Soil Remediation Plan for Site Decommissioning and Radioactive Materials License Termination

Radioactive Materials License CO-369-01
Canon City Milling Facility

March 30, 2011

Cotter Corporation (N.S.L.)
Canon City Milling Facility
P.O. Box 1750
Canon City, CO 81215-1750

Table of Contents

Introduction 1
Section A: Soil Cleanup Criteria 2
Regulatory Specifications 2
Radium Benchmark Dose Modeling 2
Receptor Scenario Selection 2
Modeling Code and Parameter Selections 3
Radium Benchmark Dose: Modeling Results 7
Sensitivity Analysis 8
Uncertainty Analysis 10
Correlations and Multiple Regression Analysis 12
Soil Cleanup Criteria for Th-230 13
Soil Cleanup Criteria for U-nat 14
References 18
Section B: Background Reference Area 19
References 21
Section C: Impacted Areas and Remedial Strategy 22
Review of Current Radiological Characterization Information 22
Remedial Strategy and Additional Characterization Requirements 23
References 25
Section D: Final Status Survey Plan 26
Data Quality Objectives 26
Final Status Survey Design and Data Assessment 27
Soil Sampling 27
Laboratory Analysis of Soil Samples 32
Gamma Surveys 34
Gamma / Soil Ra-226 Correlations 35
Data Quality Assurance / Quality Control 36
Laboratory Analysis QA/QC 36
Soil Sampling QA/QC 36
Gamma Surveys QA/QC 37
References 39
Appendix A 41

Introduction

Cotter Corporation began processing uranium ores at the Canon City Milling Facility (CCMF) in 1958 in support of cold war era initiatives pursued by the Atomic Energy Commission (AEC) under the Atomic Energy Act (AEA). Prior to 1971, all uranium yellow cake production in the United States was under direct control of the federal government. In 1971, uranium production became privatized as national priorities shifted towards nuclear power generation.

In 1978, the Uranium Mill Tailings Radiation Control Act (UMTRCA) was passed, which requires the U.S. Department of Energy (DOE) to remediate inactive mill sites that had processed uranium for the federal government prior to 1971 (Title I sites), and to conduct long term surveillance and monitoring of all uranium mill sites after reclamation. Uranium mills active after 1971 are considered Title II sites.

The U.S. Nuclear Regulatory Commission (NRC) is the lead agency for regulating active uranium mills in the United States. The State of Colorado has become an "Agreement State" with the NRC, meaning that the State has assumed authority to license and regulate radioactive materials within the State of Colorado, including uranium mills.

Within this regulatory framework, the CCMF must be decommissioned and reclaimed under criteria at least as restrictive as those set by the NRC. The NRC criteria are consistent with health and safety standards developed by the U.S. Environmental Protection Agency (EPA) for the possession, transfer, and disposal of 11e.(2) byproduct material. Uranium byproduct material, however, is specifically exempted from EPA regulatory authority under the Resource Conservation and Recovery Act (RCRA).

The Radiation Control Unit of the Colorado Department of Public Health and Environment (CDPHE) has established radiological cleanup criteria for soils at uranium mill sites in the State of Colorado [6 CCR 1007-1, Part 18, Appendix A, Criterion 6(6)]. These criteria are identical to those set by the NRC in 10 CFR 40, Appendix A. In terms of determining site-specific soil cleanup levels that meet these criteria and demonstrating compliance, relevant regulatory guidance documents from the NRC and other federal agencies are applicable to all uranium mills, including the CCMF.

Cotter Corporation has performed a large amount of interim soil remediation over the past several decades and site conditions have changed considerably over the years. The CDPHE has requested an update to the site reclamation plan including updated provisions for final remediation of impacted soils at the site. This document provides a detailed soil remediation and final status survey plan for site decommissioning and termination of Radioactive Materials License CO-369-01. General components of this plan are organized by section as listed in the Table of Contents.

The scope of this document is limited to determination of radiological soil cleanup criteria that are applicable under the radioactive materials license and Criterion 6(6), remedial strategies to achieve compliance with those criteria, and how compliance will be demonstrated. Engineering and construction issues related to soil removal, disposal, re-grading, and re-vegetation are issues covered elsewhere in the overall site reclamation plan.

Section A: Soil Cleanup Criteria

Regulatory Specifications

Soil cleanup criteria for uranium mills in Colorado are specified in 6 CCR 1007-1, Part 18, Appendix A, Criterion 6(6). The criteria for radium in soil are prescriptive numeric limits, defined as an average above background concentration of 5 pCi/g across any 100 m^2 area to a depth of 15 cm, and 15 pCi/g for any underlying 15-cm depth increment. Criterion 6(6) further outlines requirements for developing cleanup criteria for soil radionuclides other than radium.

For radionuclides other than radium, namely uranium (U-nat) and thorium (Th-230), Criterion 6(6) indicates that cleanup criteria are to be derived using a dose-based benchmarking approach. This involves determining the maximum total dose rate to a critical receptor within 1,000 years due to Ra-226 and its progeny, Pb-210 (NRC, 2003), given respective soil concentrations equivalent to the numeric 5 pCi/g above background cleanup standard for radium. This dose rate is termed the Radium Benchmark Dose (RBD).

Once the RBD is determined, dose-based soil standards called Derived Concentration Guideline Levels (DCGLs) are individually determined for U-nat and Th-230. Each DCGL is determined by modeling a soil concentration that would result in a dose equivalent to the RBD under the same critical receptor scenario. Calculated DCGLs represent the basis for soil cleanup levels for U-nat and Th-230, pending application of ALARA (As Low As Reasonably Achievable) principles to determine final cleanup levels (NRC, 2003).

For Th-230, there is an additional regulatory requirement. The amount of residual (above background) thorium that can remain in soils at the site must not exceed a concentration that would result in the buildup of Ra-226 to levels exceeding 5 pCi/g within 1,000 years. This requirement has specific numeric limits of 14 pCi/g in the top 15 cm of the soil profile, and 43 pCi/g for any underlying 15-cm thick subsurface layer, assuming that Ra-226 concentrations are near background (NRC, 2003).

Radium Benchmark Dose Modeling

Receptor Scenario Selection

A number of potential land uses and corresponding critical receptor scenarios were considered for RBD modeling. These included a commercial or industrial worker, a recreational receptor (e.g. expansion of the nearby golf course), residential housing development, and a rural residential farmer. The rural residential farmer scenario was selected as the most plausible land use within the foreseeable future for reasons described below.

Upon license termination and site decommissioning, the Department of Energy (DOE) will assume long term stewardship of the site. Legal access and land use will be restricted under this direct institutional control. Groundwater monitoring in areas of the site well beyond the footprint of the tailings impoundments will likely continue long after site closure, necessitating institutional control over a considerable buffer zone surrounding the impoundments. These circumstances are expected to prevent commercial or residential development or other land uses involving public access to formerly impacted areas. However, it is appropriate to consider potential failures of institutional control.

If long-term DOE stewardship and groundwater monitoring control mechanisms were to fail, secondary institutional control mechanisms, local and/or regional, would likely assume jurisdiction. There is a long history of local and regional concerns regarding potential health risks associated with the facility and there would likely be significant opposition to such land uses, particularly with mill tailings disposal cells located onsite. It is improbable that commercial or residential development or other forms of general public access would be sanctioned by county or state government agencies.

In addition to direct institutional control mechanisms, there are indirect economic ones. Canon City is a small community, historically attracting little commercial or industrial development. The town location is somewhat removed from major corridors of commerce in Colorado. The local economy has historically experienced relatively little growth, based primarily on nearby State and Federal prisons, limited tourism associated with local attractions, and farming or ranching along the Arkansas River valley. Economic incentives for commercial or residential development in this area are unlikely to improve significantly in the foreseeable future.

Of all possible receptor scenarios, a rural residential farmer is considered the most plausible exposure scenario should any or all control mechanisms fail. A single individual or family erecting a small home or trailer at the site might attract less attention and potentially face fewer regulatory or legal obstacles in terms of access and using the land for limited agricultural activities.

Modeling Code and Parameter Selections

The RBD for the Canon City Milling Facility was developed using the RESRAD-OFFSITE computer code (ANL, 2009). RESRAD-OFFSITE can be used to model doses to a receptor living within a zone of contamination, or at a location removed from the contamination. Here, the assumed receptor scenario was a rural residential farmer living within a hypothetical zone of contamination after site decommissioning.

RESRAD-OFFSITE has a number of advantageous features versus earlier versions of RESRAD, including improved groundwater modeling capabilities, visual mapping tools, comprehensive and versatile graphics utilities, and robust sensitivity/uncertainty analysis features.

The dose pathways selected for the rural residential farmer receptor scenario included external gamma, inhalation, plant and meat ingestion, drinking water, and incidental soil ingestion. The radon pathway was excluded per Criterion 6(6) specifications. The aquatic foods pathway was excluded as an unrealistic source of potential exposure at the site. The milk pathway was excluded per guidance provided in Appendix H, NUREG-1620 (NRC, 2003).

A number of exposure pathways and model parameters used for the resident farmer scenario were based on an assumption that despite the semi-arid climate (about 0.34 m/yr precipitation on average), sufficient irrigation water could be obtained from the onsite well and delivered to onsite agricultural areas. It was further assumed that a farmer could plausibly obtain 25% of consumed fruit, vegetables, grains, and meat from these areas (NRC, 2003).

The contaminated zone was modeled based on gamma survey data collected across the site including the Old Ponds Area (OPA), standing mill facilities, and outlying areas. While considerable remediation has been performed in the OPA, it is assumed that additional cleanup in the OPA will be required to

meet all remedial criteria. The footprint of other areas expected to require soil remediation were extensively studied and characterized in a soil cleanup volume report (Tetra Tech, 2008).

Figure A1 depicts areas predicted to have soil Ra-226 concentrations in excess of the gross cleanup criterion (6 pCi/g, including 1 pCi/g for background) based on gamma survey data from several comprehensive studies (see Section C). These areas have gamma readings in excess of 23 µR/hr, an exposure rate statistically predicted to have underlying soil Ra-226 concentrations of 5 pCi/g or less (with a 95% level of confidence).

Figure A2 shows a corresponding hypothetical site layout for a rural residential farmer dose modeling scenario, where the receptor's residence and all agriculture areas are located within a zone of homogeneous soil contamination. Per NUREG-1620 guidance (NRC, 2003), radium-226 and Pb-210 soil concentrations in the contaminated zone were set at 5 pCi/g above background to a depth of 15 cm.

The areal extent of the modeled contamination zone was set at 310 acres, roughly centered at the location of the original mill facilities. The contaminated area to the east of the Primary impoundment is generally thought to involve a thin layer of wind transported material across a steep, rocky and partially forested escarpment. That area is not expected to be remediated due to construction impracticability and environmental impact concerns. For these reasons, and because a resident farmer could not reasonably be expected to engage in productive agricultural activities in this area, it was not considered in the dose modeling.

A subsurface soil contamination model was not considered as it was assumed that all areas and soil depths can be successfully remediated to surface layer cleanup standards. This assumption is based on numerous characterization studies to date which indicate generally decreasing soil concentrations with depth, that most residual soil contamination is relatively shallow (e.g. less than 30 cm), and that areas with deeper contamination have lower bounds to which impacted soils can be successfully removed without unreasonable costs. This assumption represents a cleanup strategy that is conservative and consistent with ALARA principles.

Model input parameters were based on site-specific information wherever possible. Specific guidance on certain model parameter values for the resident farmer scenario, provided in Appendix H of NUREG-1620 (NRC, 2003) and/or RESRAD user manuals, were followed as applicable. RESRAD-OFFSITE defaults, considered "broadly applicable" across the United States, were used for all other parameter inputs. Model parameter values that were modified from program defaults, along with rationale and references are provided in Table A1.

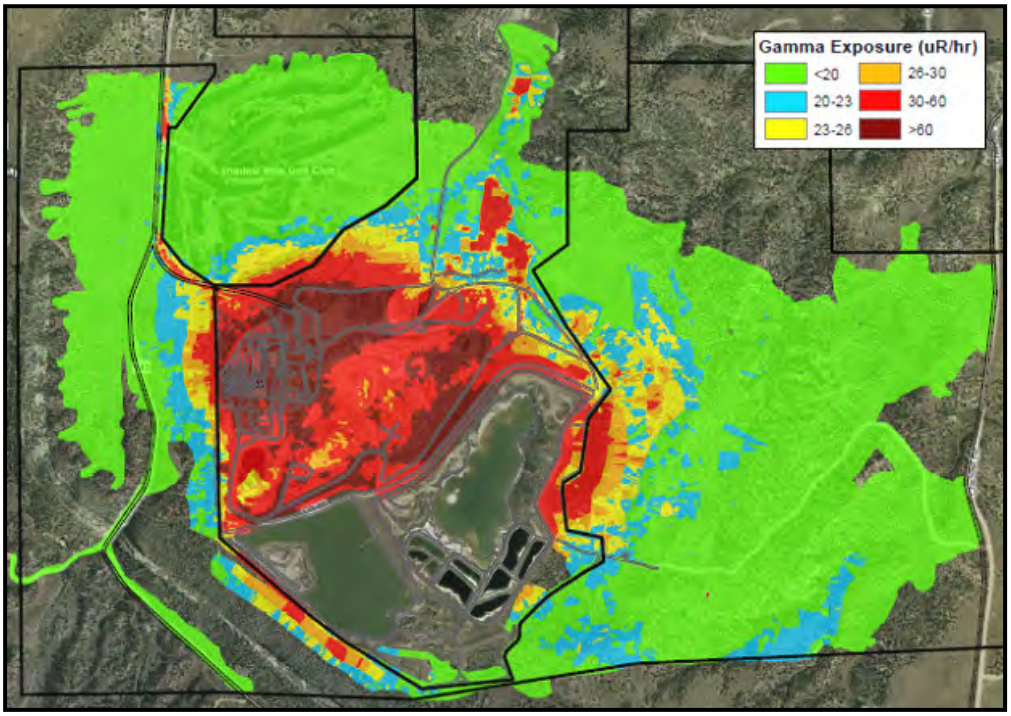


Figure A1: Gamma survey results depicting areas expected to exceed the gross soil Ra-226 cleanup criterion with a 95% level of confidence (areas with gamma readings greater than 23 µR/hr).

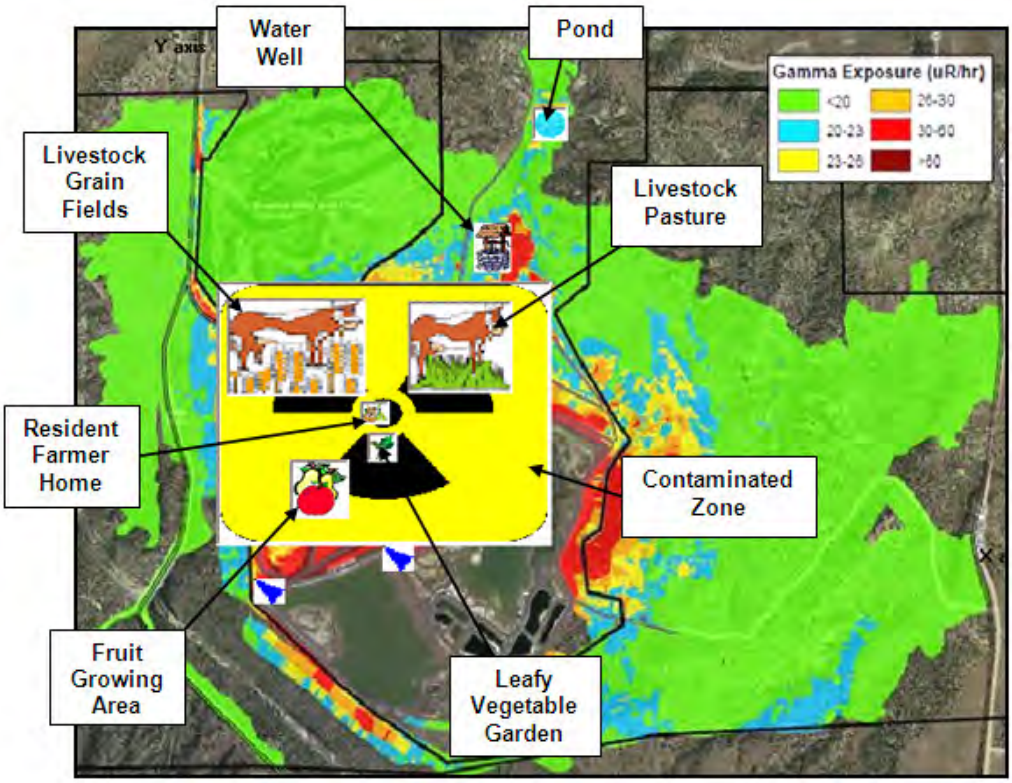


Figure A2: Site layout for the rural residential farmer dose modeling scenario.

Table A1: Model input parameter values, rationale and references for input selections other than RESRAD-OFFSITE default values.

MODEL PARAMETER	PARAMETER VALUE	RATIONALE / COMMENTS	SOURCE / REFERENCE
Occupancy Factors			
Fraction onsite indoor occupancy	0.5	Per guidance provided in RESRAD user's manual	Table 2.3, RESRAD Version 6 User's Manual
Fraction onsite outdoor occupancy	0.25	Per guidance provided in RESRAD user's manual	Table 2.3, RESRAD Version 6 User's Manual
Fraction per agricultural area	0.05	4 agricultural areas, included in "onsite outdoor occupancy" with remaining 0.05 fraction spent in other onsite areas	RESRAD-OFFSITE Version 2.5 User's Manual
Gamma Shielding			
Gamma penetration factor	0.45	Mean of 0.3 - 0.6 range cited in NUREG-1620	Appendix H, NUREG-1620
Contamination Zone			
Area (acres)	310	Includes OPA, current mill building areas, parts of the surrounding areas	OPA Gamma Survey and Soil Volume Reports (Tetra Tech)
Thickness (m)	0.15	Defined by regulatory cleanup criteria	10 CFR 40, Appendix A
Total Porosity	0.1	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Hydraulic Conductivity (m/yr)	5.5	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Field Capacity	0.0809	Loamy sand	Appendix B, Table 2.1-2, RESRAD-OFFSITE User's Manual, 2007
Evapotranspiration Coefficient	0.8	Mean of cited range for semi-arid uranium mill sites	Appendix H, NUREG-1620
Soil Erodibility Factor	0.12	Loamy sand	Appendix B, Section 2.4, RESRAD-OFFSITE User's Manual, 2007
Length parallel to aquifer flow (m)	1100	Estimated from site layout scenario	
Cover & Management Factor (C)	0.13	Tall weeds/short brush, 50% cover, 20% cover in contact with ground surface	Appendix B, Table 2.6-2, RESRAD-OFFSITE User's Manual, 2007
Unsaturated Zone			
Thickness (m)	8.5	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Total Porosity	0.1	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Effective Porosity	0.1	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Hydraulic Conductivity (m/yr)	5.5	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Field Capacity	0.0809	Loamy sand	Appendix B, Table 2.1-2, RESRAD-OFFSITE User's Manual, 2007
Saturated Zone			
Thickness (m)	250	Assumes saturated zone extends into underlying bedrock	RESRAD-OFFSITE default value, Version 2.5
Total Porosity	0.1	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Effective Porosity	0.1	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Hydraulic Conductivity (m/yr)	55	Site-specific estimate	Hydrosolutions (consulting hydrogeologist)
Agricultural Areas			
Fraction on Contaminated Zone	1	Defined by regulatory cleanup criteria	10 CFR 40, Appendix A
Volumetric water content	0.0809	Loamy sand	Appendix B, Table 2.1-2, RESRAD-OFFSITE User's Manual, 2007
Cover & Management Factor (C)	0.13	Tall weeds/short brush, 50% cover, 20% cover in contact with ground surface	Appendix B, Table 2.6-2, RESRAD-OFFSITE User's Manual, 2007
Evapotranspiration Coefficient	0.8	Mean of cited range for semi-arid uranium mill sites	Appendix H, NUREG-1620
Meteorological Data			
MET wind data	STAR data	Site-specific, developed for MILDOSE Modeling	Two Lines, Inc. (Dr. Craig Little)
Annual Precipitation (m)	0.34	Area-specific (published mean statistic for Canon City)	U.S. Climate Data website
Consumption Rates			
Fraction of meat, fruit, grain, and vegetables from contaminated zone	0.25	Assumes sufficient irrigation water could be obtained from onsite well	Some nearby residents use groundwater wells to irrigate lawns and gardens

Radium Benchmark Dose: Modeling Results

Radium Benchmark Dose modeling results indicate that a rural residential farmer living within a hypothetical 310-acre contaminated zone at the decommissioned Canon City Milling Facility would receive a maximum total effective dose equivalent (TEDE) of 25.8 mrem/yr due to Ra-226 and Pb-210 concentrations of 5 pCi/g each residing in the top 15 cm of the soil profile (Figure A3). The maximum dose rate is received at 0.5 years from time zero, the majority which is due to external gamma radiation with a small contribution from plant ingestion and very small to negligible contributions from other pathways (Figure A4).

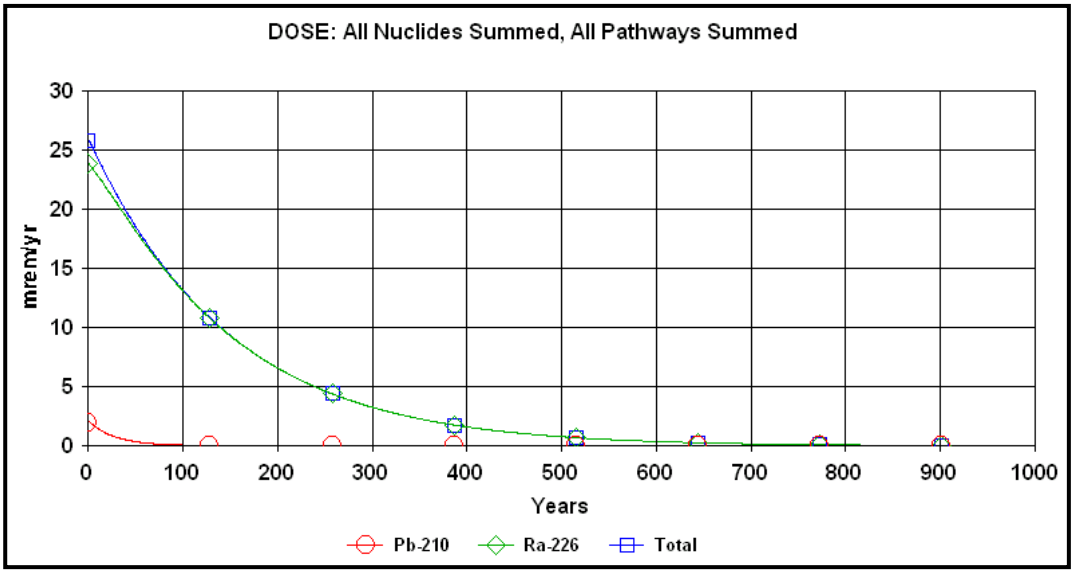


Figure A3: Radium Benchmark Dose modeling results.

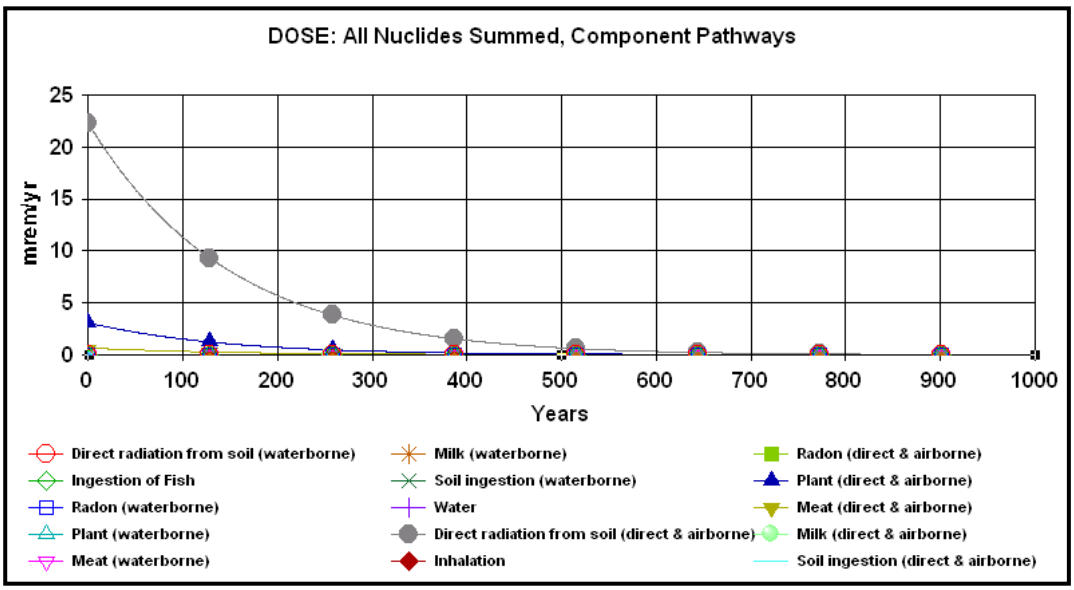


Figure A4: Component dose pathways for the RBD.

Sensitivity Analysis

A sensitivity analysis was performed on many model input parameters, particularly those with potential to significantly impact the calculated RBD based on assessment of the component pathways shown in Figure A4. To illustrate the utility of sensitivity analysis, the thickness of the contaminated layer was allowed to vary by a factor of 2 from the 15-cm base value. Though prescriptively defined by the RBD methodology, the thickness of the contaminated layer (15 cm by definition) is likely to be important as gamma radiation is the primary component of total dose in this model.

Using this range of values for contaminated layer thickness illustrates how sensitive the calculated RBD is to this parameter (varying by ± 8 mrem/yr from the base value) (Figure A5). The relative amount of sensitivity to varied input values over time also provides clues as to other potentially important model parameters to test such as erosion or leaching rates.

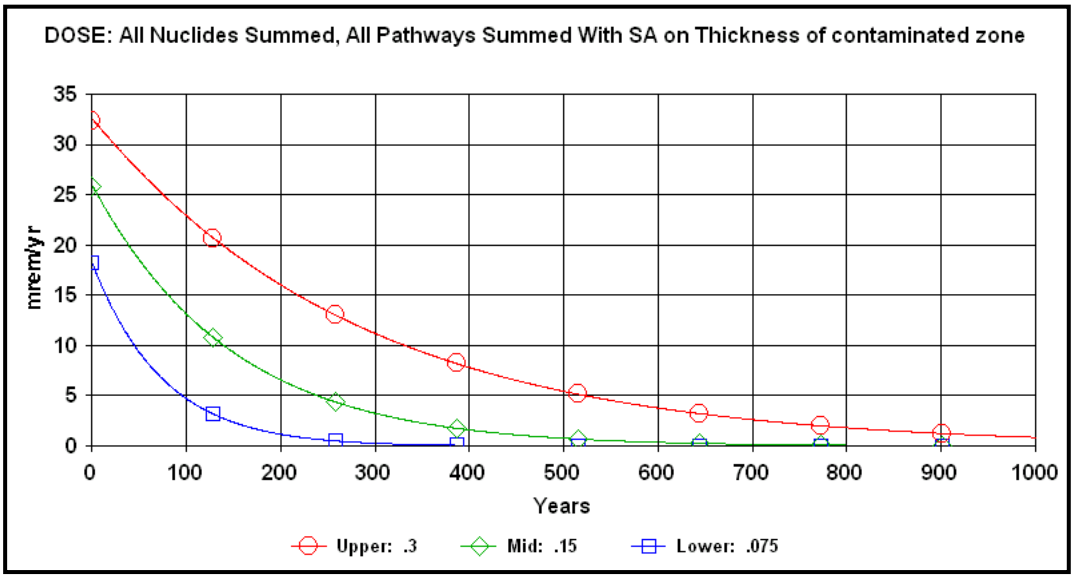


Figure A5: Sensitivity analysis on the thickness of the contaminated zone.

Using this general assessment approach, and with an emphasis on model parameters where values other than program defaults were used, 19 potentially important model parameters were tested with sensitivity analysis. The results are tabulated in Table A2. Gamma penetration factor and onsite indoor and outdoor occupancy factors and were the only notable variables identified with respect to affects on the calculated Radium Benchmark Dose (max dose at time = 0.5 years). This makes sense given the dominance of the external gamma pathway.

Occupancy factors for onsite indoor and outdoor exposures under a rural resident farmer scenario are discussed in the RESRAD user manual and NUREG-1620. There is a discrepancy between these sources that appears to be due a typo in NUREG-1620. The RESRAD user manual recommends values of 0.5 and 0.25 respectively for indoor and outdoor occupancy factors for a resident farmer scenario (rationale and references are provided). Conversely, NUREG-1620 cites factors of 0.25 and 0.5 for indoor and outdoor occupancy factors, values exactly reversed from the RESRAD guidance. Presumably, NUREG-1620 intended to cite the same values recommended in RESRAD guidance as an outdoor time fraction of 0.5 would require a farmer to spend 12 hours per day, 365 days per year outside (clearly unrealistic).

Table A2: Results of sensitivity analyses on select model parameter values.

MODEL PARAMETER TESTED	SENSITIVITY MULTIPLIER	TESTED VALUES (high, base, low)	NOTABLE IMPACT ON MAX DOSE?
External Gamma Penetration Factor	1.5	0.675, 0.45, 0.3	Yes, ± 4 to 5 mrem/yr at max dose
Fraction onsite indoor occupancy	1.2	0.55, 0.5, 0.41	Yes, ± 1 to 2 mrem/yr at max dose
Fraction onsite outdoor occupancy	1.2	0.3, 0.25, 0.21	Yes, ± 2 mrem/yr at max dose
Distribution Coefficient (Kd, cm^3/g)	5	350, 70, 14	No, significant dose sensitivity limited to later years due to leaching losses
Precipitaion (cm)	2	68, 34, 17	No, significant dose sensitivity limited to later years due to erosional/leaching losses
Crop Management Factor	2	0.26, 0.13, 0.065	No, minor dose sensitivity limited to later years due to erosional losses
Soil Erodibility Factor	2	0.24, 0.12, 0.06	No, minor dose sensitivity limited to later years due to erosional losses
Fraction occupancy in agricultural areas	2	0.2, 0.1, 0.05	No, dose sensitivity absent across all reporting times
Length of Contaminated Zone (m)	2	2702, 1351, 675	No, dose sensitivity absent across all reporting times
Width of contaminated Zone (m)	2	2250, 1125, 563	No, dose sensitivity absent across all reporting times
Total Soil Porosity	2	0.2, 0.1, 0.05	No, dose sensitivity absent across all reporting times
Field Capacity	2	0.1, 0.0809, 0.04	No, dose sensitivity absent across all reporting times
Hyrdraulic Conductivity (m/yr)	2	11, 5, 2.75	No, dose sensitivity absent across all reporting times
Unsaturated Zone Thickness (m)	2	17, 8.5, 4.25	No, dose sensitivity absent across all reporting times
Saturated Zone Thickness (m)	2	500, 250, 125	No, dose sensitivity absent across all reporting times
Saturated Zone Hydraulic Conductivity (m/yr)	2	110, 55, 27.5	No, dose sensitivity absent across all reporting times
Irrigation to Leafy Vegetables (m/yr)	2	0.4, 0.2, 0.1	No, dose sensitivity absent across all reporting times
Soil Ingestion Rate (gm/yr)	2	73, 36.5, 18.25	No, dose sensitivity absent across all reporting times

The gamma penetration (shielding) factor describes the effect of the building structure on the level of gamma radiation existing indoors (i.e. the fraction of outdoor gamma radiation available indoors). The RESRAD-OFFSITE default is 0.7, which is conservative in terms of erring in favor of higher modeled doses. Appendix H of NUREG-1620 recommends a gamma shielding factor between 0.3 and 0.6. A mean value from the latter guidance range (0.45) was used for this modeling.

Uncertainty Analysis

Probabilistic uncertainty analysis is used to determine uncertainty in the calculated result (in this case the RBD) due to variability in parameters used as model inputs. An uncertainty analysis was performed on all parameters identified through sensitivity analysis to have notable impacts on the calculated RBD. This included the gamma penetration factor and onsite indoor and outdoor occupancy factors.

To perform an uncertainty analysis, the distribution of each model parameter (variable) in question must be specified. Although RESRAD-OFFSITE has default distributions for many variables, those provided for parameters selected for this analysis appeared inconsistent with values specified in relevant guidance for the resident farmer scenario.

Default values are reported to be "generally applicable", and it is thus assumed that such values are based on statistical measures of central tendency (means or medians) from general distributions, not necessarily those specific to resident farmers. Median default values from distributions provided in RESRAD-OFFSITE for parameters in question were much lower than values indicated in the relevant guidance for the resident farmer scenario.

As a result, it was necessary to model plausible distributions for these parameters. Simple triangular distributions were assumed, with bounding values (minimum, mode, maximum) selected based on available pertinent information and professional judgment. Probabilistic utilities in RESRAD-OFFSITE were used to generate model input distributions for each parameter. The results (Figure A6) are assumed to represent reasonable approximations of variability in these parameters for rural residential farmers in this region.

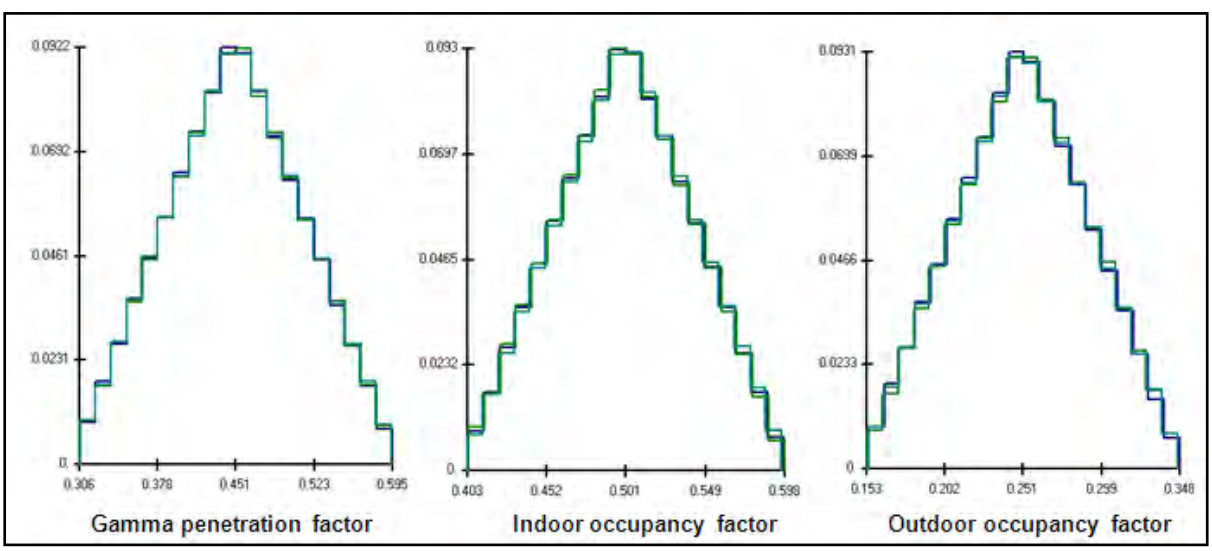


Figure A6: Parameter distributions generated for uncertainty analysis testing.

Sampling specifications for the uncertainty analysis included a random seed number, with three repetitions of 1000 semi-random value selections from the parameter distributions shown in Figure A6. The sampling algorithm used was Latin Hypercube, with sample selection groupings based on correlated or uncorrelated parameter relationships.

Results of the uncertainty analysis represent a population of predicted RBD values that approximates a normal (Gaussian) distribution (Figure A7). Figure A7 provides quantitative probabilistic and statistical information regarding the total amount of uncertainty associated with the calculated RBD due to variability in gamma shielding factors and indoor/outdoor exposure time fractions under a resident farmer scenario.

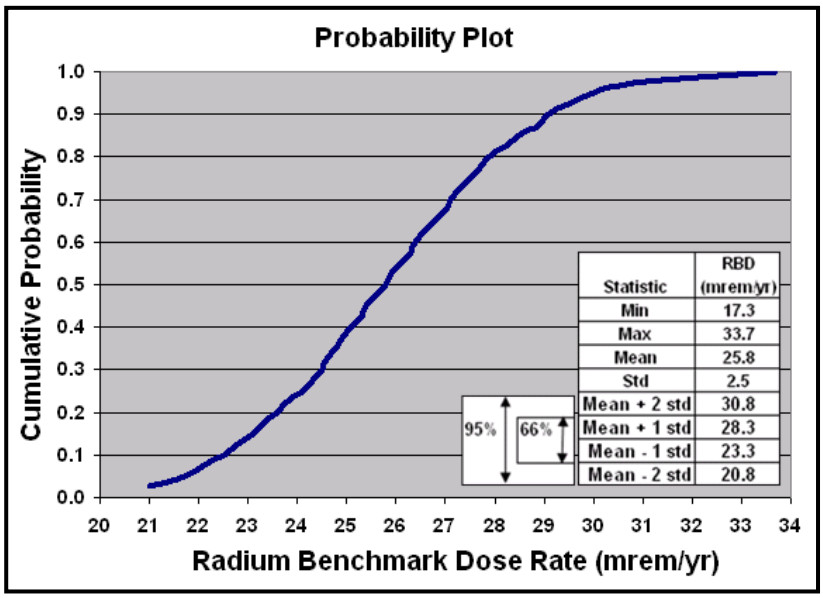


Figure A7: Probabilistic results of the uncertainty analysis. Tabular summary statistics are also provided, including percentages of results falling within ±1 and ±2 standard deviations from the mean.

For example, data from the curve in Figure A7 indicate a 95% probability that the RBD for a resident farmer under this scenario is less than 30.0 mrem/yr. Conversely, there is only a 5% probability that the RBD under this scenario is less than 21.7 mrem/yr. This raises an issue regarding the RBD approach to determining DCGLs for Th-230 and U-nat.

Remedial criteria and assessment methods are typically designed to limit Type I error rates to 5% (NRC, 2000). It might seem reasonable to base a DCGL on the 5th percentile of the distribution of predicted RBD values, yet doing so would have only a 5% probability of being warranted under the benchmarking approach. Conservative measures to reduce decision errors and minimize dose must be balanced against remedial costs and other factors.

Correlations and Multiple Regression Analysis

Another feature of the probabilistic/uncertainty analysis tools in RESRAD-OFFSITE is the ability to examine correlative relationships between generated populations of model input and output values. This can reveal additional information about the relative importance of various input parameters with respect to model output.

A qualitative comparison of slope and degree of data dispersion among relationships between model output and the three input parameters tested by uncertainty analysis (Figure A8), suggests that outdoor occupancy factor is the most important variable for predicting the RBD. Gamma penetration factor appears somewhat less important, while indoor occupancy factor seems least important of the three input variables.

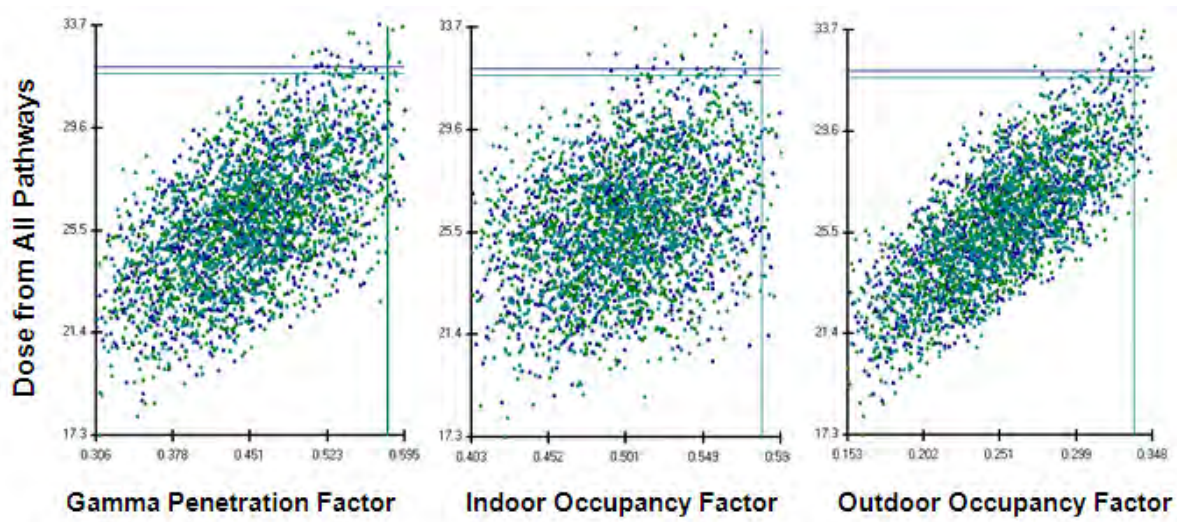


Figure A8: Correlative relationships between predicted dose from all pathways (RBD output) and model input parameter values generated from the probabilistic/uncertainty analysis.

A partial explanation for such modeling differences may be related to physical factors that govern exposure pathways. For example, external dose due to gamma radiation from Ra-226 in soil is the primary component of total maximum dose (the RBD). Outdoors, the source term for gamma radiation (soil Ra-226) is held constant in the model and there is no shielding.

Variability in predicted external dose is dependent only on the amount of time spent outdoors (gamma shielding or indoor occupancy factors have no influence). Conversely, variability due to uncertainty in the indoor occupancy factor also depends on uncertainty in the shielding factor because shielding governs the amount of gamma radiation available indoors.

Quantitative indications of the relative importance of these parameters were also generated by multiple regression modeling. Specifically, standardized partial regression coefficients are useful for quantitative evaluations because differing units between variables are standardized to allow direct comparisons. These measures account for the fact that multiple variables being assessed are each included in the regression model.

Standardized partial regression coefficients generated in RESRAD-OFFSITE (Table A3) quantitatively confirm that outdoor occupancy factor is the most important parameter with respect to impact on calculated RBD, followed by gamma penetration factor and indoor occupancy factor.

Table A3: Standardized partial regression coefficients (SPRC).

Probablistic Variable	Mean SPRC
Onsite Outdoor Occupancy Factor	0.75
Gamma Penetration Factor	0.56
Onsite Indoor Occupancy Factor	0.34

All three model input parameters examined are important with respect to calculated RBD, but the estimated amount of associated uncertainty does not indicate a high probability of significant error in the calculated RBD, nor for soil cleanup standards based on the RBD. Moreover, there is insufficient data or scientific justification for using values for these parameters other than those selected based on guidance provided in NUREG-1620 and RESRAD user manuals.

Soil Cleanup Criteria for Th-230

Based on the calculated RBD (25.8 mrem/yr), a Th-230 soil concentration required to produce an equivalent maximum dose rate (a DCGL for Th-230) was modeled using the same receptor scenario, exposure pathways, and parameter assumptions. Only soil concentration was allowed to vary in an iterative process until a DCGL resulting in a maximum dose rate of 25.8 mrem/yr was identified.

The concentration of Th-230 in soil that resulted in a maximum dose rate equivalent to the RBD was 99.5 pCi/g. This dose rate occurs at 351 years (Figure A9). The reason for the total dose peaking hundreds of years after time zero is because of the decay of Th-230 and corresponding buildup of Ra-226. This is also the reason that external gamma dose was again the primary component of the maximum total dose. Contributions from plant ingestion and other pathways were small to negligible (Figure A10).

Because the calculated DCGL for Th-230 concentration in soil is much higher than the numeric limit cited in NUREG-1620 (based on build-up of Ra-226 in excess of 5 pCi/g within 1000 years), further assessment was not necessary. Soil Ra-226 concentrations after the cleanup are expected to be near background levels and thus, the numeric limit for Th-230 of 14 pCi/g is both applicable and more restrictive and will thus be used as the soil cleanup level for Th-230.

Sensitivity and uncertainty analyses for the calculated DCGL for Th-230 were not necessary as the potential amount of prediction error due to variability in input parameters is expected to be very small relative to the absolute difference between the calculated DCGL and the numeric regulatory limit. This expectation is qualitatively supported by the amount of probabilistic uncertainty estimated for RBD modeling.

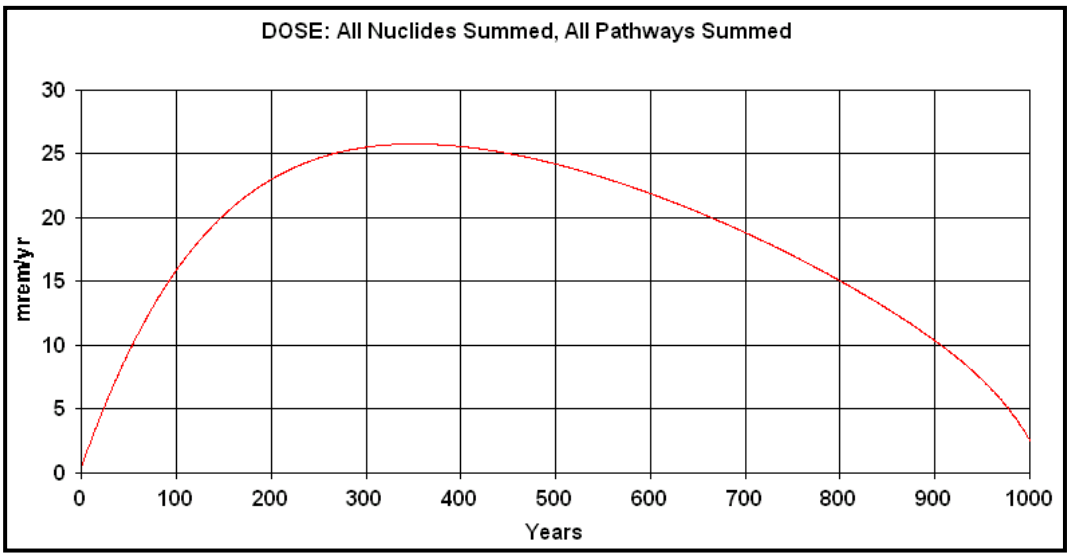


Figure A9: Modeled dose from a soil Th-230 concentration of 99.5 pCi/g.

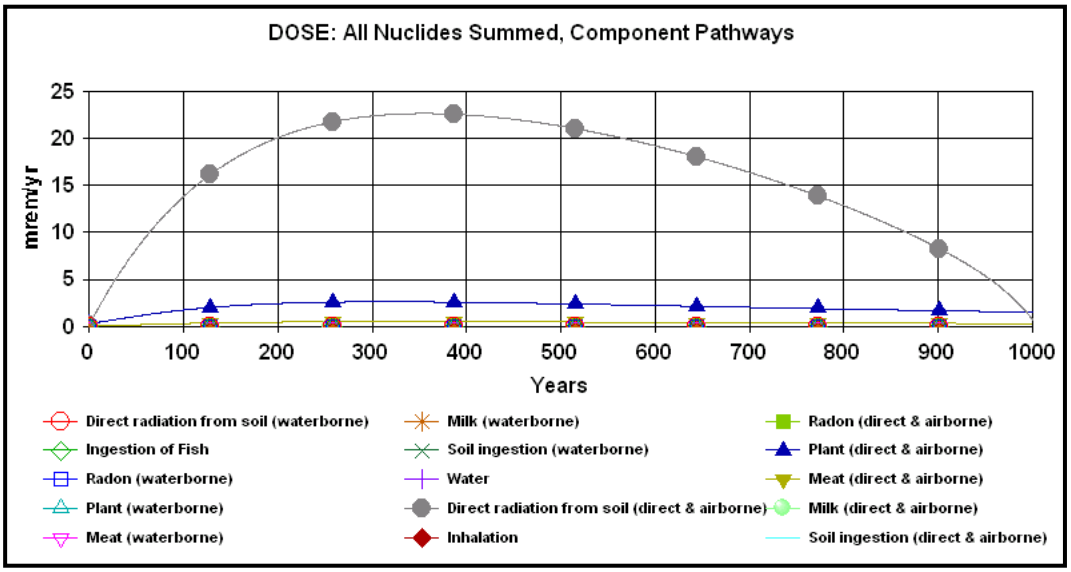


Figure A10: Component dose pathways from a soil Th-230 concentration of 99.5 pCi/g.

Soil Cleanup Criteria for U-nat

Also based on the calculated RBD (25.8 mrem/yr), a U-nat soil concentration required to produce an equivalent maximum dose rate (a DCGL for U-nat) was modeled using the same receptor scenario, exposure pathways, and parameter assumptions. To select U-nat concentration values for this modeling, total radioactivity was partitioned by constituent uranium isotopes as follows: 49% for U-238, 49% for U-234, and 2% for U-235. Only soil U-nat concentration was allowed to vary in an iterative process until a DCGL resulting in a maximum dose rate of 25.8 mrem/yr was identified.

The concentration of U-nat in soil that resulted in a maximum dose rate to a resident farmer equivalent to the calculated RBD is 598 pCi/g. This dose rate occurs at time zero (Figure A11). External gamma exposure is the primary component of the maximum total dose due to short lived decay progeny of U-238 (Th-234 and Pa-234). Contribution from plant ingestion is small and dose from other pathways are very small to negligible (Figure A12).

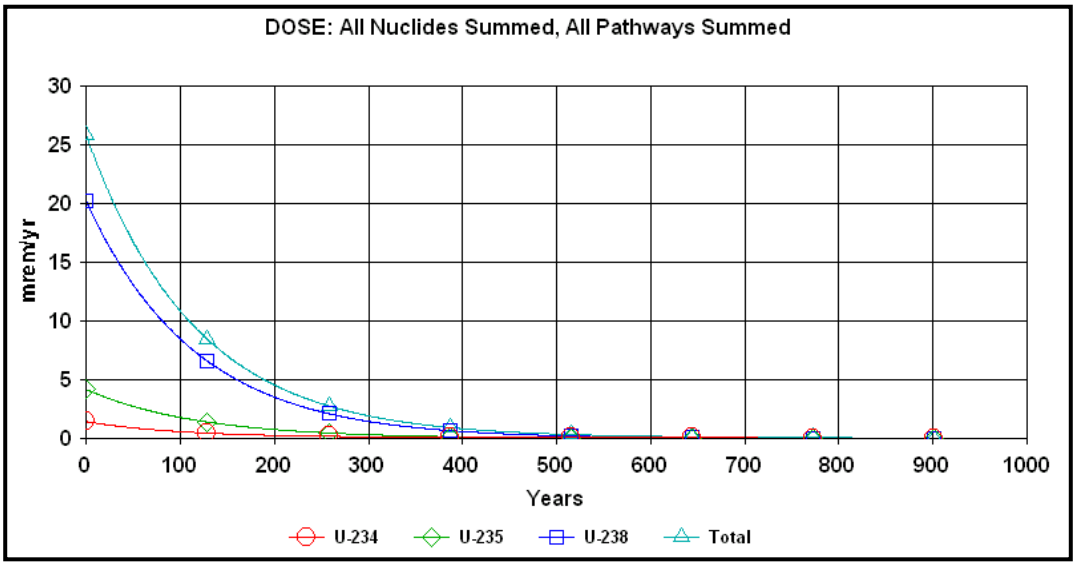


Figure A11: Modeled dose from a soil U-nat concentration of 598 pCi/g.

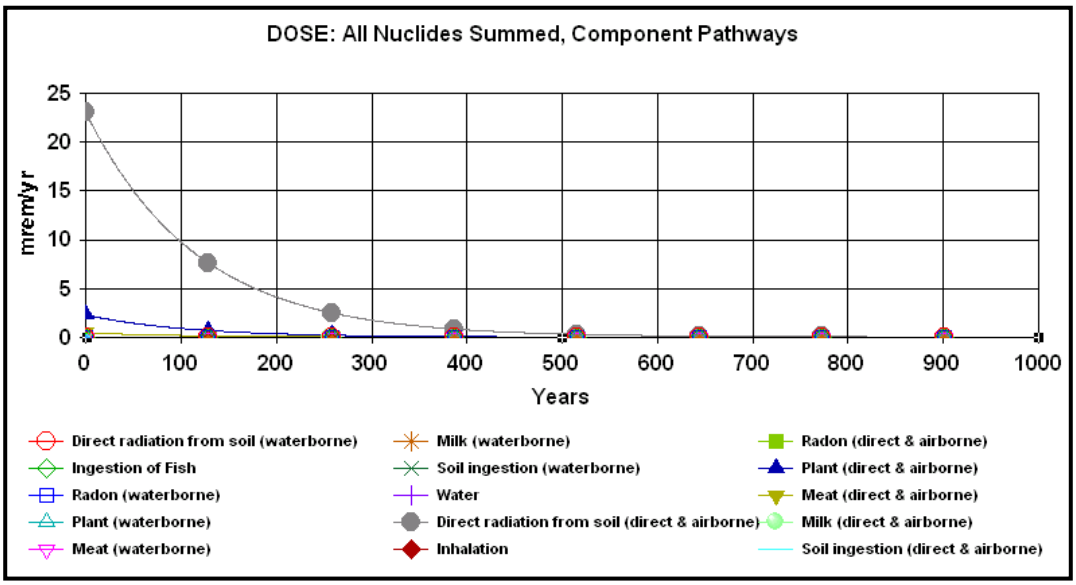


Figure A12: Component dose pathways from a soil U-nat concentration of 598 pCi/g.

Criterion 6(6) requires that cleanup levels based on the RBD also be ALARA. Appendix H of NUREG-1620 describes removing an additional 2 inches of soil as a potentially appropriate measure to fulfill this requirement. A proposed alternate approach for meeting the ALARA requirement is to base the uranium DCGL on a lower, probabilistic-based value of the RBD.

An alternate benchmark dose value based on 1 standard deviation below the mean RBD as provided in Figure A7 (23.3 mrem/yr) results in a DCGL for U-nat of 540 pCi/g. A benchmark dose value based on 2 standard deviations below the mean RBD (20.8 mrem/yr) results in a DCGL of 482 pCi/g. This approach offers a conservative and probabilistic basis for ALARA reductions in the DCGL for U-nat. Selecting the most appropriate alternate benchmark dose for determination of a final DCGL requires some additional evaluation.

Guidance provided in Appendix H of NUREG-1620 indicates that chemical toxicity must also be considered in deriving a soil concentration limit if soluble forms of uranium are present. The solubility of residual uranium at the site has not been characterized, but could involve both soluble and insoluble forms. The majority of this material is believed to consist of unprocessed, insoluble residues from natural ore.

The Agency for Toxic Substances and Disease Registry has published a toxicological profile for uranium (ATSDR, 1999), which includes the following recommended annual limits on uranium intakes based on chemical toxicity:

- Ingestion intake limit = 51.2 mg/yr (based on toxicity for a 70 kg adult)
- Air concentration limit for inhalation intakes (insoluble forms) = 8 µg/m^3
- Air concentration limit for inhalation intakes (soluble forms) = 0.4 µg/m^3

The calculated DCGL for U-nat (598 pCi/g), along with the potential alternative DCGL values suggested above (540 and 482 pCi/g), were used to generate estimates of corresponding intakes to compare against these ATSDR limits. Calculations of relevant ingestion and inhalation intake metrics are as follows:

$$\text{Uranium Ingestion}\left(\frac{\text{mg}}{\text{yr}}\right) = \left(\text{SC}\,\frac{\text{pCi}}{\text{g}}\right)\left(\frac{\text{mg}/\text{kg}}{0.677\,\text{pCi}/\text{g}}\right)\left(0.001\,\frac{\text{kg}}{\text{g}}\right)\left(\text{SIR}\,\frac{\text{g}}{\text{yr}}\right)$$

$$\text{Uranium Air Conc.}\left(\frac{\mu\text{g}}{\text{m}^3}\right) = \left(\text{SC}\,\frac{\text{pCi}}{\text{g}}\right)\left(\frac{\text{mg}/\text{kg}}{0.677\,\text{pCi}/\text{g}}\right)\left(1000\,\frac{\mu\text{g}}{\text{mg}}\right)\left(0.001\,\frac{\text{kg}}{\text{g}}\right)\left(\text{MLI}\,\frac{\text{g}}{\text{m}^3}\right)$$

Where:

		Value used	Parameter Source
SC =	soil concentration	Potential DCGL	Calculated / ALARA adjusted
SIR =	soil ingestion rate	36.5 g/yr	(RESRAD default)
MLI =	mass loading for inhalation	0.0001 g/m^3	(RESRAD default)

The ingestion calculation assumes that the concentration of uranium in ingested soil particles is equivalent to that residing in bulk soil at the ground surface. For the inhalation pathway, site soils can generally be characterized as loamy sand and under conditions of low mass loading of total suspended particulates (TSP) in air above such soils, TSP can be significantly enriched with radionuclides relative to the bulk soil (Wasiolek, 2009). A concentration enrichment factor for TSP in the range of 2 to 5 is appropriate to assume under such conditions. However, under conditions of high mass loading, such as

those expected with agricultural land uses in a dry and windy region, TSP enrichment factors are thought to approximate unity (Wasiolek, 2009).

Although there is marginal justification for assuming an enrichment factor for uranium concentrations in TSP, an enrichment factor of 4 was used for conservatism. Uranium intake pathway estimates are shown in Table A4. These uranium intake parameter estimates vary relatively little from one another, and all are well below corresponding ATSDR recommended limits, indicating that that chemical toxicity is not a limiting consideration with respect to DCGL selection for uranium.

Table A4: Calculated uranium intake estimates and corresponding ATSDR limits.

Intake Toxicity Parameter	Recommended Limit (ATSDR)	Potential Uranium DCGL (pCi/g)		
		598	540	482
Ingestion Intake (mg/yr)	51.2	32.2	29.1	26.0
Inhalation air conc. ($\mu g/m^3$)	8[a] / 0.4[b]	0.35	0.32	0.28

a) Limit for insoluble forms of uranium
b) Limit for soluble forms of uranium

By definition, an ALARA requirement for DCGL determination must consider not only dose reductions, but also the reasonableness of economic and other factors related to the cleanup. Remediating large amounts of additional soil to gain a small reduction in potential dose to a resident farmer could significantly increase costs, unnecessarily increase short-term health risks to workers and the general public, and potentially result in detrimental environmental impacts. In this case, the difference in modeled doses between the two potential ALARA-adjusted DCGLs is only 2.5 mrem/yr.

A U-nat soil cleanup level of 540 pCi/g is conservatively protective in terms of uncertainty in the RBD, justified in terms of ALARA principles, and is consistent with the requirements of the RBD approach and Criterion 6(6). Soil cleanup levels for Ra-226 and Th-230 are expected to be limiting, and should generally result in U-nat concentrations well below this ALARA-adjusted DCGL. Moreover, any areas left with U-nat concentrations approaching this DCGL would likely be very small in areal extent, further reducing any potential for doses in excess of the RBD.

The ALARA principle will be further implemented for all of these radionuclides by one of two methods. The first option is to excavate an additional 2 inches of soil once gamma exposure rate readings indicate a 95% probability of compliance with the 5 pCi/g above background radium standard (the corresponding gamma cut-off value for the site has been established at 23 µR/hr). The second option, if more practical to implement in terms of guiding excavations, will be to continue excavations until gamma readings approach about 20 µR/hr, a value close to the upper range of gamma exposure rates measured in the background reference area.

Finally, the unity rule will ensure that any combination of radionuclides left behind after the cleanup will not exceed the calculated RBD. This rule states that the sum of the ratios of final radionuclide concentrations to respective cleanup standards will not exceed unity. A summary of RBD modeling and DCGL development results, along with final *above background* soil cleanup levels for the Canon City Milling Facility is shown in Table A5.

Table A5: Summary of modeled RBD, corresponding DCGLs, numeric standards, and final above background soil cleanup levels.

Radionuclide	RBD (mrem/yr)	DCGL (pCi/g)	Numeric Standard (pCi/g)	ALARA-adjusted RBD (mrem/yr)	ALARA-adjusted DCGL (pCi/g)	Final Soil Cleanup Level (pCi/g)*
Ra-226	25.8	-	5	-	-	5
Th-230	25.8	99.5	14	-	-	14
U-nat	25.8	598		23.3	540	540

**Once gamma measurements indicate Ra-226 is in compliance, a reasonable amount of additional soil will be will be removed for ALARA reductions (an additional 2 inches or until gamma readings approach 20 μR/hr).*

References

ANL (Argonne National Laboratory, Environmental Science Division). 2009. RESRAD-OFFSITE Computer Code for Windows. Version 2.5. Developed under the joint sponsorship of the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission for site-specific radiological dose and risk assessment for both on-site and off-site individuals. Release date: August 15, 2009.

ATSDR (Agency for Toxic Substances and Disease Registry). 1999. Toxicological Profile for Uranium. Division of Toxicology/Toxicology Information Branch, Atlanta, GA.

U.S. Nuclear Regulatory Commission (NRC). 2000. Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Revision 1. NUREG 1575. Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC). 2003. NUREG-1620. Standard review plan for the review of a reclamation plan for mill tailings sites under Title II of the Uranium Mill Tailings Radiation Control Act of 1977. Final Report. June, 2003. (Appendix H).

Wasiolek, M.A. 2009. Modeling the inhalation enhancement factor in prospective radiological risk assessment. Radioprotection, vol. 44, No. 5 (2009) 221-225.

Section B: Background Reference Area

The criteria for radionuclides in soil, whether specified in Criterion 6(6) as prescriptive numeric limits or dose-equivalent standards, are all defined as "above background" concentrations.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) defines background in terms of a reference area having "similar physical, chemical, radiological, and biological characteristics as the survey unit(s) being investigated but has not been contaminated by site activities (i.e., non-impacted)" (NRC, 2000). The applicability of MARSSIM is limited to surface soils with relatively uniform soil concentrations (NRC, 2000). Such circumstances are expected once soil cleanup efforts have been completed and the site is ready for the final status survey.

Background levels of radionuclides in soil for the Canon City Mill Site were previously determined in accordance with the Remedial Action Plan (RAP) under the site's CERCLA (Superfund) designation. In the mid 1990's, a joint task group representing Cotter, the CDPHE, and the EPA completed comprehensive assessments of cleanup criteria and site closure issues as part of a "Total Quality Environmental Management" (TQEM) project.

The TQEM project included a study of key radionuclides in background soils in small, local drainage basins similar to the Sand Creek basin encompassing the mill site (Cotter/CDPHE/EPA, 2005). Results (Table B1) were included in a multi-volume TQEM project completion report. Reportedly after additional evaluation and testing, the same values were cited by CDPHE in a 2005 RAP Status Update (CDPHE, 2005) and need for further evaluation was indicated to be unnecessary (Table B2).

Table B1: Soil radionuclide concentrations for five background reference areas within local watershed sub-basins (Cotter/CDPHE/EPA, 1995).

Basin	Sampling Site	U-nat (mg/kg)	U-nat (pCi/g)	Ra-226 (pCi/g)	Th-230 (pCi/g)
Chandler	48	2.4	1.6	1.6	2.3
	28	2.4	1.6	1.6	2.2
	99	2.3	1.6	1.6	2.1
	710	2.4	1.6	1.6	1.9
Fawn Hollow	17	2.0	1.4	1.3	2.7
	46	1.6	1.1	2.0	3.6
	41	2.5	1.7	1.7	2.6
	210	2.4	1.6	1.4	2.8
East Coal Creek	23	1.6	1.1	0.9	1.2
	74	1.7	1.2	1.0	1.3
	37	1.7	1.2	0.9	1.0
	51	2.0	1.4	1.1	0.9
Caldirola No. 1 Mine	104	1.3	0.9	1.1	1.7
	66	2.4	1.6	1.3	1.6
	38	2.1	1.4	1.1	1.9
	56	2.3	1.6	1.1	1.7
Oak Creek North	26	2.4	1.6	1.0	1.3
	48	1.6	1.1	0.9	1.1
	44	2.1	1.4	0.9	0.9
	92	2.4	1.6	1.1	1.3
	Mean	2.1	1.4	1.3	1.8
	Std. Dev.	0.4	0.3	0.3	0.7

*Adapted from Table DG2, TQEM Report, Volume 2 (Cotter/CDPHE/EPA, 1995)

Table B2: Background radiological properties of soils and sediment at the site as cited by CDPHE in the 2005 RAP Status Update (CDPHE, 2005).

Target Element	Unit	Media	Background Mean[1]	Upper Confidence Limit[2]
U-nat	mg/kg	Soil	2.1	2.9
		Sediment	2.0	3.4
Ra-226	pCi/g	Soil	1.3	1.9
		Sediment	1.1	1.7
Th-230	pCi/g	Soil	1.8	3.2
		Sediment	1.5	3.1
Gamma[3]	μR/hr	Soil	14.6	18.6
		Sediment	15.2	20.0

[1]Adapted from RAP Status Update (CDPHE, 2005)
[2]Numeric level of confidence not specified (presumed 95%)
[3]Unshielded gamma exposure rate at waist level

Background soil concentrations in the above tables are consistent with values typical of natural background soils across the United States (Myrick et al., 1983). However, under MARSSIM protocols, the background reference area should be surveyed using sampling and analytical methods identical to those used for the survey units. MARSSIM calls for discrete sampling points along semi-randomized grids. The sampling methodology used to generate the background values shown in Tables 1 and 2 involved composite sampling within 100 m^2 areas to a depth of 6 inches for consistency with the cleanup criteria specified for uranium mills in Criterion 6(6).

New background reference area sampling is proposed as part of final status surveys at the site for several reasons, including: 1) there is a spatial discrepancy between MARSSIM sampling protocols and soil cleanup criteria for uranium mills, 2) about two decades have elapsed since the TQEM background data was generated and analytical technology and methods may differ, 3) the number of sample results from the TQEM study may not satisfy the number needed under MARSSIM protocols, and 4) NUREG-1620 specifies that background samples should be collected within 2 miles of the site and include geologically and chemically similar soils that are not impacted by site activities (NRC, 2003).

Comprehensive, GPS-based gamma surveys have been conducted across much of Cotter owned property and the adjacent golf course. Spatial analysis of these data using a kriging (statistical interpolation) program in ArcGIS® (ESRI, 2008) has resulted in a detailed spatial characterization of the distribution of gamma exposure rates across the site (Figure B1).

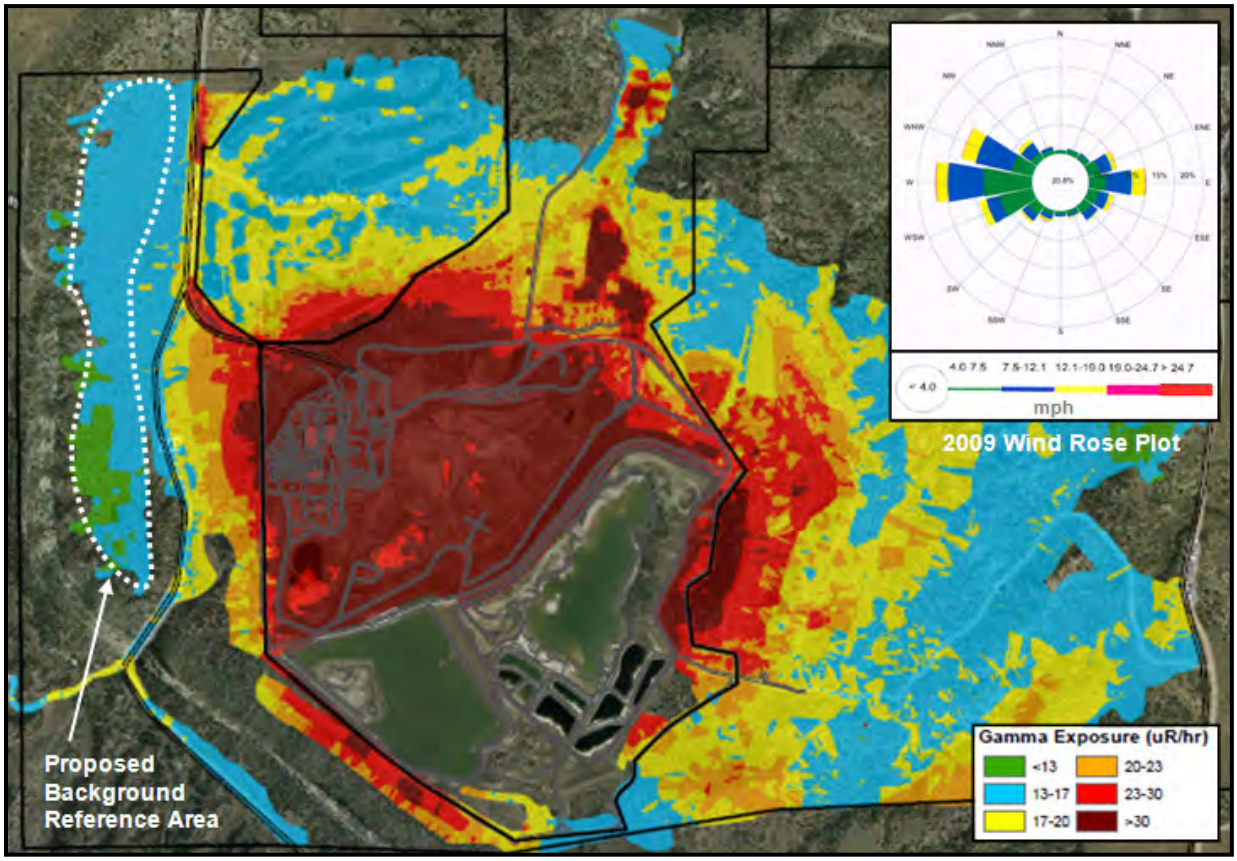


Figure B1: Gamma exposure rates across Cotter property in relation to prevailing winds and the proposed background reference area for final status surveys.

Also shown in Figure B1 is a typical wind rose (direction, frequency and wind speed) for the mill site, along with the proposed background reference area for final status surveys. Given that prevailing wind directions come from the WNW, the proposed background reference area is generally upwind of impacted areas at the site. This appears particularly true with respect to winds strong enough to result in measurable windblown migration of radionuclides. In addition, the proposed background reference area slopes towards Sand Creek and is thus hydrologically upgradient of impacted areas at the site. Gamma exposure rates in the proposed background reference area are consistent with the range of background gamma values acknowledged for the site by CDPHE (Table B2), and provide direct quantitative and spatial evidence that little if any measurable migration of radionuclides from mill activities has occurred in this area.

References

Cotter/CDPHE/EPA. 1995. Canon City Milling Facility Total Quality Environmental Management (TQEM) Project Summary Report. November 1995.

Colorado Department of Public Health and Environment (CDPHE). 2005. Cotter Canon City Uranium Mill, 1988 Remedial Action Plan, Summary and Status – August 2005.

Environmental Systems Research Institute (ESRI). 2008. ArcGIS, an integrated collection of Geographic Information Systems (GIS) software products providing a standards-based platform for spatial analysis, data management, and mapping. URL: http://www.esri.com/software/arcgis/index.html.

Myrick, T.E.; Berven, B.A.; Haywood, F.F. 1983. Determination of Concentrations of Selected Radionuclides in Surface Soil in the U.S. Health Physics, Vol. 45, No. 3 (September 1, 1983, pp. 631-642).

U.S. Nuclear Regulatory Commission (NRC). 2003. Standard review plan for the review of a reclamation plan for mill tailings sites under Title II of the Uranium Mill Tailings Radiation Control Act of 1978. Final Report. NUREG 1620. Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC). 2000. Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Revision 1. NUREG 1575. Washington, D.C.

Section C: Impacted Areas and Remedial Strategy

Review of Current Radiological Characterization Information

In the past two decades, a large amount of data and information has been developed with respect to terrestrial gamma radiation and associated levels and spatial distributions (both horizontal and vertical) of radionuclides in soil at the Canon City Milling Facility and in surrounding areas. This information is necessary to develop soil cleanup strategies and final status survey plans as part of the site decommissioning and license termination process. A review of some of the most pertinent studies to date in this regard, along with relevant information that has been generated is summarized below. Important data from each study are provided in corresponding sections of Appendix A.

1. In 1992 and 1994, Cotter conducted a high density drilling program across the Old Ponds Area (OPA) and portions of current/historical mill areas to characterize the spatial distributions (both horizontal and vertical) of uranium (U-nat) and molybdenum (Cotter/CDPHE/EPA, 1995; EMS, 2005). A total of 148 bore holes were drilled to depths ranging from 30-50 feet. Composite samples from 5 foot depth increments were collected and analyzed. In 2005, Environmental Management Support Inc. updated and refined earlier maps of associated areas expected to require remediation in order to help mitigate groundwater impacts as part of the OPA Alternatives Assessment Report (EMI, 2005) (Appendix A, Section 1).

2. In conjunction with a "Total Quality Environmental Management" (TQEM) project in the early 1990's, Cotter completed a study of background radionuclide concentrations in soils and sediments in small, local drainage basins similar to the Sand Creek basin encompassing the mill site (Cotter/CDPHE/EPA, 2005) (Appendix A, Section 2). The TQEM project also provided estimates of the volume of soils that would require remediation (304,000 cubic yards, not including soils and sediments along Sand Creek which have since been fully remediated).

3. In 2005, MFG Inc. performed a detailed gamma survey and characterizations of U-nat, Th-230 and Ra-226 in surface soils along County Road 143 and the mill access road (MFG Inc., 2006) as part of a public risk assessment for these areas (Appendix A, Section 3).

4. In 2007, Tetra Tech performed a comprehensive gamma survey of the OPA, along with gamma/Ra-226 correlation measurements and sampling to also characterize Ra-226 concentrations at the soil surface based on gamma survey readings (Tetra Tech, 2007). Maps showing statistical probabilities of soil Ra-226 concentrations in excess of the cleanup standard (5 pCi/g above background) were also developed (Appendix A, Section 4).

5. Also in 2007, Tetra Tech performed an extensive gamma survey of areas surrounding mill facilities, the OPA, and the tailings impoundments (Tetra Tech, 2008). This survey covered large portions of Cotter owned property, including outlying areas well away from site facilities and historic operations to determine the maximum measurable extent of Ra-226 migration due to wind transport processes. It also included gamma/Ra-226 correlation sampling to statistically predict, with a 95% level of confidence, the areal extent of surface soils with Ra-226 concentrations in excess of the cleanup standard (5 pCi/g above background), along with estimates of the associated volume of soils expected to require cleanup (Appendix A, Section 5).

This study also included additional drilling/depth sampling at locations near mill facilities to better define subsurface contamination and associated volumes of soil that will require remediation. All of the volume estimates in this study, including "wind-blown" surface soils in outlying areas, as well as soils impacted to greater depths near historic milling facilities (Appendix A, Section 5), were generated in order to update remedial surety estimates. The final surety volume estimate was 311,480 cubic yards, very similar to the 304,000 cubic yard cleanup volume estimated by the TQEM project team over a decade earlier (Cotter/CDPHE/EPA, 1995) without the benefit of nearly as much detailed radiological survey data.

6. In 2008, S.M. Stoller completed additional cleanup of the OPA based partially on the drilling program results presented in the 2005 Environmental Management Support report (EMI, 2005) and the 2007 OPA Gamma Survey report (Tetra Tech, 2007). Final results of the Stoller cleanup (Stoller, 2008) add updated, current characterization information for the OPA (Appendix A, Section 6).

7. In 2009, Cotter submitted a report on an interim cleanup of the mill access road which included a post-cleanup gamma survey and comparisons with earlier, pre-cleanup gamma survey data (Cotter, 2009) (Appendix A, Section 7).

8. In 2010, Cotter performed a detailed radiological survey of gamma exposure rates and soil radionuclide concentrations across Cotter property in the vicinity of air particulate monitoring station AS-210 (near the northwest corner of the Shadow Hills Golf Course). Characterization results and associated dose assessments were submitted to CDPHE in March of 2011 (Cotter, 2011) (Appendix A, Section 8).

9. In February of 2010, Cotter conducted a gamma survey of remaining portions of the golf course not previously surveyed. Results were compiled along with all other gamma survey data for the site (from the above studies) and spatial analysis of these data using a kriging (statistical interpolation) program in ArcGIS® (ESRI, 2008) resulted in a detailed spatial characterization of the distribution of gamma exposure rates across the entire site and outlying areas (Appendix A, Section 9).

Remedial Strategy and Additional Characterization Requirements

Radiological characterization data from past studies provide a clear understanding of the areal (horizontal) extent of impacted soils at the site. The vertical extent of impacts to subsurface soils is reasonably well characterized in most areas, but subsurface characterization data seldom provide high certainty with respect to the spatial distributions of subsurface contamination relative to cleanup criteria. The remedial strategy is to remove all surface and subsurface soils with radionuclide concentrations in excess of soil surface cleanup standards. Excavations will begin at the surface in all areas where gamma readings exceed 23 µR/hr, and will continue vertically until real-time radiological screening measurements indicate that compliance has been achieved or until bedrock is encountered. The amount of subsurface soils remediated will thus depend not on the amount or accuracy of available subsurface characterization data, but on the amount of subsurface contamination actually present.

Given this general remedial strategy, two relevant data gaps have been identified. First, the CDPHE has expressed concerns regarding a lack of subsurface characterization information at the locations of historic leach fields. It is possible that remediation in these areas could show evidence of compliance

with soil cleanup criteria before the depth of the leach field has been reached. Under such circumstances, this issue will be addressed by excavating test pits to the depth of the leach field and sampling corresponding soils. If the data shows evidence of underlying contamination in excess of the cleanup criteria, excavations will continue until any subsurface contamination associated with the leach fields has been successfully remediated, or until bedrock is encountered.

Secondly, there is need for an updated gamma survey of the OPA in order to determine what areas remain to be remediated with respect to Ra-226 compliance after the Stoller soil cleanup project. The Stoller cleanup targeted U-nat and molybdenum, but likely removed most or all Ra-226 above the cleanup criteria in the process. These areas may thus require no further excavation prior to final status surveys. Once a new gamma survey of the OPA is performed, areas of Ra-226 compliance can be evaluated based on previous gamma/soil Ra-226 correlations that have been developed at the site.

The justification for use of previous correlation data to assess compliance and guide remedial efforts is that all three previous gamma/soil Ra-226 correlations (from the Roadside Risk Assessment, the OPA study, and the Volume study), though somewhat different from one another in terms of slopes and intercepts, each resulted in a probabilistic gamma cut-off value of 23 µR/hr, a value expected to achieve compliance with the soil Ra-226 cleanup criterion (about 6 pCi/g including background) with a high statistical level of confidence (Figure C1).

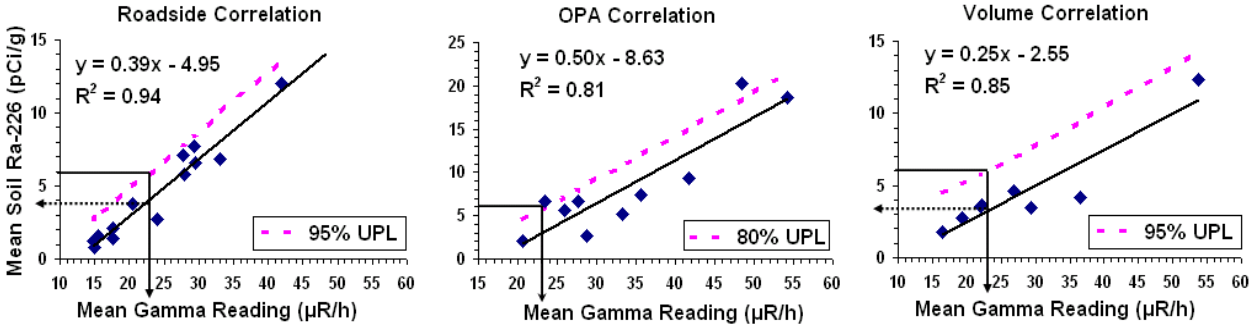


Figure C1: Comparison of three independent gamma/soil Ra-226 correlations developed in different areas of the site. In each case, the gamma cut-off value that provided a high (project-specified) statistical probability of compliance with the soil Ra-226 cleanup criterion was 23 µR/hr.

With respect to Th-230 compliance, Th-230 is normally expected to be far less susceptible to leaching and vertical migration than Ra-226 in soil systems and it is thus reasonable to assume that successful cleanup for Ra-226 compliance will also achieve compliance with Th-230 criteria. However, this may not be true in areas where acidic tailings solutions were historically present. Thorium itself cannot be readily detected in situ and thus interim soil sampling and gross alpha screening measurements in the laboratory may be conducted to provide reasonable evidence of Th-230 compliance prior to definitive verification with the final status survey.

Regarding U-nat compliance, uranium tends to be somewhat more susceptible to leaching and vertical migration in soil systems versus Ra-226, however, the cleanup criterion for U-nat is two orders of magnitude greater than that for Ra-226. Again, it is likely that successful cleanup for Ra-226 compliance will also achieve compliance with U-nat criteria in most areas of the site, but the OPA and mill process facility areas may be different in this regard. An X-ray florescence (XRF) screening program for U-nat

may also be conducted to help guide excavations and provide reasonable assurance that the final status surveys will demonstrate compliance.

The Cotter Laboratory has recently obtained a state-of-the-art inductively coupled plasma mass spectrometry (ICP-MS) system capable of analyzing soil samples for U-nat, and potentially Th-230 concentrations. This may decrease analytical lead times for these radionuclides versus past methods, which offers the possibility that this resource could perform the same function as screening methods to help guide excavations and provide assurance of compliance prior to final status surveys. These issues are further discussed in Section D of this report.

References

Cotter/CDPHE/EPA. 1995. Canon City Milling Facility Total Quality Environmental Management (TQEM) Project Summary Report. Volume 2. November 1995.

Cotter Corporation. 2009. Interim cleanup of the access entry road, Cotter Canon City Milling Facility. December 28, 2009.

Cotter Corporation. 2011. Radiological Survey and Dose Assessment for Cotter Property near Air Particulate Monitoring Station AS-210. March 11, 2011.

Environmental Management Support, Inc. (EMI). 2005. Alternatives assessment, Old Ponds Area, Cotter Canon City Mill Site. March 17, 2005.

Environmental Systems Research Institute (ESRI). 2008. ArcGIS, an integrated collection of Geographic Information Systems (GIS) software products providing a standards-based platform for spatial analysis, data management, and mapping. URL: http://www.esri.com/software/arcgis/index.html.

S. M. Stoller. 2008. Old Pond Area source removal implementation report. December, 2008.

Tetra Tech. 2007. Old Ponds Area at the Cotter Canon City Mill site: gamma survey and soil Ra-226 Characterization. Prepared for Cotter Corporation and S.M. Stoller Corporation. November 23, 2007.

Tetra Tech. 2008. Estimate of the volume of contaminated soil at the Cotter Corporation Uranium Milling Facility, Canon City, Colorado. November 3, 2008.

Section D: Final Status Survey Plan

Data Quality Objectives

The first step in designing final status surveys for the site is to identify and specify data quality objectives (DQOs) that will help to ensure that the data collected are pertinent and of sufficient quality and quantity to correctly assess compliance with cleanup criteria and determine whether impacted areas at the site can be released for unrestricted use. The following DQO statement summarizes key elements of this initial planning step as outlined in MARSSIM:

A. **State the problem**: A large number of radiological investigations at the Canon City Milling Facility over the past several decades have identified and characterized the nature and spatial distribution of residual (above background) levels of radionuclides in soils resulting from historic operations at the site. In accordance with the conditions of the radioactive materials license pertaining to site decommissioning, Cotter is responsible for remediation of contaminated soils and proper disposal in engineered onsite repositories. The objectives are to achieve release of impacted areas for unrestricted use, and to terminate the radioactive materials license. Upon completion of soil remediation activities, a final radiological status survey must be conducted to determine with a high level of confidence whether or not each survey unit at the site qualifies for unrestricted release under applicable regulatory decommissioning criteria.

B. **Identify the decision**: Is the level of residual contamination in each survey unit below the release criteria.

C. **Identify inputs to the decision**: Final radiological survey data, including results of gamma scans and direct soil sampling, will be used to determine compliance with the release criterion in each survey unit based on MARSSIM survey and assessment methods. MARSSIM is widely accepted as the regulatory standard for such assessments. Site-specific soil cleanup criteria are presented in Section A of this report. A combination applicable regulatory decommissioning standards and guidelines, as well as previous radiological characterization data, were used to develop these cleanup criteria.

D. **Define the study boundaries**: Based on the overall gamma survey map of the site (Appendix A, Section 9), all areas with gamma exposure rate readings in excess of 23 µR/hr will be considered Class 1 impacted areas. Areas with gamma exposure rates between 17 and 23 µR/hr will be considered Class 2 areas, and areas below 17 µR/hr will be considered consistent with the range of natural background and non-impacted locations. The background reference area is defined in Section B. The contaminated area to the east of the Primary impoundment is generally thought to involve a thin layer of wind transported material across a steep, rocky and partially forested escarpment. This area is not expected to be remediated due to construction impracticability and environmental impact concerns. In addition, given the terrain, plausible occupancy times for any potential receptor in this area would not be expected to result in significant doses. This area was also excluded from remedial consideration in the Remedial Action Plan (RAP) under the CERCLA (superfund) designation for the site.

E. **Develop a decision rule**: Soil radionuclide concentration data in each survey unit will be numerically evaluated against applicable cleanup levels ($DCGL_W$ values) specified in Section A of this report (Table A5). If all data in the survey unit are less than the cleanup levels, the survey unit meets the

conditions for unrestricted release and no statistical testing is required. If some samples in a given survey unit remain above the cleanup levels, a statistical Wilcoxon Rank Sum Test (WRS) will be used to evaluate whether or not median above background concentrations are statistically greater than corresponding $DCGL_W$ values. In addition to evaluations of each survey unit against $DCGL_W$ values, any smaller, localized areas identified by gamma scans or soil sampling as having potential for elevated levels ("hot spots"), will be additionally sampled and evaluated against a secondary ($DCGL_{EMC}$) criterion as described in MARSSIM. Finally, to ensure that the combination of radionuclides within a given survey unit will not result in doses greater than the radium benchmark dose, the unity rule (described below) will be applied as described in section I.11.3 of Appendix I in MARSSIM.

F. **Specify limits on decision errors**: The null hypothesis for statistical testing on final status survey sampling results is that the survey unit exceeds the cleanup criterion. Descriptions and acceptable rates on Type I and Type II decision errors (α and β respectively) are outlined below. The values chosen for α and β are independent of one another in terms of limiting respective chances of Type I or Type II errors.

- A Type I error would occur if a survey unit were to be incorrectly released for unrestricted use. The consequences of this type of error would include the potential for a future critical receptor at the site to receive an above background dose greater than the radium benchmark dose (25.8 mrem/yr). For final status survey assessments, α will be set at 0.05 (meaning only a 5% chance that a Type I error would occur). This value for α is typically required by regulators as being adequately protective in terms of insuring that the dose limit for any survey unit will be correctly assessed by the final status survey and respective statistical testing.

- A Type II error would occur if a survey unit were to be incorrectly prohibited from an unrestricted use designation. The consequences of this type of error would include a tremendous amount of unnecessary costs incurred by the licensee. For final status survey assessments, β will be set at 0.1 (meaning only a 10% chance that a Type II error would occur). This error rate is up to the licensee to select as it affects the amount of risk the licensee is willing to accept that a clean survey unit will fail the test due to an insufficient number of samples being taken.

Specific components, justifications, and technical details supporting these summary DQO statements are provided in the remainder of Section D.

Final Status Survey Design and Data Assessment

Soil Sampling

Upon completion of soil cleanup at the site, final status surveys to demonstrate compliance with cleanup criteria will be based on MARSSIM guidance (NRC, 2000). Soil cleanup levels for each radionuclide of concern as specified in Section A of this document (Table A5) will be used to calculate for each survey unit (as well as for the background reference area) a weighted sum of fractions for measured concentrations divided by corresponding $DCGL_W$ values across all radionuclides (denoted by T_W) as described in Appendix I.3.11 of MARSSIM.

The value T_W is a weighted fractional measure of the individual radionuclide concentrations present relative to the maximum combined amount that is allowable under the unity rule, where the maximum allowable value of T_W is unity. Determination of the minimum number of samples required, along with $DCGL_{EMC}$ "hot spot" compliance, will follow the same guidance with respect to application of the unity rule. This assessment methodology will ensure that the final radionuclide mixture in any given survey unit will not exceed the maximum combined amount that is allowed within the regulatory framework. The applicable formulas are as follows:

$$T_W = C_1/D_1 + C_2/D_2 + C_3/D_3$$

$$\sigma = [(\sigma_1/D_1)^2 + (\sigma_2/D_2)^2 + (\sigma_3/D_3)^2]^{0.5}$$

$$T_{EMC} = C_1/E_1 + C_2/E_2 + C_3/E_3$$

Where:

T_W = Total fraction of unity rule $DCGL_W$ limit
T_{EMC} = Total fraction of unity rule $DCGL_{EMC}$ limit
σ = Total variability among all radionuclides
C_1 = Median soil U-nat in survey unit
C_2 = Median soil Th-230 in survey unit
C_3 = Median soil Ra-226 in survey unit

D_1 = $DCGL_W$ for U-nat
D_2 = $DCGL_W$ for Th-230
D_3 = $DCGL_W$ for Ra-226
E_1 = $DCGL_{EMC}$ for U-nat
E_2 = $DCGL_{EMC}$ for Th-230
E_3 = $DCGL_{EMC}$ for Ra-226

As specified in Criterion 6(6), soil cleanup criteria for uranium mills are based on average above background concentrations across any 100 m^2 area to a depth of 15 cm, and for subsurface contamination, 100 m^2 areas for any underlying 15-cm depth profile increment. This raises a spatial inconsistency with MARSSIM protocols for final status surveys, which involve discrete sampling points along semi-randomized sampling grids across much larger survey units. Depending on the degree of spatial variability present, a single discrete sample may not accurately represent the average concentration across a corresponding 100 m^2 area.

However, a fundamental assumption underlying MARSSIM-based sampling protocols and statistical testing for final status surveys is that soil radionuclide concentrations within the survey unit being evaluated are uniform. After remediation of soils in each survey unit is believed to be complete based on radiological screening measurements, relatively uniform concentrations can generally be expected.

If the uniformity assumption is reasonably valid and the survey unit passes a Wilcoxon Rank Sum (WRS) statistical test for compliance with the $DCGL_W$ (based on discrete sampling), the majority of 100 m^2 sub-areas will theoretically also be in compliance. Although this assumption represents a recognized weakness in the MARSSIM-based concept of the DCGL and related statistical testing, the authors of MARSSIM developed an additional survey mechanism to help address this issue.

MARSSIM actually has two types of DCGL. The primary DCGL applies to the survey unit as a whole (denoted as $DCGL_W$). MARSSIM guidance recommends that survey units can range in size up to 10,000 m^2 or more depending on survey unit classification and site circumstances. The $DCGL_W$ specifies the median net (above background) concentration across the entire survey unit at which compliance is evaluated. If statistical WRS testing indicates that the median net concentration in the survey unit is less than the $DCGL_W$, the survey unit passes the primary test for compliance.

In addition to evaluations of each survey unit against the $DCGL_W$, any areas identified by gamma scans or soil sampling as having potential for concentrations in excess of the $DCGL_W$ would be sampled and assessed against a secondary "hot spot" criterion using an elevated measurements comparison (EMC) procedure. To develop this secondary criterion, termed the $DCGL_{EMC}$, RESRAD can be used to calculate

site-specific dose/area factors (simply referred to as area factors). An example calculation of an area factor (AF) for a 100 m^2 hot spot relative to a $DCGL_W$ of 5 pCi/g for Ra-226 across a hypothetical 10,000 m^2 survey unit, and a corresponding calculation of the respective $DCGL_{EMC}$ is as follows:

AF = 10,000 m^2 dose from $DCGL_W$ / 100 m^2 dose from $DCGL_W$
= (22.5 mrem) / (2.8 mrem)
= 8.0

$DCGL_{EMC}$ = ($DCGL_W$ × AF)
= (5 pCi/g × 8.0)
= 40 pCi/g

Thus, in this example, 40 pCi/g represents the maximum average above background soil Ra-226 concentration within a 100 m^2 hot spot that would maintain compliance with the overall dose limit for Ra-226 in soil within a 10,000 m^2 survey unit. A table of various AFs covering a range of possible hot spot dimensions can be entered into COMPASS software (ORAU/ORISE, 2007) and the program will model a curve of $DCGL_{EMC}$ values versus hot spot size. If subsequent COMPASS calculations for final status survey data were to show that all hot spots in a survey unit, in combination with the general median concentration, results in a dose in excess of the dose limit, the survey unit would fail the secondary requirement for demonstrating compliance.

There is, however, a caveat regarding the concept of "dose limit" in this context with respect to Ra-226 and Th-230 because technically, $DCGL_W$ values for these radionuclides are not based on the radium benchmark dose (total dose from Ra-226 plus Pb-210) but on more limiting numeric standards. As a result, application of the $DCGL_{EMC}$ methodology in combination with the unity rule for this site is only partially dose-based. The net effect of this inconsistency in the regulatory framework is to lower the effective dose limit below the RBD as defined in Criterion 6(6).

A series of site-specific dose estimates for various area sizes were calculated using $DCGL_W$ values for each relevant radionuclide to understand the effect of increasing contaminated area size on dose and AF (Figure D1). The results indicate that as contaminated area size increases above 100 m^2, dose increases quickly until affect thresholds are reached that cause the relationship to plateau yet still vary to some degree. Beyond about 10,000 m^2, the relationship becomes very consistent and dose increases only slightly with further increases in the size of the contaminated area. Note that doses at $DCGL_W$ values (numeric or dose based) for each radionuclide are below the radium benchmark dose. Corresponding AFs among these radionuclides are nearly identical for areas greater than about 200 m^2 (Figure D1).

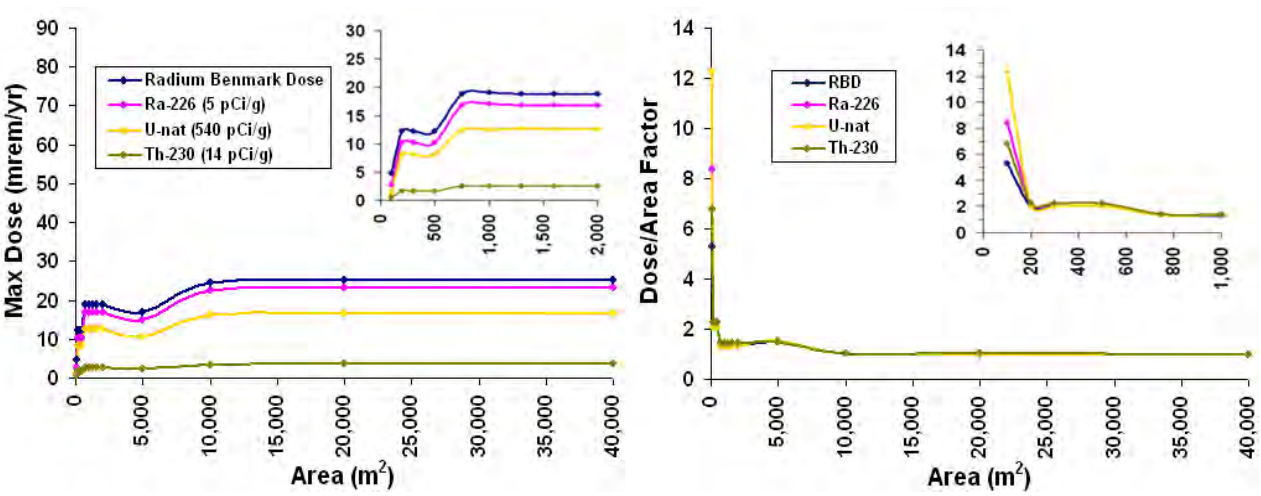


Figure D1: Left: relationship between size of contaminated area and dose. Right: calculated area factors relative to a maximum area of 40,000 m^2 (about 10 acres).

The dose/area relationship results in Figure D1 bring up an important consideration regarding practical limitations on the size of final status survey units at this site. The total areal extent of impacted areas expected to require remediation is on the order of 350 acres or more. Most of this area will be classified as Class 1 per MARSSIM guidance. This guidance recommends a maximum survey unit size of 2,000 m^2 for Class 1 areas and up to 10,000 m^2 for Class 2 areas. Under these recommendations, well over 700 survey units and 17,000 individual soil samples would be required for Class 1 areas alone. This is clearly not a practical or reasonable approach for demonstrating compliance at this site, particularly given the spatially intensive radiological scrutiny that will occur during soil remediation (down to the width of an excavator bucket) and the implications of the modeled dose/area relationships (Figure D1) in the unlikely event that even a small area of significantly elevated soil were missed by the cleanup.

Fortunately, many MARSSIM design protocols are flexible and survey unit size is one that can be adjusted to accommodate site circumstances provided that reasonable and effective alternate strategies to demonstrate compliance are available and can be justified (see Section 2.6 of MARSSIM). It will be far more practical in this situation to use much larger survey unit areas, increase the minimum number of samples per survey unit, and rely to a greater extent on high density gamma surveys with automated, GPS-based data collection systems. This strategy will help ensure that any "hot spots" of significance with respect to potential doses will be identified, yet data production, data management, and final status survey assessments for the site will be kept to manageable levels and the amount of time required to complete this work will be within reason.

MARSSIM recommends selecting or grouping survey units according to areas of relatively distinct historical operations and/or by the nature of contamination present. Given the overall size of the site, and relatively well defined historic operational sub-areas, a maximum target survey unit size of about 10 acres (40,000 m^2) is considered reasonable and appropriate. This would result in about 35 Class 1 survey units across the site. A sense of the size of this survey unit area in relation to impacted areas at is shown in Figure D2. The actual size and shape of each survey unit will vary according to practical considerations such as maintaining relatively even groupings within operational areas and considering topography or other site features that can serve as logical survey unit boundaries.

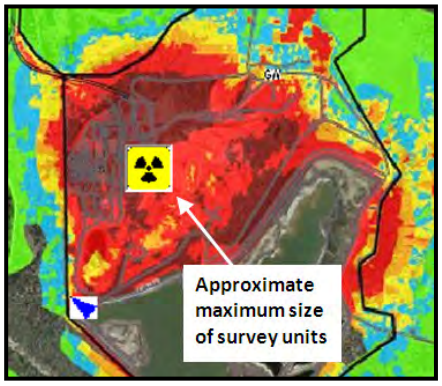


Figure D2: Approximate dimensions of a proposed 10-acre Class 1 survey unit relative to the extent of impacted areas at the site.

Once initial results of final status surveys are available, any individual soil sample result significantly in excess of the cleanup criterion for any radionuclide, or any area with gamma readings significantly in excess of the corresponding gamma cut-off value, will be flagged for further investigation. The definition of "significant" in this context will be values greater than two to three times the upper range of corresponding background values and/or subject areas greater than 100 m^2 in lateral extent. If determined to have an average concentration exceeding the $DCGL_{EMC}$ for a corresponding hot spot size, further remediation will be required before the survey unit can be considered in compliance. Any secondary hot spot remediation will require additional gamma scanning and soil sampling in order to verify and document that compliance was achieved.

A prospective minimum number of samples required within each survey unit was calculated using COMPASS software (ORAU/ORISE, 2001). COMPASS was developed at Oak Ridge Associated Universities to aid users in planning and implementing MARSSIM surveys. Several input parameters impact the number of samples needed to satisfy statistical testing requirements, including:

1. Acceptable rates on Type I and Type II decision errors (in this case, $\alpha = 0.05$ and $\beta = 0.1$ were used as specified in the DQO statement).

2. The lower bound on the grey region (LBGR). The LBGR represents the expected median concentration across the survey unit prior to the final status survey (after the cleanup is completed). A MARSSIM default value of 50% of the combined $DCGL_W$ value of 1 under the unity rule (0.5) was used for the LBGR.

3. Anticipated total variability in soil radionuclide concentrations in the survey units after remediation. Based on past experience, the amount of variability (standard deviations from mean values) in U-nat , Th-230, and Ra-226 concentrations in a given survey unit after the cleanup are expected to be in the range of ± 4, 6, and 2 pCi/g respectively. Per MARSSIM guidance, the corresponding total variability relative to a combined $DCGL_W$ value of 1 under the unity rule is ± 0.58.

Given these input parameters, COMPASS calculations resulted in a total of 38 soil samples in each survey unit (along with 38 background reference area samples) as the minimum number necessary to satisfy WRS testing requirements (Figure D3). The prospective power curve in Figure D3 predicts, for example, that if median values for each radionuclide from 38 soil samples in a given survey unit resulted in a calculated T_W value of 0.6 under the unity rule, there is a 90% probability that the survey unit will pass the WRS test. This curve represents the statistical "power" of the test to correctly assess compliance given the expected amount of variability, the specified limits on decision error rates, and the number of samples collected.

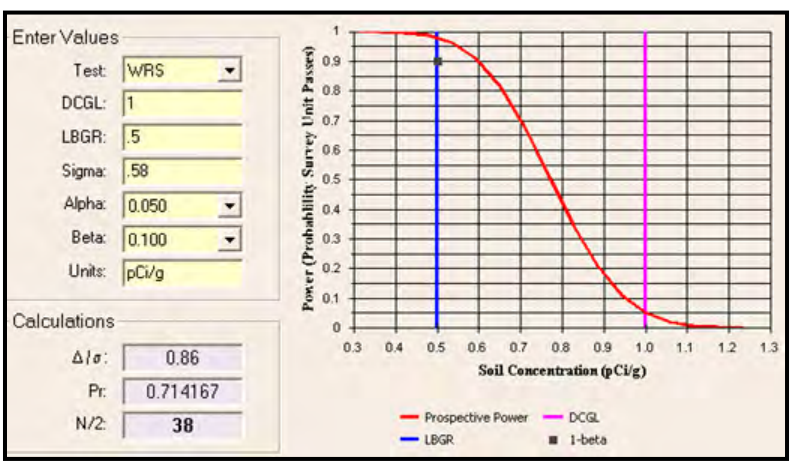


Figure D3: COMPASS results for prospective calculation of the number of samples required within each survey unit.

Because the size of Class 1 survey units may range up to 10 acres, the number of samples per survey unit will be increased to attain an average sampling density of at least 4 samples per acre (40 samples per 10-acre survey unit). This will result in over 1,400 samples being collected across Class 1 impacted areas

at the site and will provide some indication of variability down to areas as small as one acre. The same number of samples will be collected in Class 2 survey units and the background reference area. Class 2 areas will have no specific limits on survey unit size, but are expected to include a number of survey units across the site delineated according factors such as proximity to operational areas of the site, geographic practicality, scientific judgment and consistency with data quality objectives.

Systematic grid sampling locations will be determined using MARSSIM formulas and protocols, or grids will be automatically designed and spatially randomized using a specialized software package such as Visual Sample Plan (a public domain software tool developed by Pacific Northwest National Laboratory for the U.S. Department of Energy).

Laboratory Analysis of Soil Samples

Conceptually, all soil samples collected as part of final status surveys will be analyzed by the Cotter Laboratory or by an accredited commercial laboratory. For soil Ra-226 concentrations, the analytical method will involve gamma spectroscopy at a commercial laboratory using a high-purity germanium (HPGe) detection system under an approved method such as EPA method 901.1 (modified for soil samples). For soil U-nat and Th-230, analyses will be conducted by the Cotter Laboratory using alpha spectroscopy, Procedure SOP 5-9 (Cotter, 2006b), or inductively coupled plasma-mass spectroscopy (ICP-MS), Procedure SOP 2-200 (Cotter, 2011).

However, due the extremely large number of samples that must be collected, processed and analyzed (likely to be in the range of 1,500 to 2,000 samples), alternate analytical screening methods may be used to generate a majority of final status survey data provided that these screening methods can be quantitatively demonstrated to produce reliable results compared to the direct analytical laboratory methods indicated above. Demonstration of the reliability of screening methods would be based on applicable data generated during the soil cleanup (prior to the final status survey). If acceptable reliability of screening data cannot be demonstrated during the soil cleanup phase of the project, all samples collected during the final status surveys will be analyzed by the above laboratory methods.

During the soil cleanup, one or more analytical screening methods for soil samples may be used to augment gamma surveys in support of excavation control. This could be important to continually assess the effectiveness of the gamma cut off value (23 µR/hr) with respect to the Ra-226 criterion (5 pCi/g above background), and to assess (relatively quickly) soil Th-230 and U-nat concentrations which are known to occur in disequilibrium with Ra-226 at the site, but may not be easily detected or reliably measured in the field.

For Ra-226, analytical screening measurements will likely be used and will involve a modified technique based on field laboratory methods described in Whicker et al. (2006). Primary modifications from the methodology used by Whicker et al., are that a 2”× 2” NaI detector will be used and the analytical calibration curve will be based on gross gamma measurements (rather than spectral analysis of specific energy peaks) for secondary soil Ra-226 reference material standards. Concentrations for these standards were established with gamma spectroscopy analysis using a high-purity germanium (HPGe) detector at a certified commercial laboratory (modified EPA method 901.1).

Aliquots of homogenized samples will be sealed in special soil counting tins and placed inside of a lead counting well during counting (Figure D4) to shield background radiation and maximize system sensitivity to Ra-226 and its decay products. Based on previous method-specific assessments of radon

ingrowth for site-specific soil samples, a statistical correction factor will be applied to initial counting results to account for the ingrowth of radon-222 and its decay products (at approximate secular equilibrium with Ra-226). This method can produce Ra-226 estimates within an hour of sample collection.

Because background gamma radiation is not 100% shielded during soil Ra-226 counting, system sensitivity to gammas associated with very low Ra-226 concentrations (near 1 pCi/g) becomes limited and the calibration curve can sometimes result in unrealistically low or even slightly negative values. The practical reporting limit for the method is believed to be about 1 pCi/g. Because this is about the average for local background soils, and because it is relatively uncommon for natural soils to have Ra-226 concentrations lower than this, all calculated estimates falling below 1 pCi/g will be assigned a value of 1 pCi/g.

Figure D4: Lead-shielded gamma counting well, NaI detector, and soil sample counting tins.

Past use of this gross-gamma screening technique has generally yielded reasonably good agreement with confirmatory analyses by HPGe gamma spectroscopy at a commercial laboratory. As the cleanup progresses, up to 10% of samples analyzed by this screening method will be sent to a commercial laboratory for confirmatory HPGe analysis. Paired analysis results for Ra-226 by both methods will periodically be added to the calibration data set to build a more robust statistical correlation and improve overall calibration accuracy.

For Th-230, analytical screening measurements, if used, will involve a calibration curve based on the statistical relationship between gross alpha and Th-230 concentrations in soil. An example of this relationship, developed in a recent study at the site (Cotter, 2011), is shown in Figure D5. Gross alpha measurements would be performed on all soil samples collected for screening during the cleanup according to Cotter Laboratory Procedure SOP 5-2 (Cotter, 2006a). About 10% of these soil samples would also be analyzed for Th-230 according to Cotter Laboratory Procedure SOP 5-9 (Cotter, 2006b) or Cotter Laboratory Procedure SOP 2-200 (Cotter, 2011). The resulting Th-230/gross alpha calibration curve would be used to convert all gross alpha measurements into estimates of Th-230 concentration.

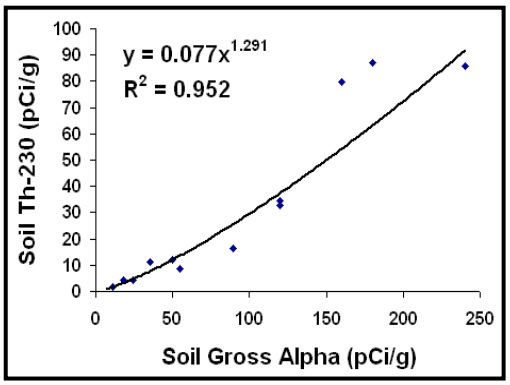


Figure D5: "Best fit" non-linear correlation between gross alpha and Th-230 measurements on 11 samples from the AS-210 study area.

The advantage of this screening technique is that Th-230 data can be generated more quickly than direct analysis, with less processing and analytical burden placed on the laboratory. Again, as the cleanup progresses, paired analysis results for gross alpha and Th-230 would periodically be added to the calibration data set to build a more robust statistical calibration curve.

Provided that sufficient resources are available, Cotter may also elect to conduct a screening program for U-nat based on XRF measurements. However, to produce reliable results with an XRF screening

program may be more complicated and time consuming than is warranted versus direct analysis by the Cotter Laboratory using newly acquired ICP-MS capability (Cotter, 2011). If ICP-MS analysis for U-nat is used to help guide the cleanup, and an approved ICP-MS based method for analysis of Th-230 can also be developed by Cotter, there would be no need for gross alpha screening because a single digestion and ICP-MS analysis would yield results for both U-nat and Th-230.

If at the end of the cleanup, any of the above screening techniques were used to support excavation control and can be demonstrated to have produced reliable results relative to confirmatory laboratory analyses, those techniques will be continued for analysis of all soil samples collected during final status surveys. Under this scenario, 10% of final status survey samples would also be directly analyzed by the Cotter Laboratory or by a certified commercial laboratory for verification purposes.

Gamma Surveys

Advanced GPS-based gamma scanning systems with automated electronic data collection have become widely used in the field for radiological assessments (Meyer et al., 2005a; Meyer et al., 2005b; Johnson et al., 2005; Whicker et al., 2008). These systems are consistent with radiological survey guidelines outlined in MARSSIM (NRC, 2000). Associated methods for application of this technology have been refined to meet various analytical objectives and regulatory requirements (Whicker et al., 2008).

Final status surveys at the Canon City Milling Facility are expected to utilize modern gamma survey systems comprised of GPS receivers, NaI-based gamma detection equipment, and computers with automated data collection and mapping software packages. These systems will be mounted on all terrain vehicles or backpacks for performing detailed final status gamma surveys within each survey unit. Up to 60 individual gamma readings and corresponding GPS measurements will be recorded per minute providing a detailed record of gamma exposure rate conditions across the survey unit.

Gamma detectors will be unshielded and positioned at about 3 feet above the ground surface. Based on past observations and experience in the field with 2” x 2” NaI detectors, lateral detector response to significantly elevated planar (non-point) gamma sources at the ground surface is estimated to be about 5 meters, giving each detector an estimated “field of view” of about 10 meters in diameter at the ground surface. This does not imply a system detector can resolve gamma readings from a small area of elevated source material 5 meters away, but does indicate that scattered photons from larger elevated source areas (e.g. 100 m^2) can be detected at that distance.

Within this conceptual framework, the effective survey track width for each scanning detector is estimated to be about 10 meters across, perpendicular to the direction of travel. If an all terrain vehicle is mounted with several detectors (Figure D6), the effective scan track width for a single pass can be significantly increased. Target scanning coverage will be 100% (approximately 10 meters between adjacent scan tracks for a single detector system), though practical considerations such as safety, terrain, and natural obstructions and other factors may dictate actual distances maintained between adjacent scan tracks. Scanning speeds will range up to 5 mph depending on the type of survey

Figure D6: Example of multiple NaI detectors mounted on an ATV for gamma surveys. Detector heights can be optimized to accommodate project objectives yet minimize access limitations due to rough terrain or tall vegetation.

(vehicle or backpack mounted) and roughness of terrain. Given that readings are recorded every 1-2 seconds, distance between adjacent scan tracks is more important than scanning speed in terms of effective scan coverage.

Based on previous qualitative assessments in the field, the minimum detectable concentration (MDC) of above background Ra-226 in surface soils that can be resolved with 2" x 2" NaI detectors at a height of 3 feet above the ground surface (i.e. the "scan MDC") is estimated to be 2-3 pCi/g from an area as small as 4 m^2. This qualitative field estimate is consistent with a corresponding scan MDC value cited in MARSSIM and COMPASS guidance documents (2.8 pCi/g).

As the size of the contaminated area increases, more scattered photons will reach the detector and the effective scan MDC will be lowered somewhat, improving system sensitivity to elevated activity concentrations both directly below the detector and in adjacent locations. Regardless of the size of contaminated area, scan MDC is ultimately limited by the relative amounts of background cosmic and terrestrial gamma radiation present, combined with the energy dependence of NaI detectors. Cosmic radiation will dominate detector response until terrestrial sources become concentrated enough to have a significant correlative impact on readings (Whicker et al., 2008). Because the cleanup criterion for Ra-226 is nearly twice the expected scan MDC, these systems will be effective for evaluating general compliance, as well as any "hot spots" significant enough to exceed applicable $DCGL_{EMC}$ criteria.

Gamma / Soil Ra-226 Correlations

Although soil cleanup criteria are based in principle on dose considerations, compliance is determined exclusively from radionuclide concentrations in soil. Once respective final status survey information is known, external doses are modeled based on soil sampling results and gamma exposure rate data is not directly used to evaluate compliance with dose limits. Nevertheless, gamma surveys are critical for final status surveys as they provide direct indications of Ra-226 in surface soils and can produce a very high density of measurements across extensive areas in a short amount of time.

Gamma surveys provide evidence of compliance with soil Ra-226 cleanup criteria in areas falling in between direct soil sampling locations. To enable such assessments, statistical correlations between gamma survey data and Ra-226 concentrations in surface soils are widely utilized and are consistent with the regulatory guidance. Correlations are variable depending on radiological conditions and thus must be site specific. As previously discussed, several gamma/soil Ra-226 correlations for the site have already been developed (Figure C1) and a statistical gamma cut off value (23 µR/hr) will be used to guide excavations for compliance with the soil Ra-226 criterion (5 pCi/g above background). This gamma cutoff value (i.e. guideline level) is based on upper prediction limits applied to the previous correlations and thus provides a high statistical probability (80-95%) of compliance.

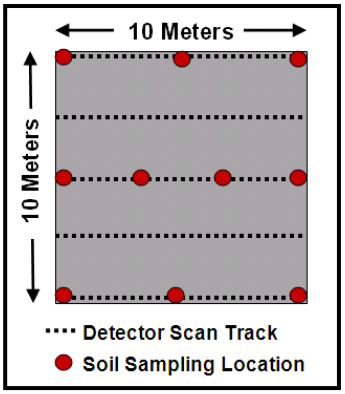


Figure D7: Gamma / soil Ra-226 correlation plot soil sampling and gamma scan design.

Existing gamma/soil Ra-226 correlations were developed by selecting a series of 100 m^2 plots representative of a range of values most relevant to radiological assessment objectives. The correlation plot measurement and sampling design is shown in Figure D7. The mean Ra-226 concentration from 10 individual soil samples collected across each correlation plot was paired with the corresponding mean gamma scan reading for the plot. Paired average gamma/Ra-226 values from

up to 10 different correlation plots were then analyzed by linear regression to generate a predictive regression equation. Upper prediction limits on the regression were also calculated in order to enable probabilistic assessments including identification of the gamma guideline level for compliance with the soil Ra-226 cleanup criterion.

Once the soil cleanup has been completed, development of a new gamma/soil Ra-226 correlation in advance of the final status survey is unlikely to be a realistic option because a statistically significant correlation requires a relatively wide range of Ra-226 concentrations among the various correlation plots. Such conditions are unlikely to be present once soil cleanup across the site has been completed.

Data Quality Assurance / Quality Control

Quality assurance and quality control (QA/QC) for radiological data generated during final status surveys will be ensured as described in this section. In general, quality assurance includes qualitative factors that provide confidence in the results, while quality control includes quantitative evidence that enables estimation of data uncertainty (i.e. accuracy and precision).

Laboratory Analysis QA/QC

The Quality Assurance Program Plan (QAPP) for the Cotter Laboratory was updated and approved by CDPHE in 2009 (Cotter, 2009). The QAPP includes policies and procedures followed by the Cotter Laboratory in order to achieve specific performance criteria which can be summarized as follows:

1. The total uncertainty in analytical data associated with measurement accuracy and precision for each specific analyte and corresponding batch of sample analyses will be kept to within ± 32%.
2. The total percentage of qualified (flagged) data for each batch of laboratory analyses will be kept to less than 10%.
3. The percentage of quality control measurements for each specific analyte and corresponding batch of sample analyses will be no less than 10%.
4. Data completeness will be maintained at better than 99%.
5. Regular and systematic independent laboratory performance evaluations will be performed.
6. Document that field sampling and monitoring programs and projects are conducted according to written plans and that provisions for data QA/QC are included.
7. Detection limit requirements will be met for 98% of measurements for each specific analyte and corresponding batch of sample analyses.
8. Provide a reporting system for sharing and tracking measurement results, quality issues, performance evaluations, problems, and corrective actions.
9. Provide a documented verification that ALARA principles are considered in implementing the QAPP.

For any samples sent to outside commercial laboratories for analysis, the lab used will be certified by a nationally recognized and State approved laboratory accreditation program such as NELAP. All results will be reviewed for QA/QC indicators such as duplicate analyses and matrix spikes.

Soil Sampling QA/QC

Field sampling and measurement protocols will be conducted in accordance with Cotter sampling Procedure EV-110 (Cotter, 2009) and will adhere to all specified QA/QC provisions. General QC

protocols from regulatory guidance documents such as MARSSIM will also be observed. Basic QA/QC provisions for soil sampling can be summarized as follows:

1. Field log books will be maintained to document field activities and observations, including date of sample collection, notes on conditions, particularly relevant or unusual observations, sampling station ID number, sampling depth, and GPS coordinates.
2. Standard equipment decontamination procedures will be followed to prevent cross contamination of soil samples between collections.
3. Proper sample containers and labeling protocols will be followed.
4. Procedures regarding sample submittals and chain-of-custody forms will be followed.

Documentation of information generated by the above soil sampling protocols will be maintained in a project hard copy file and will also be converted into electronic format for archiving on Cotter servers.

Gamma Surveys QA/QC

The basis and specifics of the QA/QC program for gamma surveys are detailed as follows:

- All NaI detection instrumentation systems used to guide excavations, develop gamma/Ra-226 correlations, and perform final status surveys will be of the same make and model. Because Ludlum 44-10 detectors coupled with Ludlum 2350 rate meters were used for past characterization surveys and gamma/Ra-226 correlations, and past correlation information will be used for cleanup guidance and related assessments, the same instrument make and model will be used for final status surveys.

- Each day that gamma scanning data will be collected, instrument QC measurements will be performed at a designated indoor location for each NaI detector intended for use. This will quantify the consistency of readings within and between detectors under controlled measurement conditions prior to scanning. The mean of 10-20 individual QC measurements of ambient background, as well as from a Cs-137 check source, will be determined indoors under identical counting geometries and recorded on corresponding QC control charts. Under these conditions, all data from any given set of properly calibrated and correctly functioning NaI scanning detectors should approximate a normal (Gaussian) distribution (Figure D8).

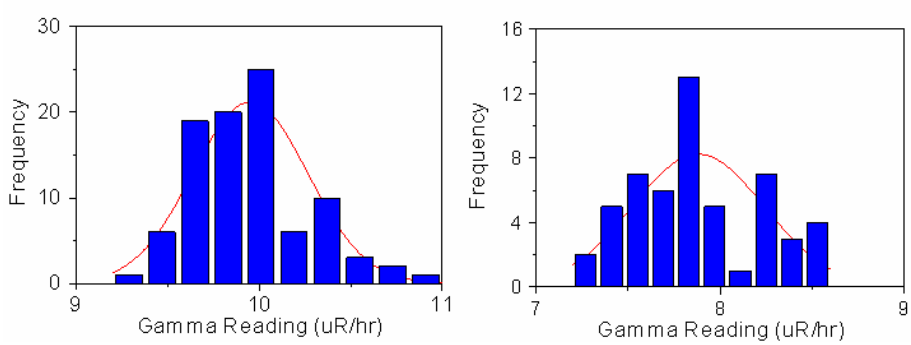


Figure D8: Example frequency histograms for two series of QC measurements from different NaI detector sets used for two separate gamma survey projects. Each series was taken indoors under controlled measurement geometries. The red lines represent theoretical normal distributions.

For normally distributed data, over 99% of measurements are expected to fall within ± 3 standard deviations from the mean. Any instrument with a QC measurement result falling outside ± 3 standard deviations from the mean of all QC measurements on both background and check-source control charts (Figure D9) will be sent back to the manufacturer for repair and recalibration prior to use. All detectors used for final status survey activities must meet these QC criteria.

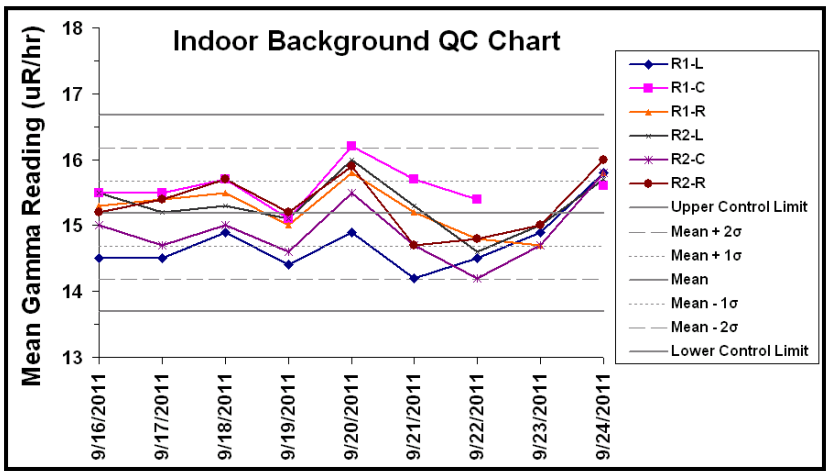


Figure D9: Example of daily indoor background instrument QC chart.

- Each day that the gamma scanning systems are to be used in during final status surveys, actual scanning performance will also be tested outdoors along a designated "field strip". The length of the field strip will be in the range of 25-50 meters along an unpaved area with relatively uniform gamma readings near background levels. This is appropriate as near background levels are expected in final status survey units. Field strip QC control charts will be developed at the beginning of the project and will be updated periodically as the project progresses in order to continuously monitor and assess gamma scanning system performance on a daily basis (Figure D10). Under actual field conditions, each scanning system must perform within acceptable field strip QC limits (within ± 3 standard deviations from the mean of all measurements) for the data to be included as valid, official final status survey results.

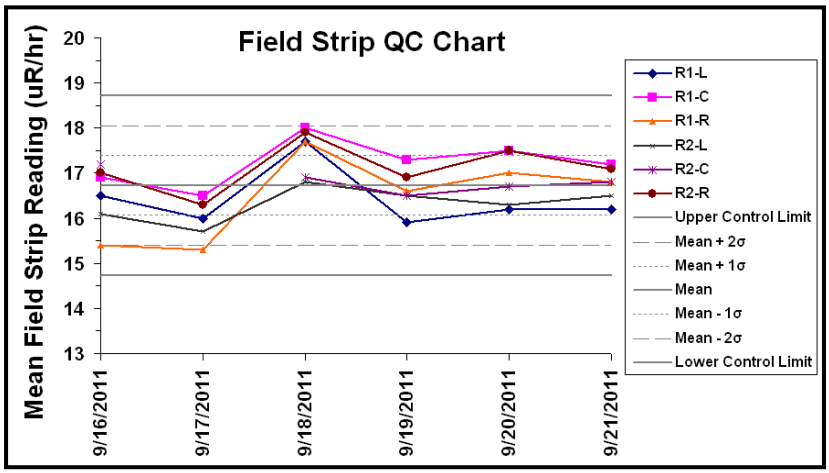


Figure D10: Example of daily field strip QC chart to continuously monitor and track scanning system performance under actual field conditions.

- All detectors used for gamma scanning will be calibrated by the manufacturer within one year prior to the date of use for final status surveys.
- A field log book of daily measurements, activities and problems related to gamma surveys will be maintained and made available for final status survey assessments.
- Daily scan results will be plotted on site maps and reviewed daily for consistency along adjacent track paths. Obvious inconsistencies will prompt further investigation and in cases where technical problems are discovered, or where the data were otherwise clearly incorrect, the affected data will be eliminated from the project database and the scan system equipment will be taken out of service pending thorough evaluation and resolution of any problems discovered. Daily scan map updates will also be used to assess the adequacy of scan coverage as surveys progress.

References

Cotter Corporation. 2006a. Procedure 5-2: Gross Alpha and Beta measurements of Soil, Water, and Other Matrices. 11/26/06.

Cotter Corporation. 2006b. Procedure 5-9: Radiochemical Procedure for Radium-226/224, Isotopic Thorium, Isotopic Uranium, Polonium-210 and Lead-210. 12/7/06.

Cotter Corporation. 2009. Procedure EV-110: Soil Sampling. 5/11/09.

Cotter Corporation. 2009. Quality assurance program plan for environmental sampling and monitoring studies for the Cotter Corporation Canon City Milling Facility and Lincoln Park, Colorado Superfund Site. May22, 2009. Approved by CDPHE August, 6, 2009.

Cotter Corporation. 2011. Radiological survey and dose assessment for Cotter property near air particulate monitoring station AS-210. March 11, 2011.

Cotter Laboratory Procedure 2-200. 2011. Inductively Coupled Plasma Mass Spectroscopy. (Currently under development, CDPHE approval anticipated in 2011).

Johnson, J.A. Meyer, H.R., and Vidyasagar, M. 2006. Characterization of Surface Soils at a Former Uranium Mill. Operational Radiation Safety. Supplement to Health Physics, Vol. 90, February, 2006.

Meyer, R.; Shields, M.; Green, S. 2005a. A GPS-based system for preliminary or remedial action gamma scanning. American Nuclear Society Topical Meeting on Decommissioning, Decontamination, & Reutilization. Denver, Colorado, August 7-11, 2005.

Meyer, R.; Shields, M.; Green, S.; Johnson, J. 2005b. A GPS-based system for radium/uranium contamination gamma scanning. Uranium Mining and Hydrogeology IV. Broder J. Merkel, Andrea Hasche-Berger (Editors). Uranium in the Environment, conference proceedings, Freiberg, September 2005.

ORAU/ORISE (Oak Ridge Associated Universities / Oak Ridge Institute for Sciences and Education). 2001. COMPASS code, Version 1.0., developed under the sponsorship of the U.S.. Nuclear Regulatory

Commission for implementation of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) in support of the decommissioning license termination rule (10 CFR Part 20, Subpart E).

U.S. Nuclear Regulatory Commission (NRC). 2000. Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Revision 1. NUREG 1575. Washington, D.C.

Whicker, R.; Whicker, M.; Johnson, J.; and Meyer, H. 2006. Mobile Soils Lab: On-site Radiological Analysis Supporting Remedial Activities. Health Physics. Operational Radiation Safety. 91(2) Supplement 1:S24-S31, August.

Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 2008

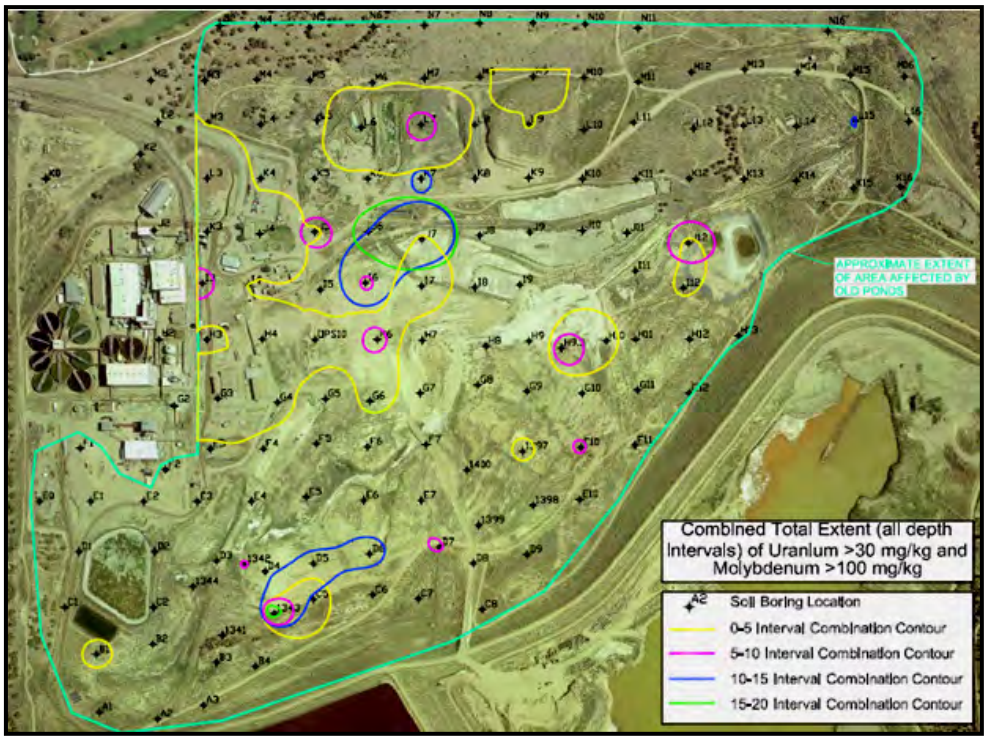
Appendix A

Radiological Characterizations for Soil Cleanup and Final Status Survey Planning: Relevant Data from Past Studies

Appendix A, Section 1:

1992/1994 OPA Drilling Program Locations and Results (Cotter/CDPHE/EPA, 1995; EMS, 2005)

1992/1994 OPA drilling locations for characterization of spatial distributions of uranium and molybdenum.



Areas and soil depths expected to require cleanup based on OPA drilling program results.

Appendix A, Section 2:

1995 Background Soil and Sediment Study Results from TQEM Report (Cotter/CDPHE/EPA, 1995)

SOILS

Basin	Sampling Site	U-nat (mg/kg)	U-nat (pCi/g)	Ra-226 (pCi/g)	Th-230 (pCi/g)
Chandler	48	2.4	1.6	1.6	2.3
	28	2.4	1.6	1.6	2.2
	99	2.3	1.6	1.6	2.1
	710	2.4	1.6	1.6	1.9
Fawn Hollow	17	2.0	1.4	1.3	2.7
	46	1.6	1.1	2.0	3.6
	41	2.5	1.7	1.7	2.6
	210	2.4	1.6	1.4	2.8
East Coal Creek	23	1.6	1.1	0.9	1.2
	74	1.7	1.2	1.0	1.3
	37	1.7	1.2	0.9	1.0
	51	2.0	1.4	1.1	0.9
Caldirola No. 1 Mine	104	1.3	0.9	1.1	1.7
	66	2.4	1.6	1.3	1.6
	38	2.1	1.4	1.1	1.9
	56	2.3	1.6	1.1	1.7
Oak Creek North	26	2.4	1.6	1.0	1.3
	48	1.6	1.1	0.9	1.1
	44	2.1	1.4	0.9	0.9
	92	2.4	1.6	1.1	1.3
	Mean	2.1	1.4	1.3	1.8
	Std. Dev.	0.4	0.3	0.3	0.7

*Adapted from Table DG2, TQEM Report, Volume 2 (Cotter/CDPHE/EPA, 1995)

SEDIMENTS

Basin	Sampling Site	U-nat (mg/kg)	U-nat (pCi/g)	Ra-226 (pCi/g)	Th-230 (pCi/g)
Chandler	13	2.9	2.0	1.6	2.3
	12	3.2	2.2	1.6	2.3
	91	2.2	1.5	1.6	3.0
	92	2.2	1.5	1.6	3.0
Fawn Hollow	19	1.6	1.1	1.0	1.5
	41	1.8	1.2	1.2	2.4
	59	2.6	1.8	1.6	2.3
	68	2.4	1.6	1.4	2.2
East Coal Creek	12	1.4	0.9	0.6	0.7
	19	1.5	1.0	0.7	0.7
	28	1.5	1.0	0.6	0.9
	45	1.5	1.0	0.6	0.9
Caldirola No. 1 Mine	95	1.3	0.9	1.4	0.8
	48	0.8	0.5	0.6	0.6
	53	0.8	0.5	0.5	0.7
	20	1.2	0.8	0.7	1.0
Oak Creek North	42	2.6	1.8	1.2	1.3
	33	2.6	1.8	1.2	1.4
	12	0.0	0.0	1.0	1.4
	75	2.2	1.5	0.8	1.3
	Mean	1.8	1.2	1.1	1.5
	Std. Dev.	0.8	0.5	0.4	0.8

*Adapted from Table DG2, TQEM Report, Volume 2 (Cotter/CDPHE/EPA, 1995)

TQEM Report, Volume 2, **Decommissioning Team** DG-28

PROJECT MANAGEMENT REPORT FORM

KEY DECISION DG: **Set how to determine which soils stay/go**

ELEMENT DG7: **Estimate volume of soil to be removed**

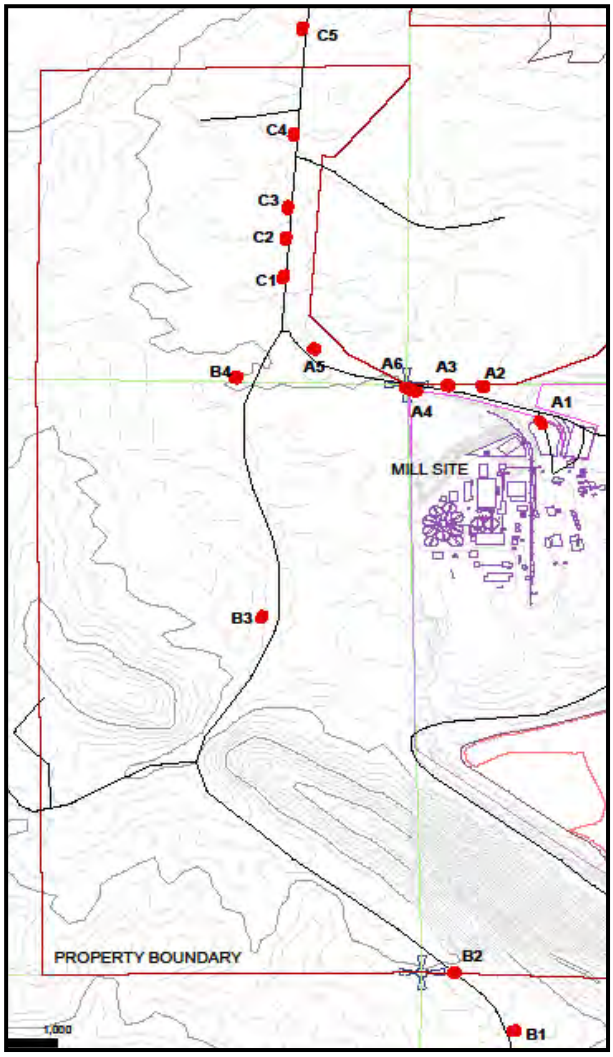
[X] action accomplished [ ] action underway
[ ] proposed action [ ] proposed specification

CONCLUSION/RESULT: Estimated total volume of open-area soils to be removed is 314,400 cubic yards.

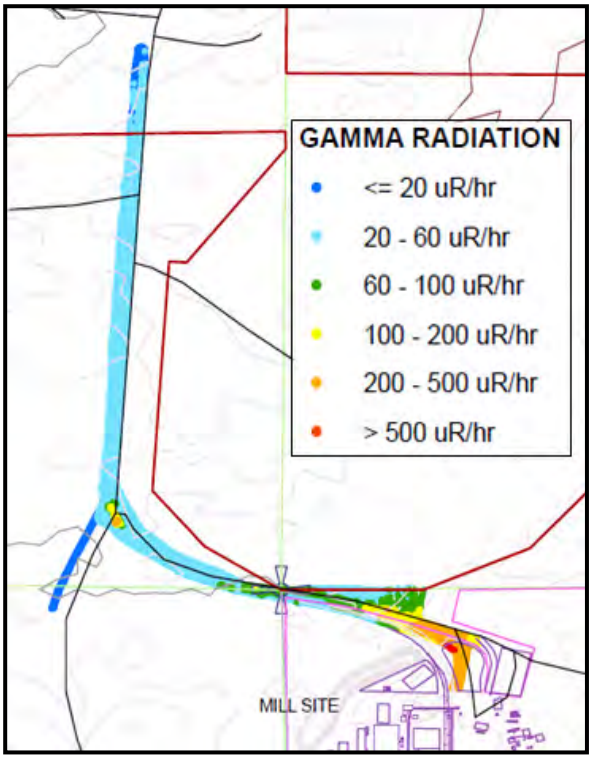
1. The **onsite soils** (within the restricted area boundary) estimate is 210 acres or 169,400 cubic yards.
2. The **offsite soils** estimate consists of
   a. soils immediately outside the restricted area boundary, estimated to be 163 acres or approximately 135,000 cubic yards, and
   b. soils and other material to be removed from Sand Creek, estimated at 10,000 cubic yards.

Appendix A, Section 3:

2005 Roadside Risk Assessment Study Locations and Radiological Results (MFG, 2005)



Soil sampling locations.



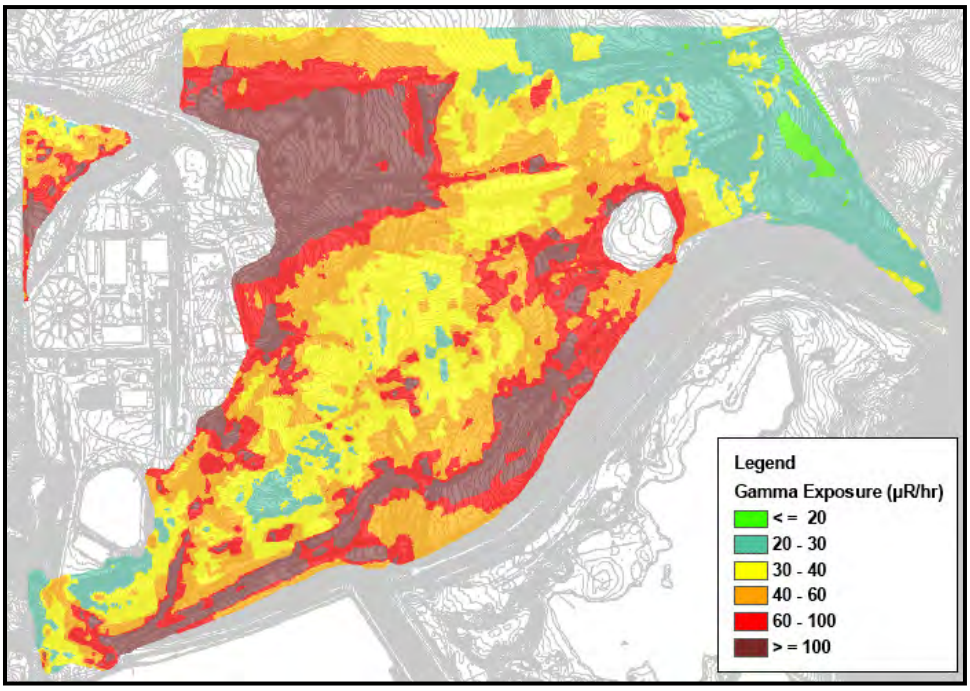
Gamma survey results.

Soil sampling results.

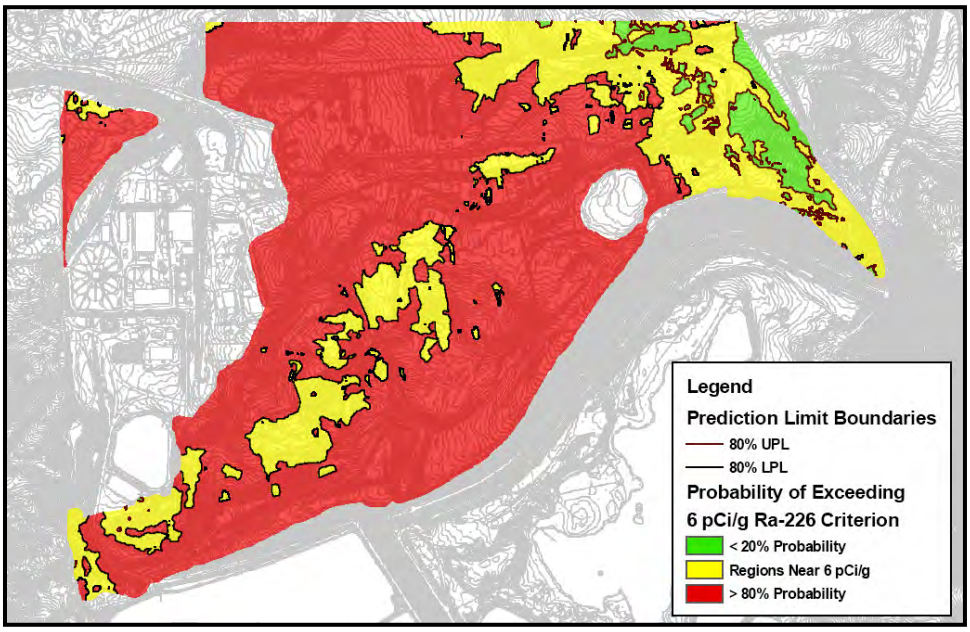
Location ID	U- nat mg/kg	U-nat pCi/g	Ra-226 pCi/g	Th-230 pCi/g
B1	1.19	0.81	0.8	0.2
B2	1.18	0.80	1.2	ND
B3	1.36	0.92	1.6	2
B4	2.55	1.73	2.1	2.4
B5	3.05	2.06	1.4	ND
C1	12.9	8.73	7.7	24
C2	29.2	19.77	14	22
C3	12.4	8.39	7.1	21
C4	8.39	5.68	5.8	25
C5	5.28	3.57	3.8	9.7
A6	6.64	4.50	6.8	29
A5	4.31	2.92	2.7	10
A4	5.62	3.80	6.6	21
A3	15.5	10.49	12	43
A2	10.9	7.38	8.1	21
A1	922	624	351	395

Appendix A, Section 4:

2007 OPA Gamma Survey and Surface Soil Ra-226 Characterization Results (Tetra Tech, 2007)



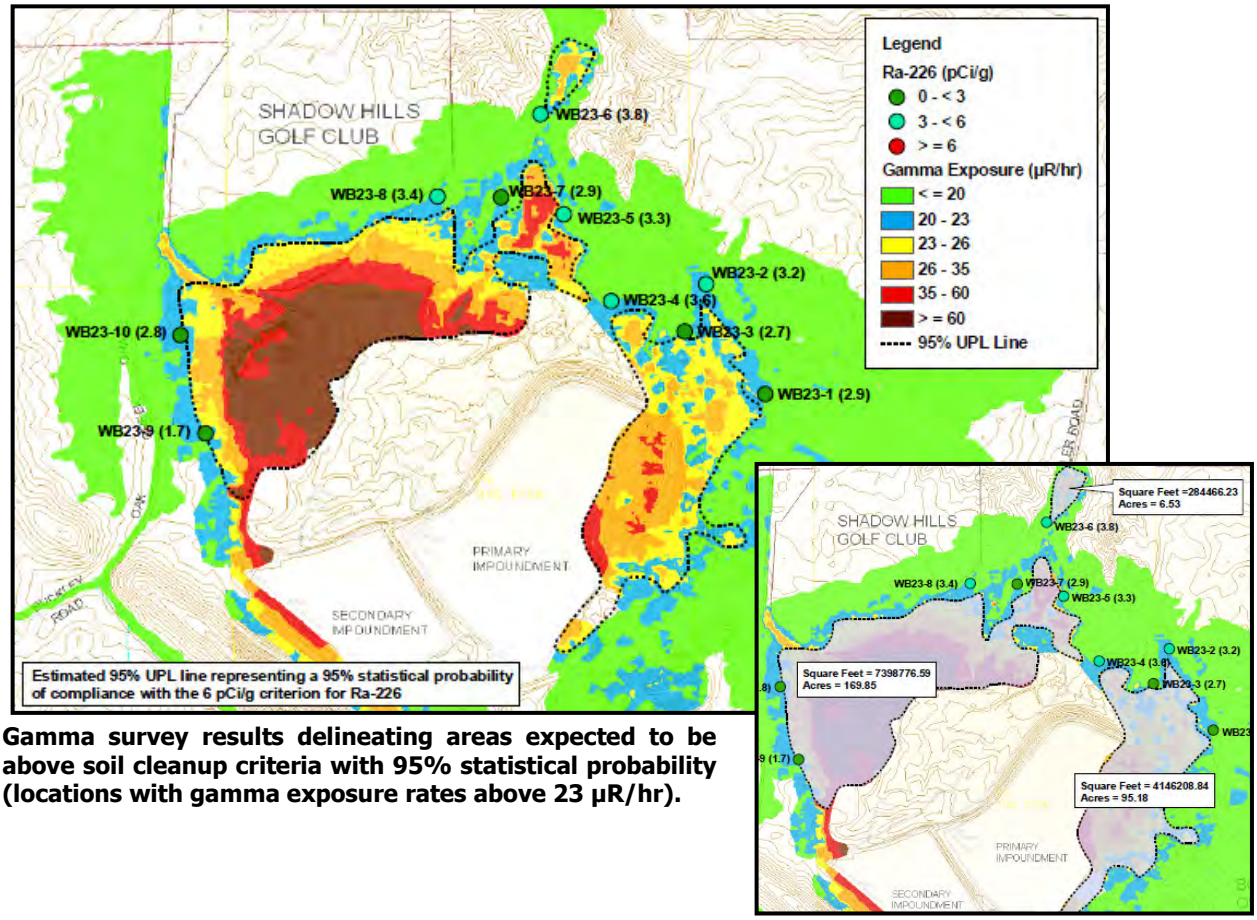
2007 OPA gamma survey results, prior to the U/Mo soil cleanup by Stoller.



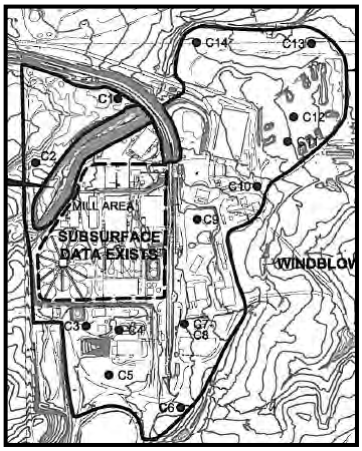
Probability map of Ra-226 concentrations in surface soils in excess of cleanup criteria, prior to the U/Mo soil cleanup by Stoller.

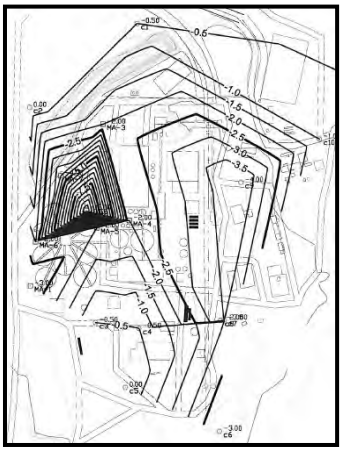
Appendix A, Section 5:

2007 Soil Volume Cleanup Estimation Study Results (Tetra Tech, 2008)



Gamma survey results delineating areas expected to be above soil cleanup criteria with 95% statistical probability (locations with gamma exposure rates above 23 µR/hr).





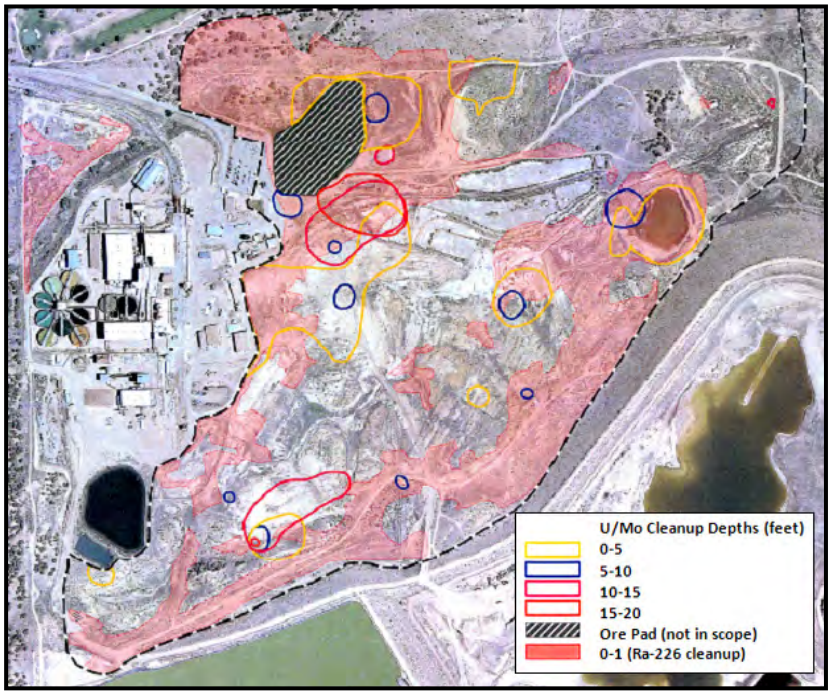
Additional soil drilling and depth profile sampling locations and resulting subsurface volume plot for contaminated soils in mill facilities areas.

Volumes of soil by area expected to require remediation.

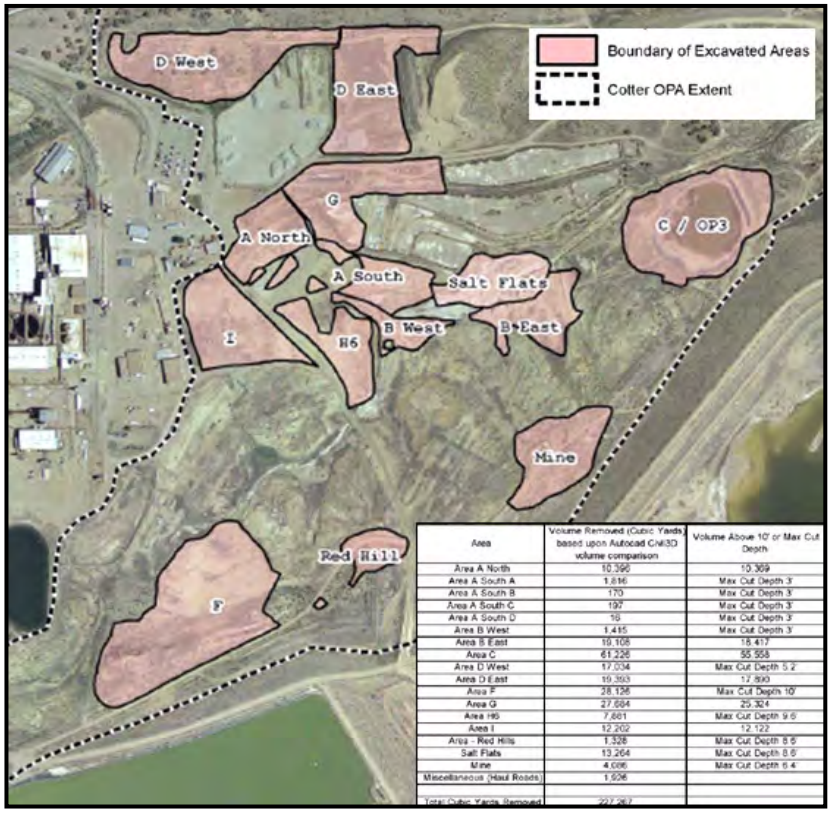
	Region	CY
Surface (0-6")	West	137,000
	East	77,100
	North	5,190
Total surface		219,290
Subsurface (below 6")	West	87,100
	North	5,190
Total subsurface		92,290
Total contaminated		**311,580**

Appendix A, Section 6:

2008 S. M. Stoller Report on Results of Additional Cleanup of the OPA (Stoller, 2008)



Anticipated extent and depth of soils requiring excavation in the OPA prior to the Stoller U/Mo soil cleanup effort.



Area	Volume Removed (Cubic Yards based upon Autocad Civil3D volume comparison	Volume Above 10' or Max Cut Depth
Area A North	10,396	10,309
Area A South A	1,816	Max Cut Depth 3'
Area A South B	170	Max Cut Depth 3'
Area A South C	197	Max Cut Depth 3'
Area A South D	16	Max Cut Depth 3'
Area B West	1,415	Max Cut Depth 3'
Area B East	19,108	18,417
Area C	61,226	55,558
Area D West	17,034	Max Cut Depth 5.2'
Area D East	19,393	17,890
Area F	28,126	Max Cut Depth 10'
Area G	27,684	25,324
Area H6	7,661	Max Cut Depth 9.6'
Area I	12,202	12,122
Area - Red Hills	1,328	Max Cut Depth 8.6'
Salt Flats	13,264	Max Cut Depth 8.6'
Mine	4,006	Max Cut Depth 6.4'
Miscellaneous (Haul Roads)	1,926	
Total Cubic Yards Removed	221,267	

Horizontal extent, volumes, and cut depth information for of soils excavated in the OPA by Stoller in 2007/2008. Cleanup goals with respect to U-nat and molybdenum were achieved in these areas.

Appendix A, Section 7:

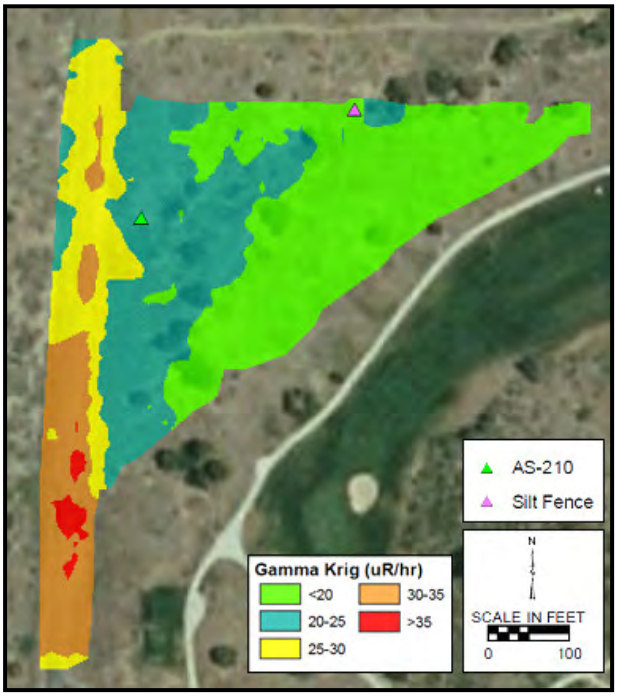
2009 Cotter Report with Pre- and Post Cleanup Gamma Survey Results (Cotter, 2009)

Gamma exposure rates along the mill access road prior to a partial, interim soil cleanup in this area in 2006.

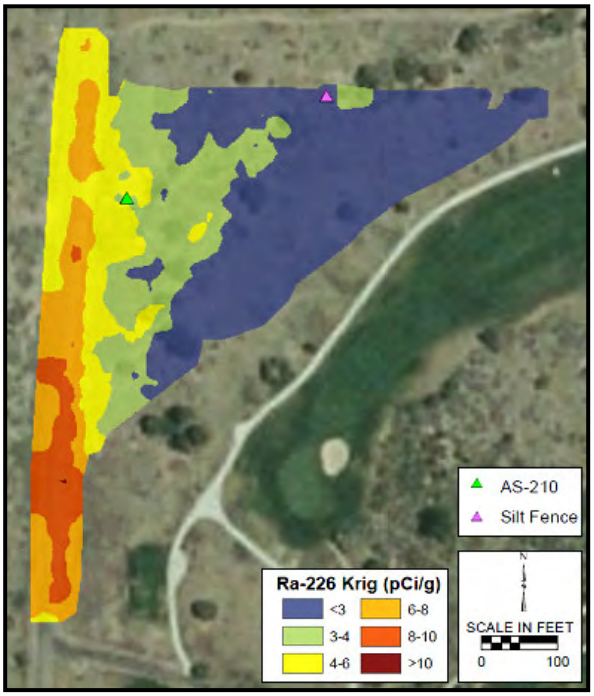
Current gamma exposure rates along the mill access road (surveyed after the partial, interim soil cleanup in this area in 2006).

Appendix A, Section 8:

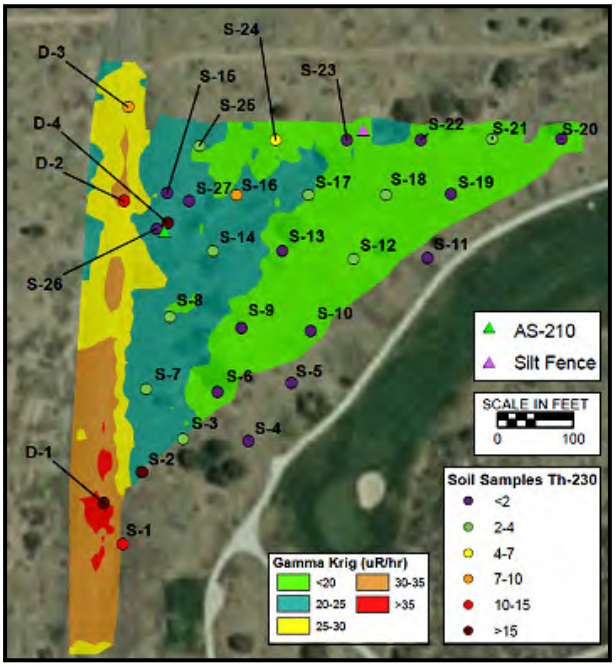
2010 Radiological Survey Data for of Areas near Air Monitoring Station AS-210 (Cotter, 2011)



Gamma exposure rates in the vicinity of AS-210.

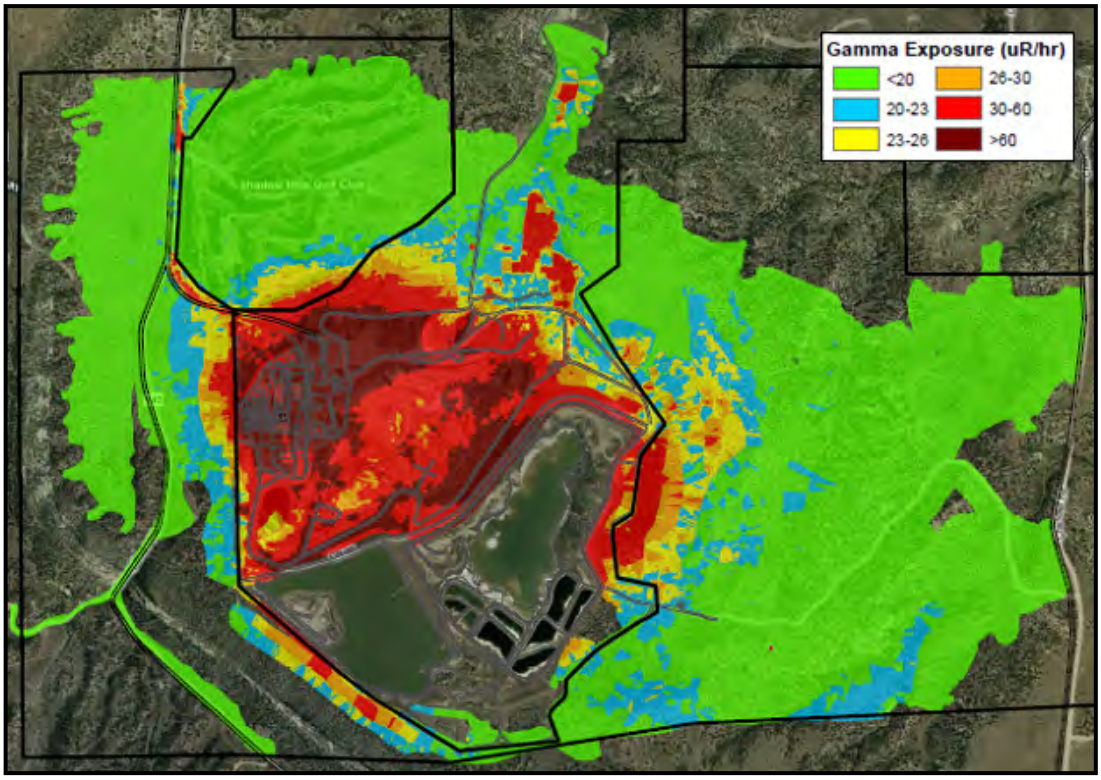
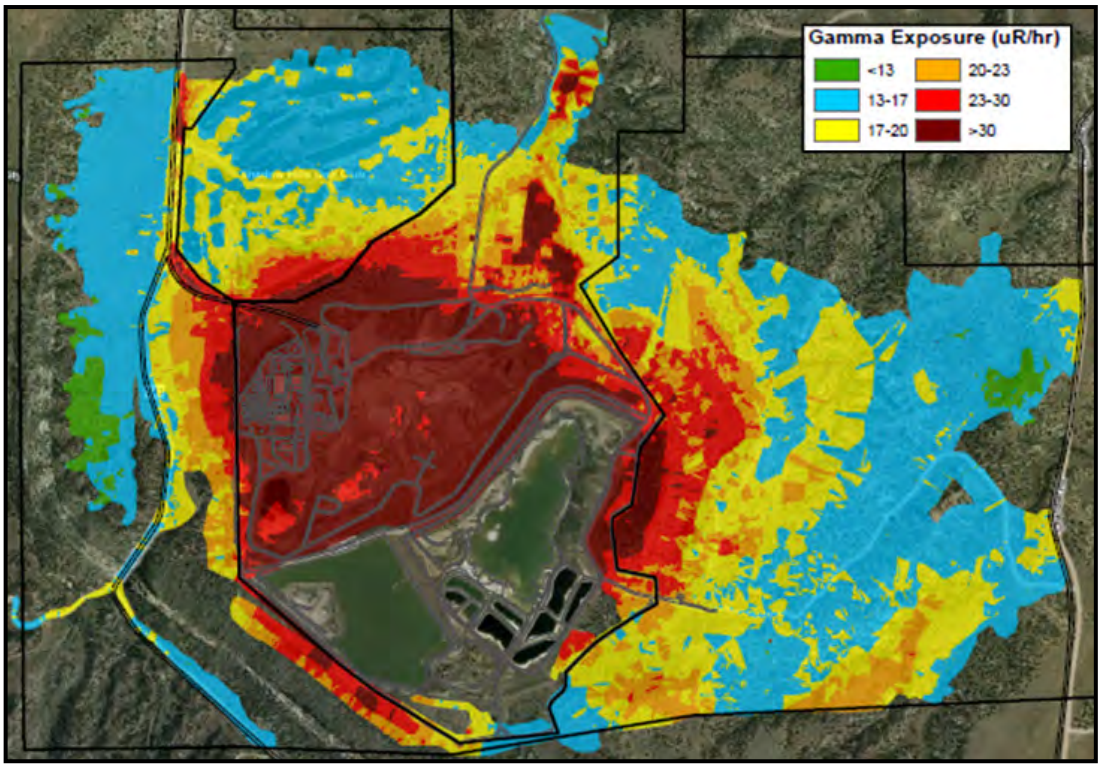


Estimated Ra-226 concentrations in surface soils in the vicinity of AS-210 based on gamma survey data.



Color-coded Th-230 concentrations in surface soils plotted on the gamma survey map.

Photo of the soil depth profile underlying the County Road showing distinct layers, including a 2-inch subsurface layer of black material believed to be responsible for elevated radionuclides in the area. The evidence indicates that this material is was imported to serve as road bed material and is not related to historic operations at the mill site.

<u>Appendix A, Section 9</u>:

Current master compilation and kriged renderings of all gamma exposure rate survey measurements collected across the site.