RADIOLOGICAL SURVEYS: METHODS, CRITERIA, AND THEIR IMPLEMENTATION

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ABSTRACT

A radiological survey provides an answer to the following question: Can a decontaminated or remediated site or structure be released for use without radiological restrictions? The answer is derived from considerations involving a host of site- and radionuclide-specific variables, pathway analyses, and future use scenarios, of which the nuclide-specific data are obtained during the survey. Deriving the answer also requires reducing the sample data to representative statistical parameters for the entire site or structure, and, in turn, determining whether the statistical parameters compare favorably with the corresponding regulatory acceptance criteria. Based on recent experience, this paper provides some insights into performing radiological surveys, with examples to illustrate this approach.

INTRODUCTION

Release of radioactively contaminated sites and structures following their remediation or decontamination for unrestricted use requires a radiological survey to demonstrate compliance with regulatory acceptance criteria, such as those specified in Regulatory Guide 1.86 of the U. S. Nuclear Regulatory Commission (NRC) (1). In performing radiological surveys, detailed plans and analytical and computational tools are used to guide the surveyor, the analyst, and the site owner toward satisfactory regulatory compliance. Of these, the survey plan, based on the past operating history and the decontamination efforts, qualitatively specifies the residual nuclides that may be present at the site, the affected media, and the detailed scope of the survey effort. Survey data obtained from a number of locations at the site are then statistically analyzed for application to the entire site, and may be used as inputs to pathway analysis models (2,3) to determine potential exposure to current or future occupants of the site. Results from the statistical analysis and the pathway analysis models for the site can, in turn, be compared with the numerical regulatory limits to determine compliance or the need for additional, perhaps localized, decontamination.

Although the approach stated above is simple in principle, its implementation in the performance of radiological surveys requires careful consideration of a number of variables, which generally fall into the following categories:

1. Acceptance limits or criteria
2. Physical survey parameters
3. Statistical methods and parameters to which the data are reduced
4. Selection of natural "background" radiation data
5. Pathway analysis models and applicable inputs, including future use-scenarios for the site or structure.

Based on experience gained from radiological surveys performed over recent years, this paper presents some practical insights into performing such surveys and accomplishing the overall objective, which is to release a site for use without radiological restrictions. Although the details presented here apply to one geographical area, we found that choices among the above variables could not be made uniformly, and the reasons for this are discussed.

BACKGROUND

Formerly used and adjoining areas of a nuclear test facility in Southern California were radiologically surveyed for residual radioactivity. Both structures (buildings) and open sites within the 117-hectare (290-acre) facility were surveyed. Suspected or potential contaminants included activation products (e.g., Co-60), fission products (e.g., Cs-137), fuel isotopes (e.g., enriched uranium), and calibration sources (e.g., Ra-226). Based on previous operating history and routine monitoring data, the contamination was known to be minor and restricted to soil (surface and subsurface) and building interiors. For purposes of discussion, this paper presents four cases of residual soil contamination, as follows:

Case A. A storage yard (Cs-137)

Case B. A side yard adjacent to a building with a previous decontamination history (also Cs-137)

Case C. A building which formerly housed a below-grade Ra-226 source with breached outer encapsulation

Case D. A building drainage system with potential Cs-137 and enriched uranium contamination

In all of these cases, through remediation efforts and surveys, residual radioactivity has been determined to be well below acceptance limits for release without radiological restrictions.

SURVEY PLAN

The surveys were performed in several steps: First, a broad survey plan was established for the entire test facility complex. Based on the operating history of the complex, the plan identified suspected radionuclides and the media to be characterized during the field survey, and established the related acceptance criteria. The plan divided the complex into 25 convenient areas and buildings. The plan also specified the statistical design, techniques, and parameters (e.g., number and size of grid locations for measurements, calculation of the test statistic--described below--etc.) to be used to reduce the data, and procedures for the calibration and use of survey instruments. Finally, the plan required performance of an interpretative analysis of the data and determination of compliance or other recommended actions, all of which were documented in a survey report for each subdivision.

As directed by the plan, gamma exposure rate data were collected at random locations within each subdivision and at background areas where no nuclear operations took place. If the field measurements showed exposure rates above certain pre-established action levels, the surveyor was instructed to collect additional gamma exposure rate data and soil samples for radiometric analyses. As discussed below, the data, after corrections for background, were statistically analyzed and compared with acceptance limits for compliance. Results from this first round of surveys typically eliminated most areas from further consideration. For those few remaining areas, the survey report recommended specific actions, including decontamination efforts in localized areas, and additional investigations by means of a second round of surveys of the affected area. The Cases A through D mentioned earlier were all subjected to this second round of investigation.

For all cases, an evolutionary approach was needed to modify the acceptance criteria, treat the data, and to demonstrate compliance on a case-by-case basis. Use was made of the U. S. Department of Energy (DOE) computer code RESRAD to implement site-specific guidelines for residual radioactivity (2). This approach, as it applied to establishing the acceptance criteria, the statistical treatment of the data, and the use of the RESRAD code, is discussed in the following sections, with illustrative examples from the four cases.

ACCEPTANCE CRITERIA

General. Federal agencies (NRC and DOE) and state regulatory authorities (e.g., State of California Radiological Health Branch) specify the criteria for acceptance of remediated sites and structures for their release and use without radiological restrictions ("unrestricted release" in NRC terminology). Typically, the criteria are provided in terms of maximum limits for external exposure rate (gamma), emission- (alpha or beta-gamma) or nuclide-specific surface contamination (removable and fixed) levels, and nuclide-specific activity concentration in the media. The recently issued pathway analyses documents by the NRC and the DOE also enable determination of an acceptance criterion for a specific site on the basis of the combined presence of several nuclides and on the basis of a credible use scenario for the site or structure (2,3). A generic acceptance limit is available for Ra-226 in soil (4). Acceptance criteria for a given survey would, therefore, have to be chosen from among these regulatory stipulations. Where the numerical value of the limit varies (from one agency to another or from one time to another within the same agency), a conservative choice must be made, as discussed below.

Gamma Exposure Rate. Although the DOE guidelines (4) recommend a value of 20 μR/h (at 1 m) above background for gamma exposure rates, a lower value of 5 μR/h above background was chosen for these surveys and was based on a previous NRC stipulation for the unrestricted release of a dismantled test reactor facility in the complex. Also, the 5 μR/h above background corresponds to the recently issued NRC limit of 10 mrem/yr (2000-h occupancy) under its "Below Regulatory Concern" policy (5).

Although it is conceivable that the limit for above-background gamma exposure rate could be set even lower than 5 μR/h (e.g., 10 mrem/yr applied to year-round occupancy), practical difficulties are encountered. In the case of the survey data discussed here, for example, a 3 to 4 μR/h variability was observed in the natural background in "clean" areas, which is close to the 5 μR/h limit. To overcome this difficulty, carefully selected "cohort" areas were used, which were adjacent to a subdivision being surveyed and had gamma exposure rates with relatively less variability. The cohort areas were verified by means of soil analyses to have only natural background radioactivity. Thus, the 5 μR/h above-background gamma exposure rate criterion was applied in all cases, with the background being established on a case-by-case basis.

Surface Contamination Levels. For both alpha- and beta-gamma-emitting nuclides, the 5,000, 15,000, and 1000 dpm/100 cm^2 average, maximum, and removable contamination levels, respectively, were used as specified in the NRC Regulatory Guide 1.86 (1). These criteria were applied in cases where interiors of buildings were surveyed.

Soil Activity Concentrations. For open sites with residual Cs-137 contamination (Cases A and B), a site-specific concentration limit was established using RESRAD. It was surmised that this contamination had resulted from release of mixed fission products and, hence, an equal activity concentration for Sr-90 was also assumed in performing the RESRAD calculations. For the case of a future residential use of the site, the RESRAD-derived soil concentration limit was calculated to be 60 pCi/g each of Cs-137 and Sr-90. Details of these RESRAD calculations are provided later in this paper.

For the case of Ra-226 (Case C), two generic limits were considered. The first, with a value of 5 pCi/g above background, corresponds to the activity concentration over the first 0.15 m of soil and the second, 15 pCi/g above background, is for soil at depths greater than 0.15 m (4).

For the case of enriched uranium that could have potentially migrated from a drain line into adjoining soil (Case D), the ratio of activity concentrations of U-235 to U-238 was compared with the same ratio for naturally occurring concentrations of the two isotopes. RESRAD-type activity concentration limits for these isotopes (or the initially suspected Cs-137 nuclide) were not needed because the findings showed only natural activity in soils adjacent to the drain line.

In summary, a 5 μR/h above-background gamma exposure rate was used as a generic acceptance criterion, the background value being established on a case-by-case basis. Acceptable surface contamination levels for building interiors were the same as specified in the NRC Regulatory Guide 1.86. Soil activity concentration limits were established on a case-by-case basis and included a RESRAD-derived value of 60 pCi/g each for the combined presence of residual Cs-137 and Sr-90 in soils.

STATISTICAL TREATMENT OF DATA

General. A statistical procedure is required to validate the applicability of data collected at random locations to an entire area or region. Once a value for such a representative statistical parameter is calculated for the data distribution, this value can then be compared with the acceptance criterion to determine regulatory compliance. A representative statistical parameter will be required for a corresponding acceptance criterion; that is, one each for the gamma exposure rate, the contamination levels, and the soil activity concentration criteria. All criteria must be met together for compliance. To our knowledge, generic regulatory guidance or standard practices (e.g., from the ASTM) for statistically treating radiological data are not available. The techniques adopted from various other sources for the surveys are summarized in the following paragraphs.

Sampling Inspection. When it is impossible, impractical, or uneconomical to measure the characteristics of every item in a group (e.g., each grain of soil in a plot or square meter of a wall), it is common to use a statistical technique called sampling inspection. This approach allows the development of conclusions and decisions on the basis of statistically representative data. The method has been widely applied in industry and military where destructive tests must be performed or where the lot size is impractically large.

Sampling inspection may be based on measurement of attributes (whether an item sampled is a reject or not) or variables (the actual value of the characteristic being measured). The latter approach (6) was most suitable for the present survey because it provides increased accuracy for the same number of inspections and because it permits estimating the probability that the entire group from which the samples are taken has items that exceed specified values.

In sampling inspections by variables, the number of data points on which measurements are obtained is first chosen to be reasonably large (greater than about 30) so that the distribution of the data should be normal (i.e., Gaussian). The mean of the distribution, xm, and its standard deviation, s, are then related to a test statistic, TS, as follows:

$$TS = x_m + ks.$$

TS and x_m are then compared with an acceptance limit (such as those described earlier) to determine acceptance or other plans of actions, including rejection of the surveyed area. In the above expression, k is known as the tolerance factor. The value of k is determined from the sample size and two other statistical sampling coefficients that are related to a consumer's risk of accepting a lot, given that a fraction of the lot has rejectable items in it. The values chosen for these coefficients corresponded to ensuring with 90% confidence that 90% of the area has residual contamination below 100% of the applicable limit (a 90/90/100 test). The choice of the values for the two coefficients is consistent with industrial sampling practices and State of California guidelines (7).

Implementation. Data from the surveys were treated using this statistical approach. The reduced data were plotted against the cumulative Gaussian probability function on a probability-grade scale. Display of data in this manner permits clear identification of data with values significantly greater than expected for the lot, based on the Gaussian distribution. Figure 1 shows illustrative data obtained for ambient gamma exposure rates obtained at one site (Case B--first-round survey). Data obtained from a second-round survey of the same area following removal of soil from the affected locations are shown in Fig. 2. Here, the data have been corrected for background. Figure 2 also shows the TS value and the corresponding 5 μR/h acceptance limit. As can be seen, TS is less than the acceptance limit, thus satisfying the gamma exposure rate criterion for this lot. Similar calculations and comparisons were applied to other data, such as soil activity concentration and surface contamination level distributions.

For the cases cited, the above approach was used to treat the gamma exposure rate data in all the first-round surveys. The approach was also used for Cases A and B during the second-round surveys. Cases C and D did not require statistical treatment during the second round of surveys because they required simple removal (for authorized disposal) of contaminated items from highly localized areas without any effect on the previously obtained gamma exposure rate data from adjacent areas. For similar reasons, soil activity concentration data from Cases C and D were also not treated using this approach; instead, the individual datum was compared with a generic acceptance criterion (Ra-226 for Case C and the ratio of U-235 to U-238 with respect to their natural ratio for Case D).

RESRAD CALCULATIONS

For Cases A and B, which involved relatively large affected areas, site-specific soil activity concentration acceptance limits were established using the RESRAD code.

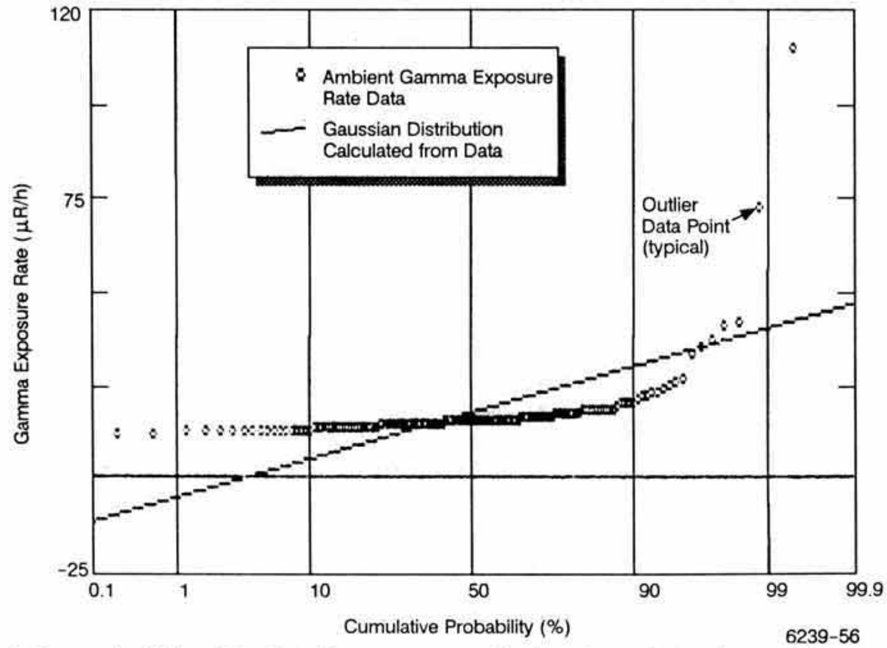

Fig.1. Cumulative probability plot of ambient gamma radiation (Case B-portions of first-round survey.)

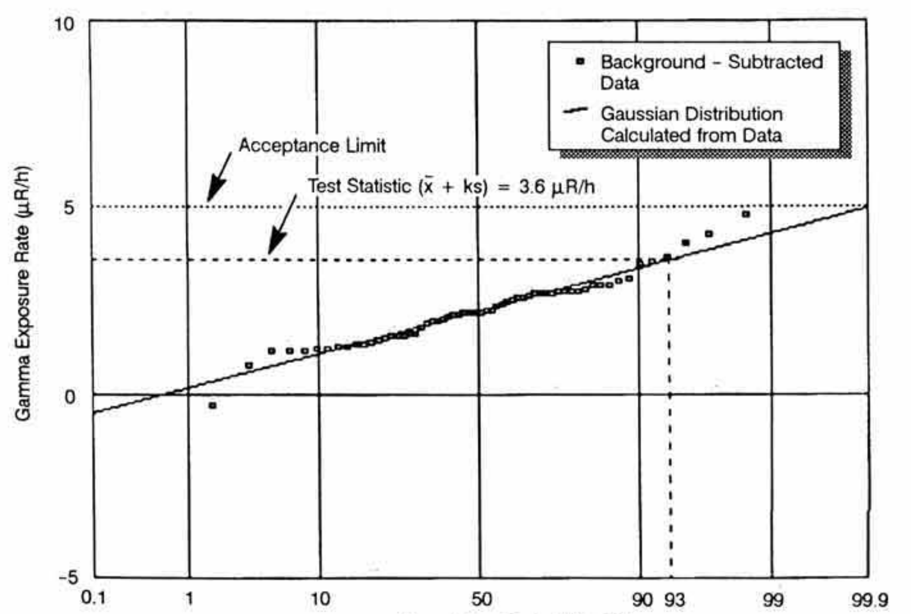

Fig.2. Background-subtracted gamma exposure rates (Case B-second-round survey after decontamination).

The technical approach to using RESRAD for determining the soil activity concentration acceptance limit for Cases A and B and for demonstrating compliance with respect to the DOE 100 mrem/yr "basic dose limit" are described below.

Overview. RESRAD calculates the effective dose equivalent to an occupant (current or future) by performing environmental and dietary pathway analyses resulting from the presence and transport of radioactivity through terrestrial media (both living and inanimate). Reference 2 provides a comprehensive description of the pathway analysis model and a users' manual for RESRAD. Similar pathway analyses models are available from other sources (3,8).

RESRAD provides results both in terms of a calculated activity concentration limit (in pCi/g) corresponding to the 100 mrem/yr effective dose for identified contaminant nuclides at a site and in terms of the effective dose equivalent for specified concentrations of nuclides. Thus, only qualitative information on the contaminant (e.g., an arbitrarily chosen concentration for Cs-137) is necessary to derive the acceptance limit. With specific data from a survey as input (e.g., the average concentration of Cs-137 and Sr-90 shown in the distribution in Fig. 2), RESRAD will provide the corresponding dose to an occupant. In both instances, however, identical site-specific data and use-scenarios must be employed to obtain comparable results.

The following categories of input data are required to implement RESRAD for a given site:

1. Soil activity concentration data
2. Site-specific geohydrological parameters
3. Dietary parameters
4. Scenario-specific parameters

In all, about 80 input parameters are required. The RESRAD manual provides ranges of input values for the geohydrological and dietary parameters for the United States, from which the code employs a set of default input values. The code further allows modifying or eliminating exposure pathways, as necessary, for a given use scenario. For obtaining realistic dose estimates, the manual recommends use of site-specific geohydrological parameter values whenever possible. Similarly, while the RESRAD default scenario corresponds to a family farm occupant at the site, the parameters affecting the scenario can be modified for considering other scenarios.

Implementation. For the sites surveyed, three credible scenarios (industrial, residential, and wilderness) were considered (the family farm default scenario was determined not to be credible for this suburban area). The default occupancy and dietary parameters were modified for each scenario. Site-specific geohydrological data were collected and used as much as possible. Where the default RESRAD value had to be used, sensitivity calculations were performed to confirm that variation of the default parameters did not significantly influence the results.

The dimensions of the contaminated zone do significantly influence results from RESRAD. In our surveys, the area of the contaminated zone was measured, but the depth of the zone had to be estimated. To be conservative, however, infinitely contaminated zone dimensions were used as inputs (about 100,000 m^2 area and 1 m depth) to establish acceptance limits. Actual dimensions, with best-estimate values for depths, were used only to determine how the RESRAD-calculated dose to an occupant compared with the basic dose limit.

With the above input data, the acceptance limits were first established for individual nuclides for each of the three scenarios. For example, Cs-137 activity concentration values for the site were 239, 71, and 3,830 pCi/g for the three credible (industrial, residential, and wilderness) scenarios, respectively. If TS for the measured data is less than the lowest of the three values, then the site would be acceptably clean for all credible scenarios. This lowest bounding value, 71 pCi/g, corresponds to the residential scenario, which, therefore, corresponds to the credible-bounding scenario. Recalling that an equal activity concentration of Sr-90 was assumed, a simple calculation showed the acceptance limit for the combined presence of both nuclides to be 60 pCi/g each for this credible-bounding scenario. Figure 3 shows a cumulative probability plot for the measured Cs-137 data (Case B) which compares the TS for this data with the acceptance limit.

Using the average of the measured activity concentration for this data from Case B (4.9 pCi/g of Cs-137) and assuming an equal activity concentration for Sr-90, RESRAD calculations were performed to determine dose to a potential residential occupant of the site. Background activity concentrations for these man-made nuclides were assumed to be zero. Also used in these calculations were the measured area of the site and the estimated depth of the contaminated zone, which was chosen to be equal to the depth to which surface soil was removed. Use of this estimate for the depth is conservative because concentration profiles for these isotopes are likely to be decreasing with depth (e.g., 9) (versus the constant value used here) and because shielding provided by near-surface soil layers would effectively eliminate any further increase in the external dose rate (which was found to be the major contributor to dose in these cases). The resulting RESRAD-calculated dose to an occupant under the credible-bounding scenario was 5.2 mrem/yr during the first year, far less than the DOE guidance value of 100 mrem/yr basic dose limit and about half of the 10 mrem/yr NRC limit. Similar low annual doses were found in Case A as well.

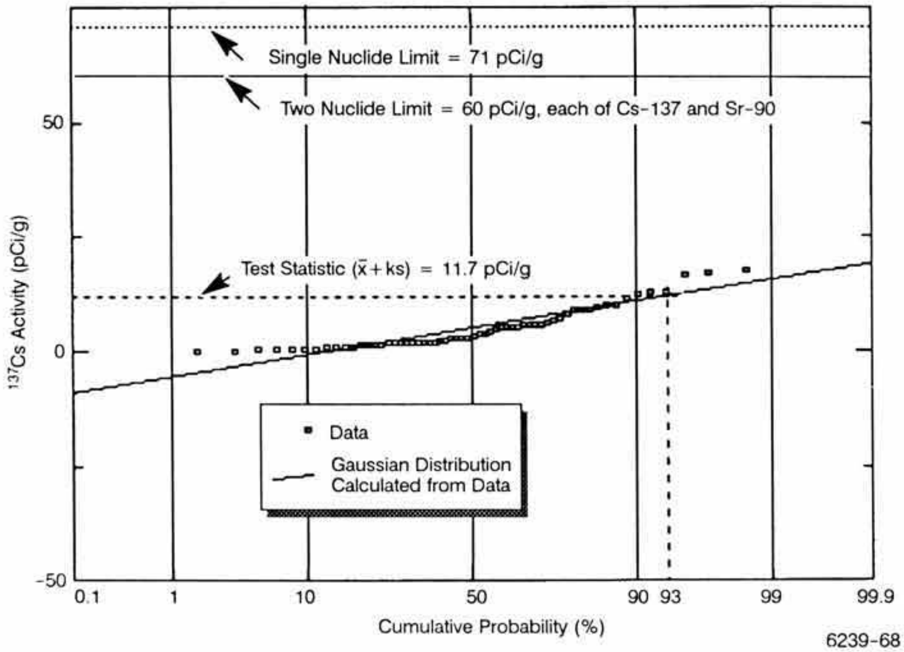

Fig. 3. Measured Soil Cs-137 activity data compared with acceptance limit (Case B--second-round survey after decontamination.)

SUMMARY AND CONCLUSIONS

Applicable generic criteria were used and site- and nuclide-specific acceptance criteria were developed for determining acceptance of decontaminated sites and structures. A case-by-case determination of the criteria was necessary, even though all the cases considered here were from within a single geographic location.

The technique of sampling inspection by variables was applied to reduce the survey data and to calculate the test statistic. Although this treatment was used in all first-round surveys and applied to gamma exposure rate measurements, it was necessary only in two of the four second-round surveys, and was applied to both gamma exposure rate and soil activity concentration data.

The RESRAD computer code was used for two of the four cases to determine conservative, site-specific soil concentration acceptance limits for Cs-137 and Sr-90 (60 pCi/g each). The generic limit for Ra-226 was used for the case of contamination of a building with this nuclide. Comparison of measured U-235-to-U-238 ratio with their natural ratio was performed in an area where enriched uranium contamination was suspect.

Based on the survey data (both first-round and second-round) and based on comparisons with the established acceptance limits, the sites or structures surveyed in all four cases were determined to be acceptably clean for release without radiological restrictions.

RECOMMENDATIONS

Although it is the survey team's and site owner's responsibility to conservatively establish acceptance limits from values within the existing regulatory framework, it is recommended that a single document listing all the relevant and available criteria be created by a standards-setting organization, such as the ASTM or the American National Standards Institute (ANSI). This should include acceptable limits or methods for distributed radioactivity, such as contaminated soil. A standard practice for statistical techniques and parameters should also be developed for use in radiological surveys by groups such as the ASTM or ANSI.

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