Determining Corrective Action Boundaries at Atmospheric Nuclear Release Sites - 9230

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ABSTRACT

Determining the corrective action boundary of surface deposited radionuclide contamination from atmospheric nuclear testing can be costly and problematic due to the large areas involved and local variability of radionuclides affecting individual sample results. Concentrations of individual radionuclides can vary greatly and exhibit significant spatial variability over large areas due to discrete radioactive particles, differential fallout patterns, and sampling error. These sources of variability can complicate site characterization and corrective action boundary determination. This paper presents practices and methods that can be used to manage these variabilities and effectively characterize atmospheric nuclear release sites. Characterization of radiological contamination at an historical atmospheric nuclear test site was conducted within various 100-square meter test plots using a combination of probabilistic and judgmental sampling approaches with a combination of measurement and evaluation techniques. Extensive sampling was conducted at this site to evaluate the effectiveness of making corrective action decisions based on aerial and ground-based grid radiation measurement techniques along with a minimal number of soil samples. The corrective action decision level (CADL) was established at 0.25 millisieverts per year of total effective dose (TED). Estimation of dose was accomplished by estimating the internal and external dose components of TED separately. The estimates of internal dose rates were derived through sampling of sieved surface soil, analysis of the samples for radiological isotopes, and calculation of the internal dose from isotopic results using the Residual Radioactive computer code. The estimates of external dose at the various test plots were derived from the placement of thermoluminescent dosimeters at each plot for a total exposure time roughly equivalent to an industrial worker year (2,250 hours). This measurement integrated the contributions to dose from all gamma emitting radionuclides present at the site regardless of their configuration (e.g., Trinity glass aggregates). Soil particle activation and initial fallout distributions are generally distributed in annular (ring-like) geometric patterns. This distribution can be depicted in aerial gamma radiation surveys or ground-based grid radiation surveys as radial isopleths of decreasing radioactivity. At an atmospheric nuclear weapons test site, these isopleth depictions provided valuable information on the shape of the radioactive contaminant plumes and were correlated to upper confidence limit (UCL) of TED estimates. The correlation to TED was accomplished by determining trends of dose along three lines from the location of the release (i.e., ground zero) to locations where the UCL of dose rates are below the CADL. A regression analysis was used to determine the locations along these trend lines where the UCL of TEDs is equivalent to the CADL. Existing aerial gamma radiation survey isopleths, and isopleths calculated based on a grid gamma radiation survey, were used to define the shape of corrective action boundaries that encompassed locations where the UCL of TEDs exceeded the CADL. This study provides a comparison of techniques for characterizing and defining corrective action boundaries that may be applied to similar atmospheric radiological release sites. Use of these techniques may result in significantly reduced costs (associated with the reduced sample collection and analysis requirements) while providing a well defined corrective action boundary.

INTRODUCTION

The first atmospheric nuclear testing release site to be characterized under the corrective action program at the Nevada Test Site (NTS) is Atmospheric Test Site T-4. This site consists of contamination of the soil in and around the T-4 ground zero (GZ) that was impacted by contaminant releases from atmospheric tower testing of four nuclear devices in the 1950s. The site includes remnants of the testing tower, an associated bunker and soil berm, and pieces of metallic and concrete debris. The site is fenced and posted as a radioactive material area (see 10 *Code of Federal Regulations* 835), and an unpaved road traverses the area (see Figure 1).

The contaminant releases associated with the activities at the T-4 site were addressed under a *Federal Facility Agreement and Consent Order* corrective action investigation. This investigation was conducted to generate the information necessary to meet the following objectives:

- Identify contamination present at the site that exceeds the corrective action decision level (CADL).
- Define the corrective action boundary as the area that exceeds the CADL.

Information needed to meet these objectives and to verify information from the radiological surveys about the shape of plume dose isopleths was obtained through the collection of 63 soil samples and various external dose measurements within 15 test plots each measuring 10 by 10 meter (m). These 15 test plots were arranged in three vectors starting near GZ and extending radially outward through the radiation survey isopleths. Five test plots were located along each vector with the objective that at least one test plot would be in an area with a dose rate greater than 0.25 millisieverts per year (mSv/yr), and at least one test plot would be in an area with a dose rate less than 0.25 mSv/yr. The locations of the test plots (A through E in Vector 1, F through J in Vector 2, and K, L, M, N, and P in Vector 3) are shown in Figure 1.

The investigation results were used to estimate a total effective dose (TED) rate at each location. These dose rates were then used to determine the need to perform a corrective action. The U.S. Department of Energy (DOE) Order 5400.5 requires that: “Authorized Limits shall be established to (1) provide that, at a minimum, the basic dose limits … will not be exceeded, or (2) be consistent with applicable generic guidelines.”[1] The basic dose limit is 1 mSv/yr with a dose constraint established with stakeholders at 0.25 mSv/yr. The CADL for radionuclides was established as the 0.25 mSv/yr dose constraint (in excess of background). To conservatively estimate the true dose at the site, the 95 percent upper confidence limit (UCL) of the mean of dose measurements at each plot location were used for decision-making.

Determining corrective action requirements for sites impacted by the atmospheric deposition of radionuclides must consider the following potential complicating factors:

1. The composition of radionuclide contamination at each site varies and is dependant upon the composition of the source device and the type of test conducted (e.g., safety experiment test versus weapons test). Contaminants from safety experiment tests result from the destruction of nuclear devices using conventional explosives in which the nuclear source material is largely non-fissioned and dispersed to the environment. Contaminants from weapons testing result from

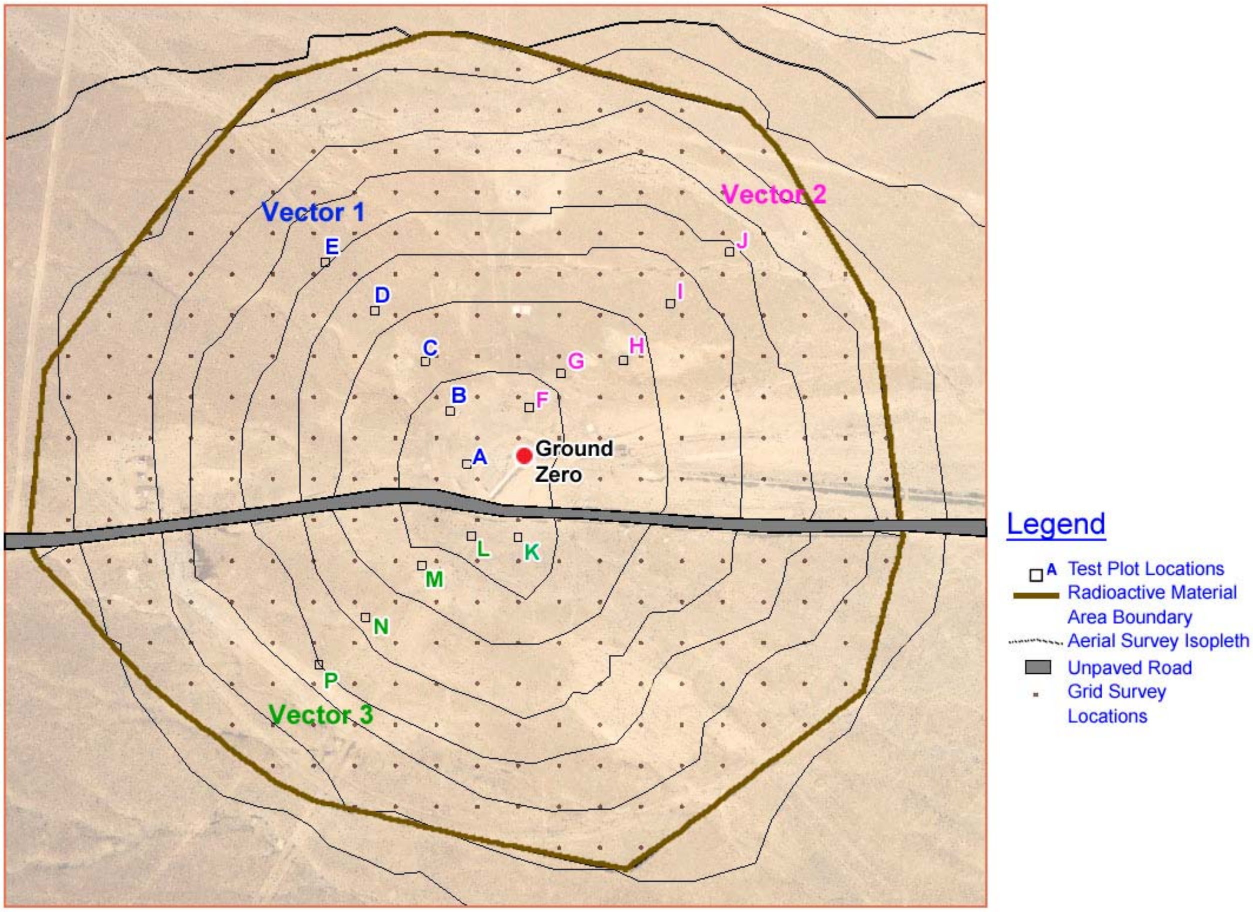

Fig. 1. T-4 site showing GZ, vectors, test plots, radioactive material area, aerial radiation survey isopleths, and grid radiation survey locations.

the detonation of a nuclear device. Most of the resulting radioactivity is due to fission products and pre-existing material (e.g., soil and debris) that has become activated although some amount of non-fissioned source material will also be present.

2. Obtaining a representative analytical result for plutonium (Pu) can be complicated due to:
    - The particle nature of Pu where particles may be non-uniformly distributed within soil samples.
    - The relatively small aliquots used for isotopic Pu analyses may not capture the discrete particles.
    - The high specific activity of Pu that can cause relatively large differences in analytical results between aliquots of the same sample depending upon the number of Pu particles that happen to be present in each analytical aliquot.
3. If non-friable Trinity glass aggregates are present, they may not be represented adequately in small analytical sample aliquots (due to size) causing analytical results to not be characteristic of site conditions. Trinity glass aggregates are formed by melting of soil from the heat generated in the nuclear detonations.
4. Relatively large areas are affected by the contaminant release.
5. Different releases may have occurred at same location.
6. Releases from different locations may overlap.

7. Migration of surface contamination may have occurred due to aerial resuspension (i.e., wind) or mass transport by storm water runoff.
8. Contamination may have been moved due to surface clearing or excavation.

To address these issues, the following three practices were developed:

- Performing separate estimates of internal dose and external dose (addresses issues 1 and 3)
- Specialized sampling and measurement techniques designed to minimize spatial variability (addresses issue 2)
- Use of aerial or grid surveys to define contaminant release distribution patterns (addresses issues 4, 5, 6, 7, and 8)

The following sections address the use of aerial or grid surveys to define contaminant release distribution patterns, the method of performing separate estimates of internal dose and external dose, the sampling methodology used to minimize spatial variability, and an evaluation of three methods of determining corrective action boundaries.

AERIAL AND GRID SURVEYS

The Remote Sensing Laboratory, then operated by Bechtel Nevada for the U.S. Department of Energy (DOE), conducted an aerial radiological survey of the T-4 site in 1994 [2]. This survey measured the terrestrial gamma radiation using sodium iodide detectors. This survey established concentric isopleths of gamma radiation centered on the T-4 GZ that represent a distribution pattern of decreasing gamma radioactivity in the form of annular isopleths (see Figure 1). The discrete isopleth lines were the only available information from this survey as no information was available about values between the isopleth lines.

During the site investigation, a grid gamma survey was performed by taking measurements of external dose rate at a height of 1 m above the ground surface with a Bicron microrem-per-hour meter. The Bicron is a low-level gamma-sensitive radiation detector that reads out in units of micro-rem per hour (micro-rem/hr) and gives tissue-equivalent photon response for x-ray and gamma radiation. The Bicron measurements were taken at each of the 319 unique survey points established on a 50-m grid (Figure 1). From this grid, the Spatial Analysis and Decision Assistance (SADA) software was used to interpolate the grid measurements and establish an annular distribution pattern of external dose rates (Figure 2) [3]. This distribution was used to evaluate the validity of using the aerial survey isopleths and to establish another estimate of dose distribution patterns.

SEPARATE ESTIMATES OF INTERNAL DOSE AND EXTERNAL DOSE

The CADL was established at a dose rate of 0.25 mSv/yr based on an industrial worker exposure scenario. The dose estimates used to compare to this action level are expressed as TED rates that are comprised of internal and external dose components. Dependant upon the types of radionuclide contamination present at any site, the TED may be predominantly comprised of either internal or external dose. This will vary dependant upon the composition of the test device and the type of test conducted. For example, the tests conducted at the T-4 site were weapons-related tower tests. Therefore, the contaminants are mainly fission products and activation products with some remaining nuclear fuel. The radionuclides present are predominantly gamma-emitters, and the TED rate at the site is driven by the external dose component. At sites where the contaminant release originates from a safety experiment test, the contaminants are mainly related to the nuclear fuel components. The radionuclides present are predominantly alpha-emitters, and the TED is expected to be driven by the internal dose component.

Another factor that affects the partitioning of internal and external dose is the exposure pathway. For the internal exposure pathway to be viable, radioactive material must enter the body through inhalation or ingestion. Radioactivity at a site that is incorporated into particles that are too large to be ingested or inhaled should not be included in the estimation of internal dose. At the T-4 site, numerous Trinity glass aggregates and rocks are present that are very cohesive and durable. A field grinding device was effective in breaking up soil aggregates while the Trinity glass aggregates remained almost completely intact. Therefore, it was concluded that although the Trinity glass aggregates impart significant radioactivity and contribute to the external dose component, they are not amenable to inhalation or ingestion and should not be included in the internal dose estimate.

Internal Dose Estimate

As the larger particles (e.g., Trinity glass) are not amenable to inhalation or ingestion, these larger particles were excluded from the homogenized sample material used to estimate the internal dose portion of the TED. The larger particles, including the non-friable Trinity glass aggregates, were separated from the sampled material by passing the sample through a #4 sieve.

Analytical results from homogenized soil samples were used to calculate the internal dose using the Residual Radioactive (RESRAD) model and computer code, version 6.4 [4]. Input parameters appropriate to the Nevada Test Site (NTS) used in this model were established with stakeholders under the following pre-defined scenario [5]:

- Industrial Work Area Scenario – Assumes continuous industrial use of a site. This scenario addresses exposure to industrial workers exposed daily to contaminants in soil during an average workday. This scenario assumes that this is the regular assigned work area for the worker who will be on the site for an entire career (225 days per year, 10 hours per day for 25 years). Due to the type of work conducted at the NTS, and the harsh climate, site workers spend much of their time in air-conditioned indoor facilities. However, for the purposes of calculating dose, it will be assumed that workers under this scenario will spend one-third of their workday outdoors.

This scenario was selected based on potential future use of the site. Other less conservative scenarios (more representative of actual site uses) could also be used with approval of the appropriate site stakeholders.

External Dose Estimate

In accordance with established protocols for environmental monitoring dosimeters at the NTS, the external dose portion of the TED was measured using thermoluminescent dosimeters (TLDs) placed at the approximate center of each test plot at a height of 1 m. This technique provides an external dose measurement at each plot as the TLDs measure the total radiation from all *in situ* materials as these measurements are independent of particle size, type, and configuration. This provides a representative measure of the actual contribution to external dose from the Trinity glass aggregates that were not included in the analytical soil samples.

The TLDs were emplaced in the center of each of the 15 test plots. The total TLD exposure time was 106 days (2,544 hours). The TLD dose measurements were adjusted to estimate the external dose for the Industrial Work Area Scenario of 2,250 annual exposure hours.

Other external dose measurement techniques may also be effective in estimating the external dose component. At the T-4 site, the Bicron microrem-per-hour meter used for the grid survey was also used to measure external dose at each plot. These measurements correlated well to the TLD readings [6].

SAMPLING

Soil samples were collected at the site to estimate the internal dose component of the TED. Investigation samples were analyzed for the gamma spectroscopy suite, isotopic americium (Am), isotopic Pu, isotopic uranium, and strontium-90, as specified for this site in the data quality objectives process based on knowledge of the type of test and test device components [7].

Sample Collection Technique

Estimating TED from soil samples is problematic due to the particle nature of Pu (where particles may be non-uniformly distributed within soil samples) and the relatively small aliquots used for isotopic Pu analyses (that may not capture the discrete particles). It is common for Pu sample results from duplicate samples to not meet precision criteria as the distribution of Pu in soil has been found to vary by a factor of 10 between individual one gram aliquots from a single soil sample [8]. This effect is due largely to the small aliquots (2 grams) used to analyze for isotopic Pu. Although a larger sample size would minimize the effect a discrete Pu particle would have on the analytical result, this is not currently an option. However, the analytical laboratory can perform an Am-241 measurement using gamma spectroscopy on a larger sample volume (i.e., 2-liter Marinelli beakers) and use the Pu to Am ratio to estimate the Pu concentration in this larger sample. The Pu to Am ratio should be fairly constant based on the ratio of these materials in the test device and the rate of radioactive decay since the release. This increased “field of view” using a larger sample volume should reduce the effects of individual particles on results when compared to the 2-gram analysis sample volumes (such as used for isotopic Pu). The resulting gamma measurement of Am-241 from the 2-liter sample was then used to generate an integrated gamma-derived Pu concentration estimate by multiplying the gamma Am-241 result from the 2-liter sample by the Pu to Am-241 ratios based on the Pu and Am isotopic analytical results.

For the T-4 site, the effect of discrete, anomalous Pu particles within the sampled material did not appear to be an issue as high variabilities within the isotopic analytical results for Pu-239 at each plot were not observed (i.e., the standard deviations were all less than half of the corresponding means). Also, any differences to the internal dose using either isotopic Pu results or gamma-derived Pu results made little difference to the TED at the T-4 site as external dose was the dominant component of TED. However, the use of gamma-derived Pu may be a useful technique for reducing the variability of Pu sample results for sites where sufficient Pu is present to make internal dose a significant portion of the TED.

Specific sampling techniques were implemented at this site to minimize variability of analytical results at each test plot. For each soil sample, aliquots of sample material were composited from nine randomized locations within the test plot. The randomized aliquot locations were selected using the Visual Sample Plan (VSP) software program with a random start, systematic, triangular grid pattern [9]. Each aliquot was collected using a vertical-slice cylinder and bottom-trowel method. A metal cylinder (7.6 centimeter [cm] diameter) was inserted to a depth of 5 cm at the aliquot location. The outside soil along one side of the cylinder was removed to permit placement of the bottom trowel, and the aliquot was removed with the cylinder. This method captured relatively undisturbed, representative subsamples of the soil to a depth of 5 cm. The diameter of the cylinder was designed to provide the requisite 2-liter sample volume when nine aliquots are composited into one sample container. The depth of 5 cm was chosen based on previous investigations which found that radionuclides with multi-year half-lives deposited from aboveground nuclear testing at the NTS are concentrated in the upper 5 cm of undisturbed soil [10, 11, 12, and 13].

Following collection of the aliquot, the material was carefully passed through a #4 mesh sieve into a bottom pan with a plastic bag liner. This plastic bag allowed for aliquot transfer to a “paint can” type container with minimal dust generation. The containers were then sealed with a lid and lock ring and shaken atop a paint shaker for three minutes to homogenize the soil before shipment to the analytical laboratory.

To provide sufficient data for the calculation of UCLs of the dose and calculation of minimum sample size requirements, four separate composite samples were collected at each test plot. The four composite samples from each test plot were used to establish a 95 percent UCL estimate of the average TED within the plot. The variability between the four composite samples was used to calculate the minimum sample size requirement for each test plot. As shown in Table I, the variability of the sample results (using the sampling techniques described herein) were small enough to require only the minimum number of samples.

Table I. Dose Statistics and Sample Size Requirements for Each Plot (mSv/yr)

Test Plot	Average Internal Dose	External Dose	Average TED	95% UCL of the TED	Minimum Number of Samples	Number of Samples Collected
A	0.0195	1.73	1.75	1.755	3	4
B	0.0161	1.18	1.196	1.203	3	4
C	0.013	1.32	1.333	1.340	3	4
D	0.0017	0.45	0.452	0.452	3	5
E	0.0009	0.1	0.101	0.101	3	4
F	0.0139	1.41	1.424	1.429	3	4
G	0.0242	1.34	1.364	1.367	3	4
H	0.0073	1.66	1.667	1.671	3	4
I	0.0012	0.3	0.301	0.301	3	5
J	0.0007	0.1	0.101	0.101	3	4
K	0.0214	2.18	2.201	2.205	3	4
L	0.0678	1.74	1.808	1.830	3	4
M	0.038	1.53	1.568	1.575	3	5
N	0.0012	0.28	0.281	0.281	3	4
P	0.0008	0.21	0.211	0.211	3	4

ESTABLISHMENT OF CORRECTIVE ACTION BOUNDARIES

Corrective action boundaries were calculated independently for each vector based on results from each plot using the following methods:

1. The aerial and grid survey isopleths that encompass locations along each vector that exceed the 95 percent UCL of the TED (TED estimated from the sum of external dose measured using TLDs and internal dose measured using analytical results).
2. The aerial and grid survey isopleths that encompass locations along each vector that exceed the 95 percent UCL of the TED. However, the TED for this method was estimated from RESRAD calculations of dose contribution based on individual radionuclide analytical results.
3. The interpolated grid survey external dose rate isopleth that corresponds to the 95 percent UCL of the 0.25 mSv/yr dose rate.

Method 1

Method 1 is applicable to sites where external dose is significant and sites where the surface is not amenable to producing representative samples (e.g., where large Trinity glass aggregates and rocks are present). For Method 1, corrective action boundaries were established based on a correlation of distance from GZ to the location along each vector where the 95 percent UCL of the average TED was estimated to be equivalent to the CADL. The TEDs used for this method were calculated from separate estimates of internal and external dose as described herein. The measured distribution pattern associated with this release site showed generally decreasing dose rates with distance from GZ. Due to surface disturbances near GZ, this pattern is not consistent within the central portion of the site. The outer three plots on each vector demonstrated a consistent pattern of decreasing dose rates with distance and encompassed the CADL of 0.25 mSv/yr. Therefore, the correlation to determine the distance along each vector from GZ to where the TED is equivalent to the CADL was based on the calculated 95 percent UCL of the TED from the outer three plots of each vector. The correlations of TED to distance from GZ are presented in Figure 2.

For comparison purposes, corrective action boundaries were established based on results from each vector (to determine if the use of a single vector would produce a similar corrective action boundary) and for each of the radiation survey methods used to define isopleths (to determine if aerial or grid surveys produced similar corrective action boundaries).

For the aerial survey, the distances to a 95 percent UCL of the 0.25 mSv/yr dose rate based CADL for all three vectors were encompassed by the fourth aerial survey isopleth (an area of approximately 370,000 m^2). The distances to a 95 percent UCL of the 0.25 mSv/yr dose rate for the first and second vectors were encompassed by the third aerial survey isopleth and the distance to the 95 percent UCL of the 0.25 mSv/yr dose rate for the third vector was encompassed by the fourth aerial survey isopleth. Had only one vector been used, the corrective action boundary may have been set at either the third isopleth (an area of approximately 250,000 square meters [m^2]) or the fourth isopleth (an area of approximately 370,000 m^2).

For the grid survey, the distances to a 95 percent UCL of the 0.25 mSv/yr dose rate were roughly equivalent to a 0.1 mSv/yr (Bicron reading) isopleth for all three vectors. The corrective action boundary decision would have been the same based on any single vector resulting in an area of approximately 280,000 m^2. The correlation of the 95 percent UCL of the TED to distance from GZ and the corrective action boundaries derived from this method are presented in Figure 2.

Method 2

Method 2 is applicable to sites where internal dose is significant and sites where the surface is amenable to producing representative samples (e.g., where large Trinity glass aggregates and rocks are not present). As in Method 1, corrective action boundaries for Method 2 were also established based on the correlation of distance from GZ to the location along each vector where the dose was estimated to be equivalent to the CADL. However, the estimates of dose for this method were based on the added contribution to dose from each of the radionuclides present in any analytical sample at levels exceeding a screening action level. Each radionuclide analytical result was converted to represent a fraction of the 0.25 mSv/yr CADL. This was done by dividing the analytical result by the concentration of that radionuclide required to generate a dose equal to the CADL. The fractions thus calculated for each of the radionuclides were then added using the sum of fractions method. A sample with a sum of fractions greater than one was considered to exceed the CADL. The calculation of distance from GZ to the where radionuclide concentrations would be equivalent to the CADL for each vector was interpolated from a correlation of distance from GZ to the sum of fractions at each test plot. As in Method 1, the correlation to determine the distance along each vector from GZ to where the sum of fractions is equal to one was based on results

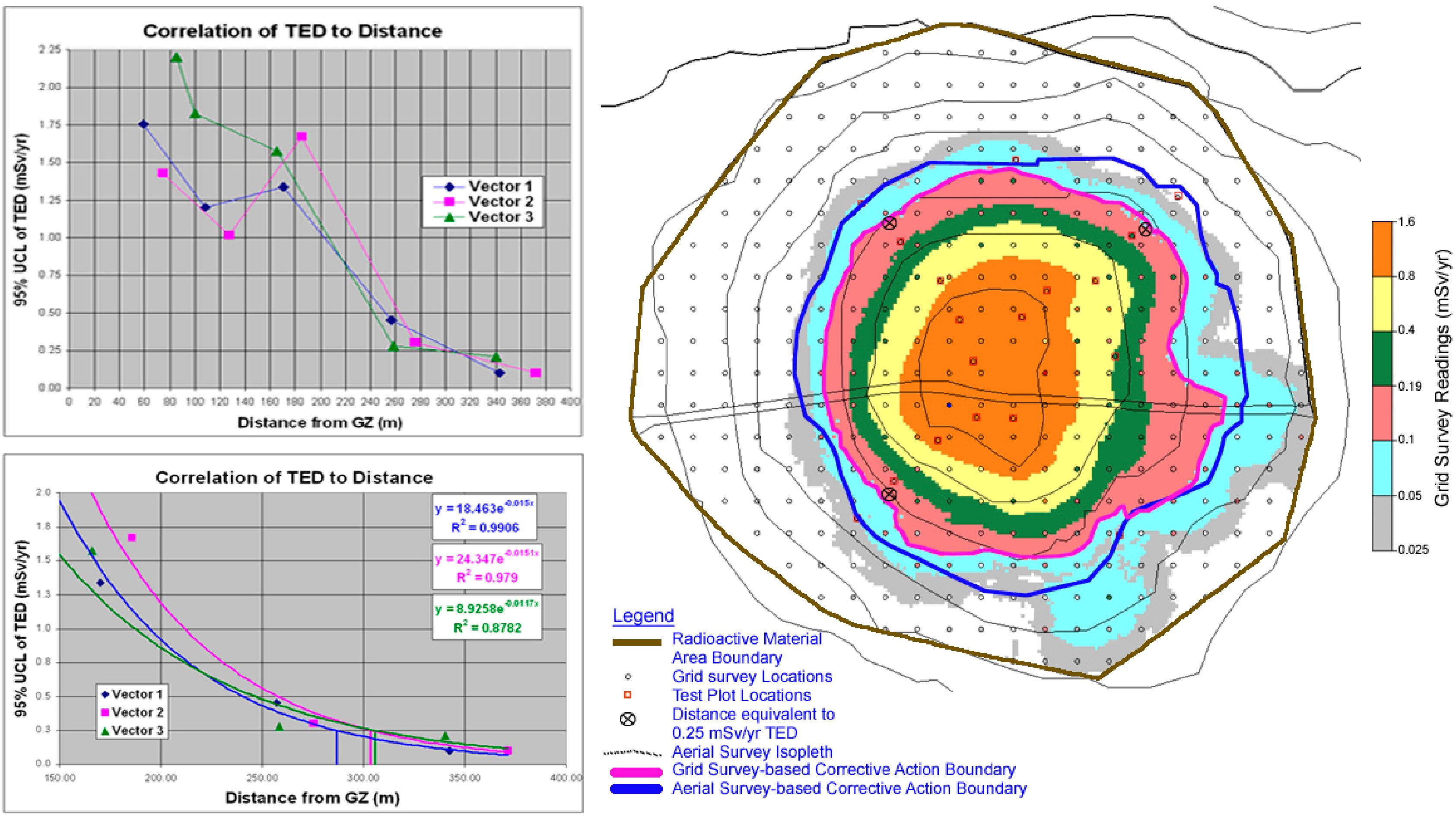

Fig. 2. Method 1. Correlation of the 95 percent UCL of the average TED to distance from GZ and the resulting corrective action boundaries (mSv/yr).

from only the outer three plots. The concentration of each radionuclide required to generate a dose equal to the CADL was estimated using RESRAD using the industrial worker scenario and both internal and external pathways.

For the aerial survey, the distances to a 95 percent UCL of the sum of fractions based CADL for all three vectors were encompassed by the third aerial survey isopleth (an area of approximately 250,000 m^2). For the grid survey, the distances to a 95 percent UCL of the sum of fractions based CADL were encompassed by the 0.19 mSv/yr grid survey isopleth (an area of approximately 200,000 m^2). For the aerial survey, the corrective action boundary decision based on any one of the three vectors would have been the third isopleth. For the grid survey, the corrective action boundary decisions based on Vectors 1 and 2 would have been associated with the 0.19 mSv/yr isopleth (an area of approximately 200,000 m^2) while the corrective action boundary decision based on Vector 3 would have been associated with the 0.0.4 mSv/yr isopleth (an area of approximately 140,000 m^2). The correlation of the sum of fractions to distance from GZ and the corrective action boundaries derived from this method are presented in Figure 3.

Method 3

Method 3 is applicable to sites where an aerial survey is not present, an aerial survey is not reliable, or where better resolution is required than can be obtained from an aerial survey. For Method 3, a corrective action boundary was established based on a correlation of the grid radiation survey readings to measured TED estimates at each of the plots. This correlation is shown in Figure 4. The grid survey reading of 0.19 mSv/yr correlated to a TED of 0.25 mSv/yr. Although both of these values use the same units, the grid values are expected to be less as they only represent external dose.

Therefore, the corrective action boundary was established as an interpolated grid isopleth of 0.19 mSv/yr. This corrective action boundary resulted in an area of approximately 200,000 m^2. The correlation of the grid radiation survey readings to measured TED estimates at each of the plots and the corrective action boundary derived from this method are presented in Figure 4.

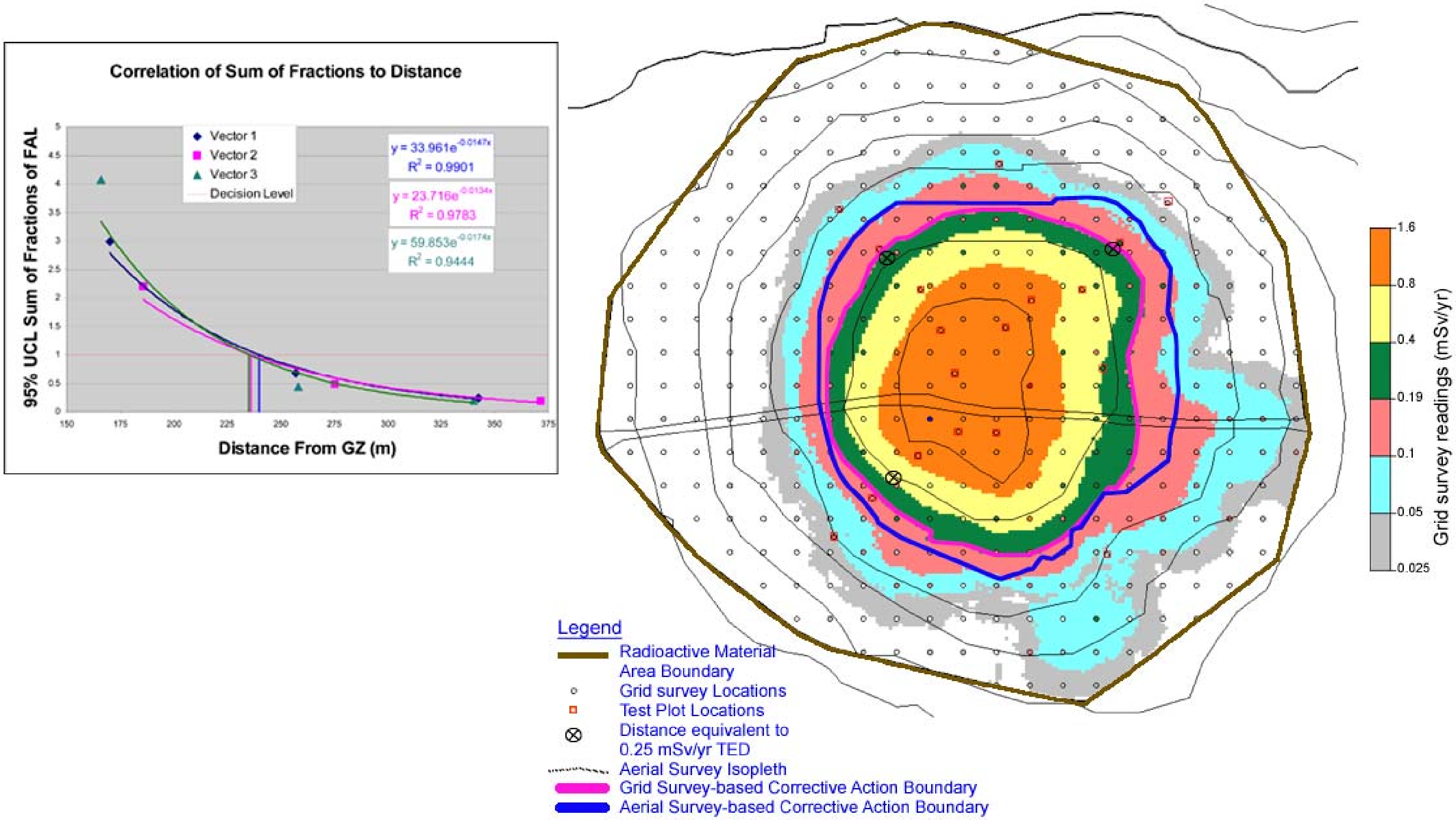

Fig. 3. Method 2. Correlation of the sum of fractions to distance from GZ and the resulting corrective action boundaries.

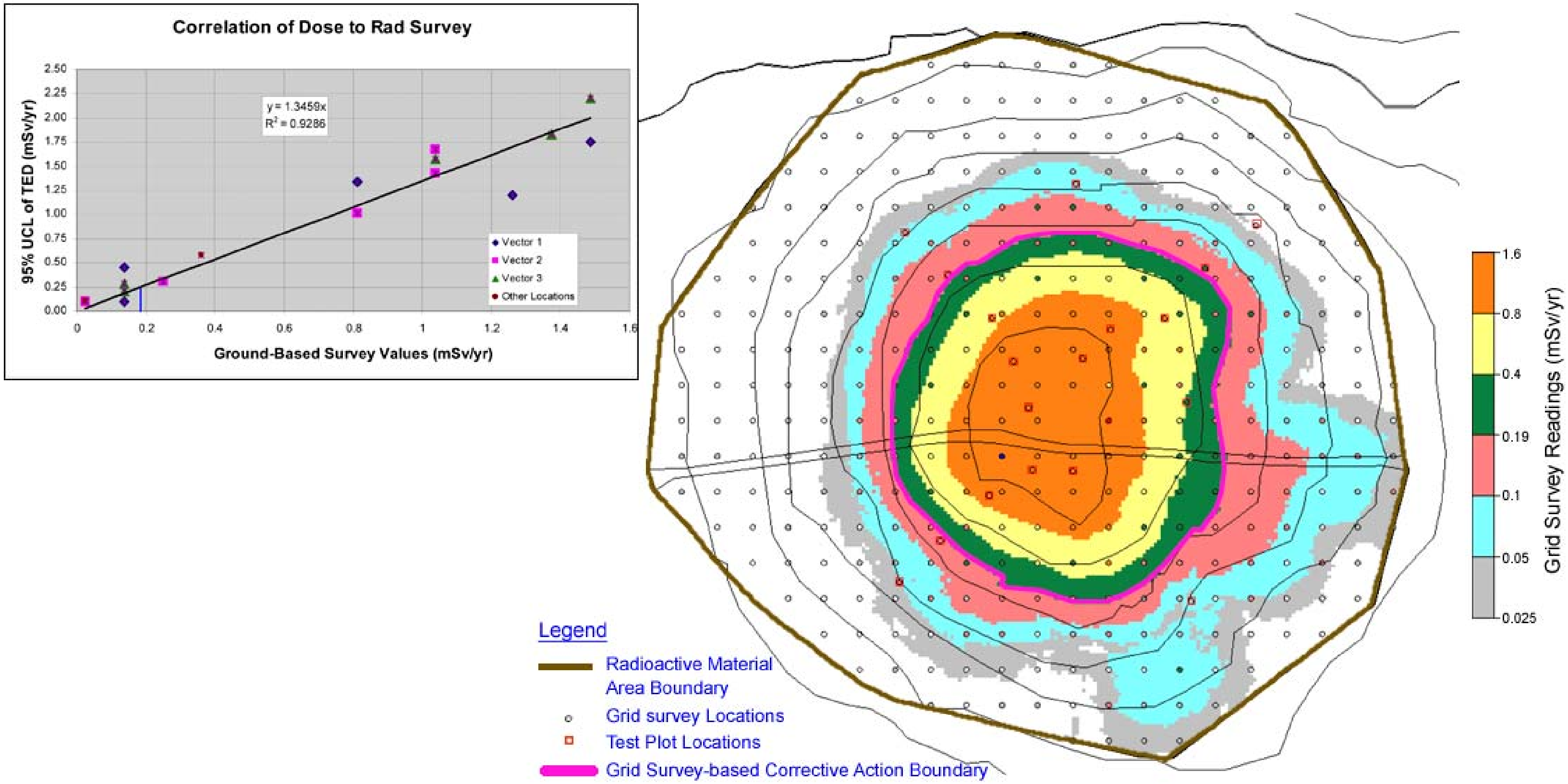

Fig. 4. Method 3. Correlation of the 95 percent UCL of the average TEDs from each test plot to corresponding interpolated external dose rates and the resulting corrective action boundary (mSv/yr).

CONCLUSION

Table II provides a summary of the areas encompassed by the corrective action boundaries established using the various techniques described herein. The observed differences in the corrective action boundaries established using either aerial or grid surveys were due largely to the number of isopleths (resolution) provided from the aerial survey. Even so, corrective action boundaries established using the aerial survey provided similar results to the corrective action boundaries established using the grid survey. Depending upon the dose action level required, the types of radionuclides present, and the sensitivity of the aerial survey, aerial surveys can be effective in defining the shape of corrective action boundaries.

Table II. Corrective Action Boundary Areas (m^2) – Based on Method, Survey Type, and Vector

		Area m^2		
Survey Type	**Method**	**Vector 1**	**Vector 2**	**Vector 3**
Aerial	1. (95% UCL TED)	250,000	250,000	370,000
Grid	1. (95% UCL TED)	280,000	280,000	280,000
Aerial	2. (95% UCL sum of fractions)	250,000	250,000	250,000
Grid	2. (95% UCL sum of fractions)	200,000	200,000	140,000
Grid	3. (Grid Survey)	200,000	N/A	N/A

Results from each of the three vectors verified the radiological distribution patterns observed in the aerial and grid radiation surveys. With the exception of Vector 3 for Method 1, a separate evaluation of each vector resulted in the same corrective action boundary for each survey type and method. If the corrective action boundary decisions were based on the results of any one of the three vectors, the corrective action boundaries would not have been significantly different. This suggests that a single vector may be sufficient to provide the TED levels needed to correlate with either aerial or grid radiation survey isopleths.

The corrective action boundaries established using each of the three methods are depicted in Figures 2, 3, and 4. The corrective action boundaries determined using the Method 1 and Method 3 were not significantly different while the corrective action boundary determined using the Method 2 was somewhat less conservative. All three methods appear to be viable and provide similar protection from inadvertent exposures.

The variability of the internal dose measurements at the T-4 site was demonstrated to be small and justified the small number of samples collected at each test plot. This was due to the methods used to collect the samples and the relatively uniform distribution of the radiological contamination from the atmospheric testing conducted at this site.

The aerial survey isopleths and the interpolated grid isopleths were both effective in defining the shape of corrective action boundaries. The aerial isopleth distribution patterns correlated well with the distribution patterns of the interpolated grid isopleths in the area where TED was greater than a dose rate of 0.25 mSv/yr. This provides support to the usefulness of aerial or grid radiological surveys in establishing corrective action boundaries for similar sites. It should be noted that the radionuclides present at the T-4 site are predominantly gamma emitters and are in a configuration that external dose is the predominant component of TED. Use of radiological surveys may also be useful in establishing corrective action boundaries at sites with atmospheric radiological deposition where radionuclides that are not gamma emitters predominate and/or where internal dose is the predominant component of TED. However, a strong correlation of radiological survey results to measured TED at concentrations near the action level will need to be demonstrated at these types of sites before using the survey results to define corrective action boundaries.

Implementation of this methodology for establishing corrective action boundaries at subsequent atmospheric release sites will need to be based on an evaluation of contaminant properties and physical characteristics that justify the distributional assumptions from the radiological surveys. Careful implementation of these techniques using field measurements, in conjunction with a limited set of analytical measurements, can be used to determine corrective action boundaries at similar atmospheric release sites.

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