected at each sample plot in the following manner:

- Each composite sample was composed of nine aliquots taken from locations within each plot. These locations were predetermined using a random start with a triangular grid pattern.
- Each composite sample was collected from 0 to 5 cm below ground surface.
- Samples were sieved to eliminate material (e.g., Trinity glass) greater than 6.4 mm diameter that cannot effectively be inhaled or ingested.
- The entire volume of the composited material collected was submitted to the laboratory for analysis.

External Dose Measurement

External dose (penetrating radiation dose for the purposes of this document) was determined by collecting in situ measurements using TLDs. The TLD placement and processing followed the protocols established in the *Nevada Test Site Routine Radiological Environmental Monitoring Plan* [6]. These TLDs were installed at the approximate center of the sample plot at a height of 1 m and left in place for approximately 94 days (equivalent to an annual industrial worker exposure duration of 2,250 hours) [2]. As the TLD exposure time at each sample plot was not the exact targeted total exposure time (2,250 hours), the resulting data were adjusted to be equivalent to an exposure time of 2,250 hours. The FAL is only applicable to radiation exposure from man-made sources at the NTS and is a value in excess of the radiation exposure that would be present if no nuclear activities had been conducted at the site (i.e., from natural background radiation). Estimates of external dose, in mrem/IA-yr, were presented as net values (i.e., dose due to natural background radiation has been subtracted from the total external dose result). Natural background external radiation was registered on TLDs placed in areas determined to be unaffected by man-made activities at the NTS. These values were significant in comparison to the industrial access year FAL.

The determination of the external dose component of the TED by TLDs was determined to be the most accurate method because TLDs were exposed at the sample plots for the entire 2,250 hours of the Industrial Area exposure scenario [2], which eliminates errors in dose-rate meter scale graduations and needle fluctuations. These errors would be magnified when as-read meter values are multiplied from units of “per-hour” to 2,250 hours. The use of a TLD to determine an individual’s external exposure is the standard in radiation safety and serves as the “legal dose of record” when other measurements are available. The project-specific TLDs are subjected to the same quality assurance (QA) checks as the routine NTS environmental monitoring TLDs.

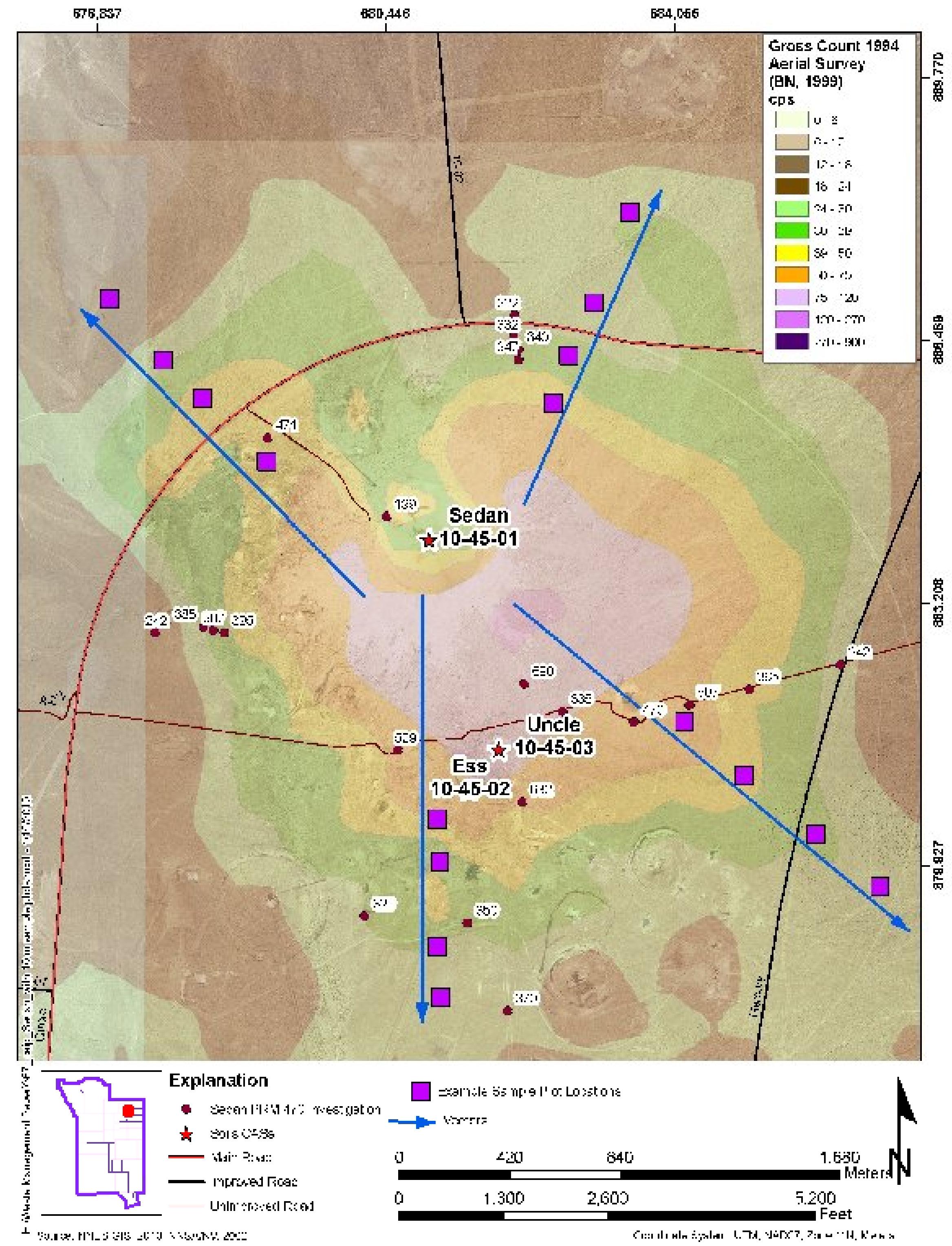

Fig. 2. Example nuclear release site [7, 8].

Buried Horizons of Contamination

If the CSM includes the possibility of buried horizons of contamination, it is necessary to determine whether buried contamination exists before sampling. As the most probable locations for buried contamination are where the deposited ejecta layer is deepest, a screening plot for determining the presence of buried contamination is established next to the first sample plot on each of the vectors nearest to the release location. The screening plot is sampled in the following manner:

1. Screen the surface sample with alpha/beta contamination meter.
2. Remove a 5-cm layer of soil from the screening plot.
3. Repeat Steps 1 and 2 until native soil is encountered.

If screening results are not significantly greater than the surface results, it is assumed that buried contamination does not exist, and only surface samples are collected and submitted for analyses. If buried contamination exists, it is conservatively assumed that the highest level of contamination observed (from surface or subsurface samples) provides dose to site workers. Therefore, the samples with the highest dose (surface or subsurface) at each plot are used for the internal dose estimate. If subsurface samples contain higher levels of contamination (that would result in a higher dose), a TLD-equivalent external dose is calculated for the sample plot based on the subsurface sample results. This is accomplished by establishing a correlation between RESRAD-calculated external dose from surface samples and the corresponding TLD readings. The RESRAD-calculated external dose from the subsurface samples will then be adjusted to TLD-equivalent values using this correlation.

The need to assess buried contamination may be tempered by visual evidence. For example, the Sedan test film [9] shows the dramatic effects of the base surge following detonation of the test. The base surge is shown scouring surface soil out to a diameter of 8 km from ground zero (GZ) and demonstrates mixing of the existing surface soil into the plume of ejected material from the Sedan test. This indicates that buried contamination levels will be roughly equal to, or less than, surface contamination levels. Surface contamination levels could be much higher due to larger size fractions of the ejecta settling onto the soil surface before the smaller size fraction of the ejecta (on which the majority of the contaminants are adsorbed). This conceptual model is supported by the results of soil sampling of depth layers at the Sedan and Schooner test sites. These results show generally decreasing contaminant levels with depth [10].

CALCULATION OF INITIAL CORRECTIVE ACTION BOUNDARY

To add another level of conservatism, the initial corrective action boundary areas are calculated for each sample plot using the 95 percent upper confidence limit (UCL) of the TED rather than the average TED. The 95 percent UCL of the TED for each sample plot is calculated as the sum of the 95 percent UCL of the internal dose and the 95 percent UCL of the external dose. The 95 percent UCL of the internal dose is calculated from the RESRAD-calculated internal dose estimates from the individual radionuclide concentrations reported in each of the four soil sample results.

The Panasonic UD-814 TLD used in the NTS environmental monitoring program contains four individual elements. The readings from each element are compared as part of the routine QA checks during the TLD processing. Element 1 is designed to measure dose to the skin and is not relevant to the determination of the external dose. The external dose measurement at each TLD location is determined from the readings of TLD elements 2, 3, and 4. The 95 percent UCL of the average external dose for each sample plot is calculated from the results of these three TLD measurements.

The corrective action boundary is established based on the correlation of the 95 percent UCL of TED from each sample plot and the corresponding radiation survey result along each vector so that a radiation survey value along each vector can be established that corresponds to the FAL (using the appropriate exposure scenario). If sample plot 95 percent UCL TED measurements meet the criteria (that at least one sample plot TED is greater than the FAL and at least one sample plot TED is less than the FAL) and a coefficient of determination (r^2) of the TED to radiological survey measurements is at least 0.9, then the resulting radiological measurement isopleth corresponding to the FAL is established as the initial corrective action boundary. Otherwise, additional sample plots are established until these criteria are met.

CALCULATION OF FINAL CORRECTIVE ACTION BOUNDARY

Initial results from Soils Project sites indicate that, when strong gamma signatures exist, Am-241 signatures from aerial gamma surveys may be masked. However, at a completed Soils Project site, the initial corrective action boundary (established using gamma radiation survey results) encompassed the areas of plutonium contamination that would result in a TED exceeding the FAL. Figure 3 shows the aerial survey Am-241 values compared to measured plutonium concentrations at the T-4 site. At this site, higher plutonium concentrations near GZ were not detected in the aerial survey Am-241 results while lower concentrations further from GZ were detected. At sites currently under investigation, additional aerial surveys for Am-241 (conducted at a lower altitude and using improved Am-241 detection equipment) will assist in the selection of sample locations. Based on the results of gamma spectroscopy surveys, if an Am-241 signature is detected outside the initial corrective action boundary, additional sample plots will be established for measuring TED where plutonium significantly contributes to internal dose at the location(s) of the highest Am-241 survey results. Additional sample plots based on Am-241 survey results are sampled in the same manner as the initial sample plots. This will either verify that the initial corrective action boundary encompasses all locations where the TED exceeds the FAL or it will cause that the corrective action boundary be extended to include plutonium-driven FAL exceedances. If TED exceeds the FAL at these locations, the correlation of TED to alpha radiation survey values will be established in the same manner used to establish the correlation of gamma radiation survey results to gamma-based sample plot TEDs. The corrective action boundary is then expanded to include the area encompassed by the alpha survey isopleth corresponding to a TED equivalent to the FAL.

The corrective action boundary is also expanded to include any areas where TED exceeds the FAL based on the migration or translocation of contamination subsequent to the release. Migration or translocation of contaminants includes the erosion of contaminated soil in stormwater runoff and the movement of contaminated soil or materials following the release from initial mitigation measures or subsequent construction activities (such as clearing a path to the GZ). The TED from these locations is determined from measurements of internal and external doses from sediment collection areas in drainages, from contaminated materials covered by clean fill material, or from contaminated materials collected in piles. Samples from these areas will be collected using the same techniques used for buried horizons of contamination.

The final corrective action boundary is established to include the default contamination boundary, the initial corrective action boundary, any additional areas that exceed the FAL based on plutonium contamination (sample plots based on the Am-241 survey), and any areas of migration or translocation of contaminants where TED exceeds the FAL.

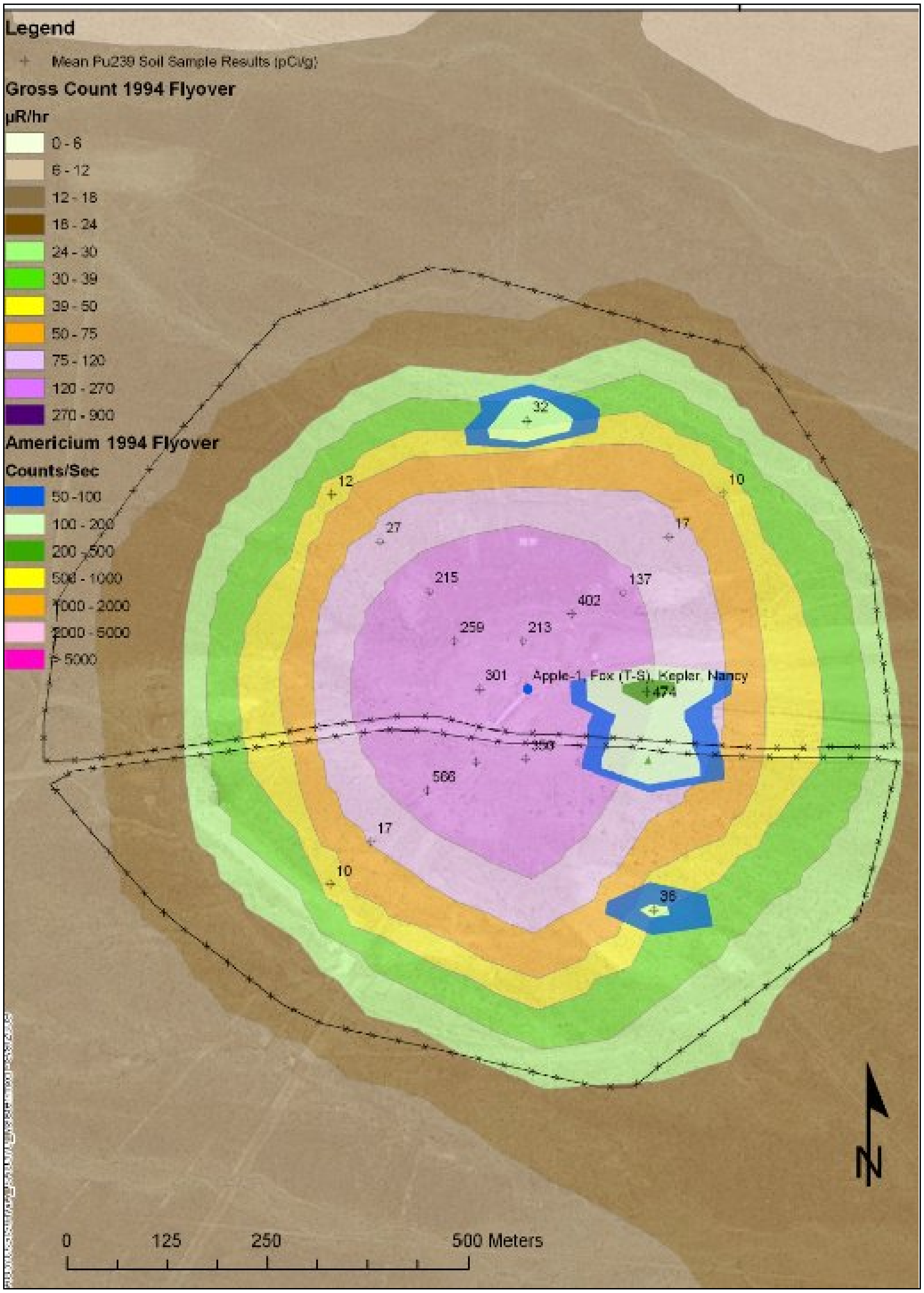

Fig. 3. Plutonium concentrations compared to aerial survey americium values [7, 8].

CONCLUSION

These techniques may be useful in determining corrective action boundaries under a wide variety of conditions at atmospheric radiological deposition sites. These variable conditions may include: large or small impacted areas; different types of nuclear source material (i.e., the radionuclides used); the amount of nuclear yield (e.g., designed nuclear devices or nuclear material coupled with conventional explosives); differential fallout patterns; and detonations in the atmosphere or underground (with/without venting).

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