Soil Segregation Technology: Reducing Uncertainty and Increasing Efficiency During Radiological Decommissioning – A Case Study

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ABSTRACT

The regulatory release of sites and facilities (property) for restricted or unrestricted use has evolved beyond prescribed levels to model-derived dose and risk based limits. Dose models for deriving corresponding soil radionuclide concentration guidelines are necessarily simplified representations of complex processes. It is not practical to obtain data to fully or accurately characterize transport and exposure pathway processes. Similarly, it is not possible to predict future conditions with certainty absent durable land use restrictions. To compensate for the shortage of comprehensive characterization data and site specific inputs to describe the projected "as-left" contaminated zone, conservative default values are used to derive acceptance criteria. The result is overly conservative criteria. Furthermore, implementation of a remediation plan and subsequent final surveys to show compliance with the conservative criteria often result in excessive remediation due to the large uncertainty.

During a recent decommissioning project of a site contaminated with thorium, a unique approach to dose modeling and remedial action design was implemented to effectively manage end-point uncertainty. The approach used a dynamic feedback dose model and soil segregation technology to characterize impacted material with precision and accuracy not possible with static control approaches. Utilizing the remedial action goal "over excavation" and subsequent auto-segregation of excavated material for refill, the end-state (as-left conditions of the refilled excavation) RESRAD input parameters were re-entered to assess the final dose. The segregation process produced separate below and above criteria material stockpiles whose volumes were optimized for maximum refill and minimum waste. The below criteria material was returned to the excavation without further analysis, while the above criteria material was packaged for offsite disposal.

Using the activity concentration data recorded by the segregation system and the as-left configuration of the refilled excavation, the end state model of the site was prepared with substantially reduced uncertainty. The major projected benefits of this approach are reviewed as well as the performance of the segregation system and lessons learned including: 1) Total, first-attempt data discovery brought about by simultaneously conducted characterization and final status surveys, 2) Lowered project costs stemming from efficient analysis and abstraction of impacted material and reduced offsite waste disposal volume, 3) Lowered project costs due to increased remediation/construction efficiency and decreased survey and radio-analytical expenses, and 4) Improving the decommissioning experience with new regulatory guidance.

INTRODUCTION

The decommissioning process used by the NRC and EPA to evaluate, remediate, and ultimately remove a site from regulatory oversight has flexibility brought about by dose-based acceptance criteria [1, 2, 3, 4, 5, 6, 7 and 8]. The process establishes a radioactivity concentration 'clean' criterion based on site specific parameters and the anticipated as-left condition of the site. Remedial decisions are subsequently made based upon the comparison of site characterization data to the cleanup criterion. When the remedial action ends with the residual concentration below the established cleanup criterion, a final status survey is performed and submitted to regulators to demonstrate compliance.

The entire process ends in final status surveys designed using the guidance of MARSSIM, Multi-Agency Radiation Survey and Site Investigation Manual, to show compliance with the derived acceptance criteria. Although the acceptance criteria are based on 3-dimensional volumetric models of the site, MARSSIM guidance is based on 2-dimensional survey surfaces [9]. The disconnect between the 3-dimensional model derivation of acceptance criteria and the 2-dimensional final status survey is easily resolved using the dynamic dose modeling/segregation technology decommissioning strategy.

COMPARISON OF SOIL REMEDIATION APPROACHES

Since the cost of transportation and disposal (T&D) of contaminated material is often the highest relative to the overall decommissioning costs, decommissioning planning centers on technical approaches that minimize waste T&D. This planning must balance activities achieving the dual objectives of minimal waste T&D and acceptable as-left site conditions. The conservative exposure scenarios (e.g., residential farmer) and inputs typically used to establish site acceptance criteria (Derived Concentration Guideline Values, DCGLs) ratchet "acceptable" to a very low threshold. While this ratcheted threshold bounds the uncertainty in the remediated site conditions (and the certainty of regulatory release), it also ensures an increase in T&D activities.

Traditionally, there has been an unfortunate imbalance during planning on the emphasis placed on achieving the dual objectives, resulting in as-left site conditions that are acceptable but at a disproportionate T&D cost. Understandably, the traditional approach was justified because it minimized the impact of uncertainties about the as-left site conditions—a natural risk avoidance measure. In contrast, recent developments in automated radiation detection system technology make possible a new approach providing an optimized balance between waste T&D costs and as-left site condition risks. A remarkable feature of the new approach is the cost-favorable reduction in unacceptable risk associated with the as-left site condition. These approaches, the traditional and new 'dynamic', are discussed below.

Traditional Approach

The hallmark of traditional soil remediation is excavating above-DCGL soil so that only below-DCGL soil remains. The DCGL values are the result of a dose assessment based on the projected as-left condition of the site. Guided by real time remedial action support surveys (RASS) using portable instrumentation, excavation proceeds until surveys indicate the remaining 'bank' soil is below the DCGL values. Next a final status survey (FSS--full or partial surface scanning and systematic random-start, equal-distance soil sampling/laboratory analysis) is performed and the results evaluated to determine whether additional remediation is necessary or the survey unit meets the acceptance criteria. Many RASS plans include intermediate sampling and preliminary screening of samples to confirm that the survey unit should meet the criteria and is ready for FSS. The RASS/FSS process involves a "hurry up and wait" routine for the construction faction of the project and an intense effort by the health physics crew.

RASS and FSS designs using MARSSIM guidance include calculations of scan Minimum Detectable Concentration (MDC) values usually at the 95% confidence level (CL), depending on the project DQOs. For sites contaminated with multiple radionuclides, the sum of fractions ("Unity Rule") is used to show compliance. Therefore, scaling factors (SFs) are also calculated at the 95% CL to relate radionuclides that cannot be detected by gamma scans of soils to radionuclides that are easily detected. The SFs reduce the MDC values so that scans can be used to indicate when remediation is complete based on the entire radionuclide mix. The SF-based scan threshold is necessarily at a very small level and results in an unrealistic but conservative guide to remediation.

The result is usually over-remediation to ensure all of the material below the acceptance criteria is removed prior to beginning the final status survey. Over remediation in this case includes sending the excess excavated material off site for disposal, escalating project cost. The as-left condition of the open land area includes areas of excavation to various depths and other areas that have not been excavated. For consistency with dose assessment assumptions, the FSS protocol often interprets the as left radionuclide concentrations as those existing in the top 15 cm (6 in) of soil of the exposed soil bank. However, the detection depth actually varies from area to area corresponding to the extent of remediation in each area. The important consequence is an ill-defined contaminated zone (CZ) that is difficult to abstract into a forward dose assessment (reassessment).

Traditional Approach Limitations

The principal limitations of the traditional approach to soil remediation are:

- Whereas the FSS provides data confirming average and elevated radionuclide concentrations within a survey unit, it does not validate other parameters of the site conceptual model used to establish DCGLs, e.g., the depth/thickness of the cover, the contaminated zone and the unsaturated zone.
- By convention, the interpretation of FSS survey unit scan data is limited to a depth of 15 cm (6 in). While the actual detection capability may be more intrusive than this, this capability is not used to abstract the source term through these deeper layers to refine the site conceptual model in a forward dose assessment. If the contamination zone extends deeper than the MARSSIM-ideal surface 15 cm (6 in), reliance on scan measurements to identify elevated concentrations is severely limited.
- Left imbalanced, the desire to reduce uncertainty in as-left site conditions by incorporating conservatisms during remediation planning (e.g., exposure scenarios, RASS/FSS scan MDC's thresholds) forces a disproportionate escalation in T&D activities.
- The efficiency of physical remediation work is compromised by labor-intensive manual RASS and FSS activities.
- Soil handling throughput and RASS/FSS activities are incompressible tasks in the project schedule. Consequently, the ability to reduce costs by accelerating time-sensitive tasks and reducing the schedule duration is very limited.

Dynamic Approach

This methodology combines a remediation strategy of over excavation of the entire impacted area, combined with real time automatic segregation of excavated material using a gamma spectroscopy system mounted above a conveyor belt. Excavated material is separated into two piles (above and below criteria) based on continuously acquired gamma spectra. Because the segregation system offers excellent counting statistics and sensitivity, the below criteria material can immediately be returned to the excavation (survey unit) as refill to "construct" the contaminated zone. The above criteria material is staged for further

segregation/blending (as necessary to satisfy waste acceptance criteria), packaging and offsite transport to a disposal facility. Depending on regulatory commitments in the decommissioning plan(s), the refilled contamination zone may be subject to a confirmatory FSS for as-left dose reassessment purposes.

To ensure the as left configuration of the CZ and cover will mirror the model used to demonstrate compliance with the dose based criteria, an initial dose assessment was performed during the planning phase of the project to specify its optimum configuration (i.e., refill construction details) and the compatibility with the impacted material to be excavated and reconfigured. The planning dose assessment may include modeling the site in its current configuration and source term abstraction with the logical critical group and exposure scenario (residential farmer, industrial worker, etc.). The planning dose result will necessarily exceed the dose criteria. Next, using characterization data estimates of impacted (greater than preliminary screening values) area size, the CZ is modeled in various refill physical/radiometric configurations to identify successful (below dose criteria) options. To gauge the precision needed during refill construction assuring success, sensitivity analyses of dose assessment parameters that are controllable during refill construction (principally CZ depth intervals) are performed. These initial dose assessment results can then be used with confidence to develop a remediation plan.

Elements of a remediation plan include: impacted area excavation logistics, material segregation, refill construction, segregating/blending above criteria material for packaging and offsite disposal, and placing clean fill cover material to grade. The remediation plan also specifies the performance and operational parameters for the automated segregation system including: the necessary gamma spectrometry data acquisition, management, and software implementation protocols (nuclide sensitivities, uncertainties, segregation setpoints, data manipulation and storage) and logic control interfaces with material handling equipment. The material handling (conveyor) equipment may also include weight and density sensors and programmable logic controllers to dynamically control feed material processing.

The development of the segregation system and software entailed significant development to achieve unparalleled counting statistics power. In fact, the system's data over-sampling capability assures that greater than 100% of the material being processed is examined by gamma spectrometry. This capability is a critical feature reducing the labor and expense of a remediation project. For example, in a traditional soil remediation project, labor-intensive RSS and FSS crews are deployed to identify remaining elevated areas with follow-on equal distant collection and laboratory analysis of soil samples to determine average radionuclide activity concentrations. If any elevated areas are identified by the FSS, the areas are either remediated again and resurveyed, or an elevated measurement comparison (EMC) is performed that (hopefully) demonstrates compliance. All of these activities are unnecessary (for the excavated volume of impacted material) with the segregation system.

Dynamic Approach Advantages.

The advantages of the dynamic approach are:

- Data over-sampling to achieve greater than 100% scan/sample coverage of the entire volume of impacted material excavated, i.e., 100% coverage characterization and final status surveys. The coverage afforded a segregation systems is far greater than a walk-over, gross gamma scan of remediated areas and exceeds MARSSIM Data Quality Objectives developed for the FSS.
- Continuous presentation of laboratory-equivalent FSS scan and discrete sample data (concurrent with material processing).
- Continuous and direct comparison of the processed material radionuclide profile to the refill acceptance criteria, eliminating the uncertainty associated with estimating the activity concentration of the material based on gross gamma count rate of a portable survey instrument.

- Continuous and direct comparison of the processed material radionuclide profile to disposal facility waste acceptance criteria.
- Remediation (construction) activities uninterrupted by RASS and FSS activities.
- Near extinction of concerns about the adequacy of site characterization in identifying surface or subsurface contaminated zones. All material, regardless of the depth located, is processed through the segregation system.
- Huge cost advantage brought about by a sorting technology allowing tasks to be significantly compressed for diminished project duration. In the case study presented below that routinely processed over 907 MT/day (1,000 ton/day), total project costs were approximately $22MM in comparison to a traditional approach project cost that was estimated to exceed $100MM.

CASE STUDY

An industrial site decommissioning project recently utilized the dynamic approach to achieve unrestricted release. Approximately 5.7 ha (14 ac) of the site were impacted by radioactive material (RAM) consisting of three primary naturally occurring radioactive material (NORM) radionuclides having predictable activity concentration relationships. During the planning phase of the project, consideration of the traditional remediation approach utilizing a residential farmer exposure scenario to derive DCGLs was given. The traditional DCGL value derived for the surrogate radionuclide was 0.1 Bq/g (3 pCi/g). At this action level, the anticipated remedial action would require precision excavation of the 5.7 ha (14 ac) parcel to depths of up to 7.6 m (25 ft), producing approximately 141,584 m^3 (5,000,000 ft^3) of material for disposal offsite. In this way, the traditional approach produced staggering waste volume, and attendant anticipated cost.

Additional work resulted in the remedial action being re-engineered consistent with the assumptions and outcomes of dynamically-derived DCGL calculations. This dynamic model approach (also using a residential farmer exposure scenario) resulted in a surrogate radionuclide segregation (for disposal) criteria of approximately 1.1 Bq/g (30 pCi/g) in conjunction with excavation of the entire 5.7 ha (14 ac) parcel. Another significant improvement was the complete viewing and segregation of all impacted soil (still defined with an activity concentration greater than 0.1 Bq/g (3 pCi/g) by a material handling (conveyor) system controlled by gamma counters (near real-time data acquisition). This system is discussed in the next section. The below disposal criteria material (average concentration of approximately 0.55 Bq/g (15 pCi/g) based on the refill cutoff at 1.1 Bq/g (30 pCi/g) is staged as excavation refill. When placed and compacted back in the excavated survey unit, the refill constitutes a contaminated zone approximately 3 meter (10 feet) thick. The dimensions of the contaminated zone achieved during refill were accurately determined using global positioning system (GPS) radio-navigation measurements and traditional survey measurements. Prior to backfill with below criteria material the excavation surface is final status surveyed. The FSS is a traditional MARSSIM designed survey including 100% coverage gross gamma scan and equal distant surface sampling for analytical analysis via gamma spectroscopy, to confirm over excavation is complete.

After developing the engineered CZ with refill, an offsite fill cover approximately 3 m (10 ft) thick is placed over the CZ to achieve the desired surface contour. The reverse dose assessment of the engineered CZ and cover yields a potential annual residential farmer Total Effective Dose Equivalent (TEDE) of approximately 0.01 mSv (1 mrem) in the maximum year. The above criteria >1.1 Bq/g (>30 pCi/g) material, approximately 56,634 m^3 (2,000,000 ft^3) averaging about 1.8 Bq/g (50 pCi/g), is shipped off site for disposal. This is a significant reduction from the 141,584 m^3 (5,000,000 ft^3) estimated using the traditional remediation approach. It is also important to note that the entire impacted area has been characterized by the over-excavation and automated segregation (greater than 100% coverage) approaches.

Segregation System

The segregation system (Figures 1 through 4) combines gamma scanning (rolling detection; Figure 4) with gamma spectrometry, the two features of MARSSIM-based FSS. The conveyor counter utilizes a fixed platform radiation detection system mounted over a rubber belt conveyor. The detector is thallium-doped sodium iodide (NaI (Tl)) encased for temperature stabilization and background radiation reduction. Gamma spectra in a pre-defined energy range are collected successively over a fixed time interval (typically 1 second) using a Multi-Channel Analyzer (MCA). The system is operated from an adjacent mobile trailer. The system includes a controller for conveyor belt speed and a sensor for conveyed material depth.

Fig. 1. Segregation system view A

Conveyor system feed material is prepared by drying (land farming) excavated material and sizing it through a vibrating screen to remove debris over 15 cm (6 in) in diameter, the maximum conveyable size. The tilled and sized feed material is loaded on the conveyor and floated to an even height across the conveyor belt width. Traveling at a typical conveyor speed of 54 kg/s (120 lb/s) beneath the suspended NaI detector, the gamma spectrum of the material is acquired and automatically compared to the segregation criteria 1.1 Bq/g (30 pCi/g). The above and below acceptance criteria material fractions fall through separate "pant leg" chutes based on signals sent from the sorting logic process computer to the chute diversion gate motor. Depending on its volume-weighted average activity concentration, the material is diverted to the above and below acceptance criteria stockpiles.

The segregation system data is processed with algorithms similar to those developed for sonar. This algorithm greatly reduces the statistical fluctuation normally encountered in scanning detection. During

each 1 s acquisition (viewing approximately 54 kg (120 lb) of soil), the process computer records the spectra and live time from the MCA, the conveyor distance traveled, and the average height of the material. While these signals are collected and monitored during operations, the system offers real time, low-level radiation alarming functions based on data analysis. In addition to the 1-second data acquisition interval, an overlapping 12 acquisition [approximately 680 kg (1,500 lb) or 1 m^3 soil fraction] averaging interval is also used to calculate activity concentration. This averaged value, representing the smallest practical modeling volume, determines whether the scanned soil fractions are above or below the segregation criteria. Since the average is re-calculated with every 1 s data acquisition, each 1 s [54 kg (120 lb)] soil fraction is averaged with 12 subsequent 1 s volumes for comparison to the segregation criteria. The practical and powerful benefit of this averaging scheme is that it provides greater than 100% MARSSIM coverage.

Fig. 2. Segregation system view B

Fig. 3. Segregation system view C

Table I lists the segregation system's typical data processing output:

Table I – Segregation System Batch Output Results

Material Processed (MT)		Activity Concentration (Bq/g)				No. of Data
Below Criteria	Total	Mean	Median	Maximum	Minimum	Acquisitions
30	31	0.41	0.40	1.11	0.10	914
91	92	0.30	0.30	0.64	0.04	2,718
75	75	0.39	0.39	0.86	0.15	2,239
494	660	0.59	0.58	1.16	0.03	11,173
620	756	0.60	0.60	1.15	0.08	13,474
737	798	0.45	0.45	0.96	0.08	19,133
516	573	0.60	0.59	1.15	0.09	10,423
478	522	0.44	0.43	1.16	0.06	10,407
238	246	0.27	0.27	0.58	0.05	5,370
117	128	0.26	0.25	0.53	0.04	2,989

The segregation system data was used to calculate a weighted average activity concentration of the material placed in the backfilled survey units. The result was 0.51 Bq/g (13.7 pCi/g). A MARSSIM final survey of the backfilled survey units was also performed. The FSS included 100% coverage gross gamma surveys of each 0.61-meter (2-foot) of material placed in the excavation to identify elevated areas and equal distant core samples through the entire depth of below criteria backfill material placed in the excavation. Each core was then gross gamma scanned for uniformity and separated into 1-meter (3.3-foot)

segments for composite sampling and laboratory analysis via gamma spectroscopy. The average of the core sample composites was 0.55 Bq/g (14.9 pCi/g), confirming the results of the segregation system.

Fig. 4. Segregation system detector dog house

SUMMARY

The development of site-specific cleanup levels and selection of a transparent site cleanup strategy, responsive to both the provisions of the regulators and project economics, are fundamental outcomes of the decommissioning process. From its earliest beginnings, decommissioning planning must focus upon these outcomes. Development and refinement of a conceptual exposure scenario for the site must factor-in vast amounts of information available from historical site assessments, site characterization events, remedial action support surveys, and final status surveys. No longer is it reasonable to accept that an economic remediation automatically follows from a static review of this information. If a dynamic view of the project is maintained, the site-specific decision on cleanup levels and cleanup strategy must be, and will be, defensible on all accounts and in all forums.

Derivation of contemporary cleanup levels must be performed in accordance with the dose-based criteria stipulated in the project plans. During the planning phase of the decommissioning project, approaches satisfying these criteria should be evaluated exhaustively in tractable dose assessments. The evaluations should rank the merits of the entire range of remediation practices, from exclusive 'hog and haul' through aggressive refill and combinations thereof. Parameter sensitivity results should be examined to direct attention to the few parameters significantly controlling dose outcomes. The engineering of the remediation approach must provide assurance that these parameter uncertainties will be controlled consistent with the site's conceptual model framework. The hallmark of the dynamic approach is objectively revealed by a reverse dose assessment showing remarkable agreement with that used to derive the cleanup levels.

The economics of arbitrary or ill-planned offsite disposal of impacted material are too great to ignore the benefits of dynamic segregation and refill. As discussed in this paper, the dynamic segregation approach offers powerful control over refill parameter uncertainty while simultaneously reducing offsite disposal capacity needs and data management loads. In contrast, the traditional remediation approach often encounters difficulty in controlling parameter uncertainty in a uniform manner that often times create regulatory concern.

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