POTENTIAL RADIUM-226 AND THORIUM REMEDIAL ACTION STANDARDS FOR THE WELDON SPRING SITE

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ABSTRACT

The 5 pCi/g cleanup standard (1,2) will not achieve a risk within the EPA CERCLA guidance range of 10^{-4} to 10^{-6}, given a resident farmer exposure scenario and an assumed 70 year exposure time following site remediation. In fact, Ra-226 concentrations above a mere 1 pCi/g will give a total risk greater than 10^{-4}. Given this reality, is the 5 pCi/g Ra-226 cleanup standard as low as reasonably achievable (ALARA)?

This paper shows the relationship between differing Ra-226 cleanup concentrations and the resultant excavation volumes, costs, and total risk. Results reveal that excavation volumes and costs increase exponentially below an Ra-226 concentration of 3 pCi/g due in part to inclusion of soils containing natural background concentrations of Ra-226. Risk reduction for these Ra-226 concentrations, however, is linear. A linear range of both excavation volume and total risk is evidenced for Ra-226 concentrations in the range of 4 to 7 pCi/g, showing that the 5 pCi/g cleanup guideline is indeed ALARA.

INTRODUCTION

The objective of the effort discussed in this paper was to provide technical support information useful for evaluating potential radium and thorium remedial action standards for the Weldon Spring site (WSS), where cleanup of a former uranium and thorium processing facility is occurring in compliance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and the National Environmental Policy Act (NEPA). To evaluate potential cleanup standards, consideration was given to the Uranium Mill Tailings Radiation Control Act (UMTRCA) standard (1), DOE Order 5400.5 (2), and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (3). The scope of the effort included Ra-226 and its daughters, Th-230, and the Th-232 decay series. The UMTRCA standard states that Ra-226 concentrations may not exceed background by more than 5 pCi/g in the first 15 cm (6 in.) layer of soil, or by more than 15 pCi/g in each successive 15 cm layer below. U.S. Department of Energy (DOE) Order 5400.5 applies this standard to radium and thorium, and states that in implementing this standard, doses must be maintained as low as reasonably achievable (ALARA). For the WSS, UMTRCA may be an applicable or relevant and appropriate requirement (ARAR) and DOE Order 5400.5 is a requirement that is to be considered (TBC). The CERCLA requires that these regulations, in conjunction with a site-specific risk assessment, be factored into a final decision on the cleanup standard used at the WSS. NCP guidance identifies a post-remediation target risk range of 10^{-6} to 10^{-4} above background. Therefore, in evaluating potential site-specific cleanup standards for radium and thorium, two questions had to be answered: (1) Do the UMTRCA standard and DOE Order 5400.5 regulations meet site-specific ALARA objectives? (2) Is it feasible to meet the target risk range of 10^{-6} to 10^{-4}? The methods used to answer these questions and provide information to propose remedial action standards are presented and discussed.

SURFACE REMEDIAL ACTION STANDARD FOR Ra-226

DOE Order 5400.5 and the Uranium Mill Tailings Radiation Control Act (UMTRCA) limit Ra-226 concentrations in the first 15 cm of soil to 5 pCi/g above background, averaged over 100 m^2 areas. In order to determine whether this standard meets as low as reasonably achievable (ALARA) objectives, consideration must be given to the errors inherent in sampling 100 m^2 areas, sample analysis, and decision making during remedial action. In addition, a risk assessment must be performed to determine whether a combination of good practice and reasonable investments can significantly reduce risks. Since the cleanup standard for the site was not known a priori, reference cleanup criteria, or action levels, were selected for the purpose of investigation. The action levels ranged from twice background to approximately 5 pCi/g plus background*. Action levels above 5 pCi/g, including background, were not investigated because the UMTRCA standard was presumed to be an accepted standard not to be exceeded. The methods used to address each of these issues are discussed in the following two subsections.

Soil Sampling Error

Following remediation, every area must be tested to evaluate whether cleanup standards have been met. At the Weldon Springs site (WSS), the Project Management Contractor (PMC) has typically done this by collecting a single composite sample from 10 to 20 individual locations within a 100 m^2 area (4). The error associated with such testing can lead to two problems: first, it could be falsely concluded that a clean area needs further remediation (false positive or Type I error); and second, it could be falsely concluded that a contaminated area is clean (false negative or Type II error). According to the central limit theorem of statistics, repeated composite sampling of a 100 m^2 area whose mean exactly meets the cleanup standard would result in a normal distribution of composite means above and below the cleanup standard. With a large data set, it is easy to determine the mean of the sample results,

* At the beginning of this work an Ra-226 background concentration of 1.2 pCi/g was assumed (4); hence, 6.2 pCi/g was chosen as the highest value for investigation. The mean background concentration was later updated to 1.005 pCi/g, but the 6.2 pCi/g investigation value was retained.

and decide whether the cleanup standard has been met with statistically high power (one minus Type II error or the probability of correctly concluding that a clean area is clean and a contaminated area is contaminated) and confidence (one minus Type I error). In practice, however, extensive sampling is both costly and time consuming.

As a result, the decision to proceed with excavation or to declare an area to be clean is commonly based on the results of a single composite sample. Note that with this limited data set, there is much less confidence and power in the data and subsequent decision making, since the standard deviation of the data about the mean is not known. To make defensible decisions on the basis of limited sampling, it becomes necessary to choose a "decision level" concentration corresponding to the cleanup standard, where the decision level concentration is the highest soil concentration that can be tolerated if an area is to be declared clean with confidence and power. In order to determine the decision level associated with various different proposed action levels, a computer simulation was performed to estimate the standard deviation in composite sampling.

The computer simulations involved proposed action levels for Ra-226 only. The following assumptions were made in the programming:

- Soil concentrations at any given point in the field are lognormally distributed, as suggested in the literature (5,6,7).
- The program simulates composite sampling by averaging 20 random samples and performing 50 iterations.
- The mean Ra-226 concentration is approximately equal to the action level being investigated, but there are randomly distributed hot spots ranging up to 25 pCi/g. This upper value for hot spots was chosen because the PMC performs walkover surveys of remediated areas using conventional portable instruments which can easily detect small area locations exceeding 25 pCi/g of Ra-226.

The Statgraphics (8) random number generator was used to simulate lognormal distributions for each action level (2, 3, 4, 5, and 6.2 pCi/g). Input values for the mean and standard deviation were selected to result in lognormal distributions with means as close as possible to the related action levels and maximum values close to 25 (see Columns 1 through 3 of Table I). Each of the distributions was then randomly sampled 20 times. The average of the 20 samples was computed (corresponding to a composite sample result), and the process was repeated 50 times. The mean and standard deviation of the 50 iterations were calculated. This process was repeated for each of the five proposed action levels from 2 pCi/g to 6.2 pCi/g. The results are shown in columns 4 and 5 of Table I.

According to the above findings, for example, a single composite sample taken from a 100 m^2 area with a mean Ra-226 concentration that meets the 5 pCi/g action level could have a result ranging from 2.5 to 7.3 pCi/g (mean plus or minus 3.4 standard deviations or the 99.99% confidence limit). However, in order to have 95% confidence that the action level has been met with a limited data set (i.e., only a 5% probability of the single composite sample exceeding 5 pCi/g), it is necessary to choose a decision level about 1 pCi/g below the action level. In other words, the action level is the value we would potentially be committed to meet, whereas the decision level is the associated concentration we would try to achieve in the field to meet the action level. Hence, the decision level will be somewhat lower than the corresponding action level. To demonstrate this, recall that the probability that any given result falls in the range from x_1 to x_2 is defined by Eq. (1) (9), and corresponds to the area under the curve between x_1 and x_2, which is a fraction of one (see Fig. 1):

$$P(x_1 < R < x_2) = \frac{1}{\sqrt{2\pi\sigma}} \int_{x_2}^{x_1} e^{-(1/2)[(x-\mu)\sigma]^2} dx \qquad \text{(Eq. 1)}$$

Where:

μ = mean of distribution

σ = standard deviation of distribution

TABLE I

Results of Soil Sampling Error Analysis

Column 1 Action Level (pCi/g)	Column 2 Mean of Lognormal Distribution (pCi/g)	Column 3 Standard Deviation of LogNormal Distribution (pCi/g)	Column 4 Mean of Sample Distribution (pCi/g)	Column 5 Standard Deviation of Sample Distribution[a] (pCi/g)	Column 6 Decision Level (pCi/g)
6.2	6.2	3.1	6.2	0.7	5.0
5.0	4.8	2.9	4.9	0.7	3.8
4.0	3.9	3.0	3.7	0.6	2.8
3.0	2.9	2.7	2.9	0.7	1.8
2.0	1.9	2.6	1.9	0.6	0.7
				$\sigma = 0.7$	

[a] The standard deviations are approximately constant for all the action levels because all of the lognormal distributions have maximum values near 25, resulting in large values of the standard deviation. Any other trends that might normally be observed are therefore hidden.

Instead of evaluating the integral to find the probability, it is possible to transform variables and use tabulated values of the area under the transformed distribution, which has a mean of 0 and standard deviation equal to 1:

$$Let\ Z = (x-\mu)/\sigma \qquad \text{(Eq. 2)}$$

where x, μ, and σ are from the original distribution, and Z corresponds to the transformed value of x.

Then

$$P(x_1<R<x_2) = P(z_1<Z<z_2) = P(\frac{x_1-\mu}{\sigma}<Z<\frac{x_2-\mu}{\sigma})$$

Figure 2 shows the transformed function. Note that with a mean of zero and standard deviation of 1, the range of values of Z corresponds to the range of values normally associated with σ. In other words, the area under the curve for values of $-\sigma<Z<\sigma$ is 0.68, and the area under the curve for values of $-2\sigma<Z<2\sigma$ is 0.95. Tabulated values of the integrated, transformed function give the area under the curve , P(Z), to the left of Z. Thus, for Z=0, P(Z)=0.5, and for Z=3.4, P(Z) is approximately 1.

With this information, the problem can be readily solved. Given an action level, and the desire for 95% confidence (chosen for the WSS) that any individual composite sample result will be below that action level, the mean concentration of the sampled area can be determined. Figure 3 shows the action level, AL. Note that the mean concentration corresponds to the decision level, DL. The critical value associated with 0.05 significance or 95% confidence is 1.65. Using Eq. (2):

$$1.65 = \frac{AL-DL}{\sigma}$$

From Table I, the average standard deviation found during the computer simulation of soil sampling was 0.7 pCi/g. Therefore, for the values analyzed in this assessment,

$$(1.65)\ (0.7) = AL-DL \qquad \text{(Eq. 3)}$$

$$DL = AL-1.2$$

In other words, the decision level for a given action level is about 1 pCi/g below the action level. Given a sample size of 50 iterations, a standard deviation of 0.7 pCi/g, and an action level-to-decision level difference of 1.2 pCi/g, the decision level is achieved with 95% confidence and greater than 90% power. Values of the power function are obtained from the normal curve probability distribution function for calculated values of the argument as follows (10):

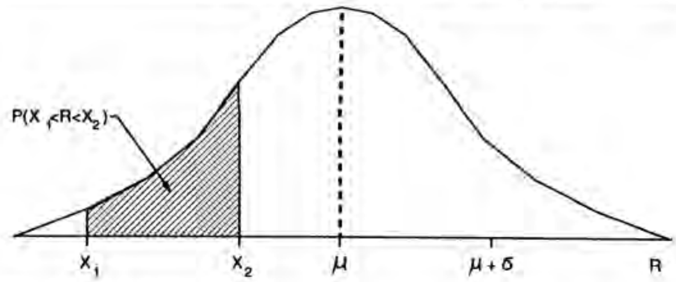

Fig. 1. Probability of volume between x_1 and x_2 for a normal distribution.

$$\Phi[Z_\alpha+(AL-DL)\frac{\sqrt{n}}{\sigma}]$$

where

Z_α = critical value for 95% confidence

n = 50

σ = 0.7

Φ = power function

The decision levels calculated from equation (3) are provided in column 6 of Table I. This ultimately means that in order to have 95% confidence that an excavated area at the WSS will meet the UMTRCA standard on the basis of limited composite sampling, the mean surface concentration of Ra-226 must not exceed approximately 4 pCi/g above background, instead of 5 pCi/g.

Risk Assessment

Volumes of soils contaminated with Ra-226 at the Weldon Spring site were estimated at selected action levels. The calculated volumes vs. action levels are provided in Table II. Disposal costs, which are approximately proportional to volume, were also computed and are listed in Table II. The values were based on 1991 costs for on-site excavation, disposal cell construction, and emplacement of wastes ($55.32/cy), and included $150.00/100 m^2 sampling costs.

A risk assessment was performed at each action level using the RESRAD computer code (11), which calculates doses for specified pathways resulting from residual radioactive materials in soil and water. For this application, RESRAD

TABLE II

Risk Assessment Results

Action Level pCi/g	Volume Above Action Level (cy)	Contaminated Area (ft^2)	Contaminated Area (m^2)	Decision Level (pCi/g)	Net Dose Rate (mrem/y)	Incremental Risk	Remediation Costs ($)	Fraction Of Soil At Background
6.2	7,100	195,000	18,000	5.0	141	2.5×10^{-3}	421,000	0[(a)]
5	8,200	252,000	23,400	3.8	120	2.2×10^{-3}	487,000	0[(a)]
4	9,800	308,000	28,600	2.8	101	1.8×10^{-3}	586,000	0[(a)]
3	12,800	444,000	41,300	1.8	84	1.5×10^{-3}	768,000	0.08
2	22,300	608,000	56,500	0.7	66	1.2×10^{-3}	1,320,000	0.49

[a] The theoretical analysis indicates that these distributions are completely different from background. However, it is expected that in any excavation, regardless of intitial concentration, some clean soils would be removed.

was used to estimate the risk that might be incurred by a farmer living on the remediated site. RESRAD assumptions for the site-specific ALARA assessment included the following:

- The post-remediation Ra-226 concentration is at the action level in the first 15 centimeters (6 in.) of soil below the surface, and at 2 pCi/g for the next 60 cm (2 ft.) interval below. This profile was chosen because soil contaminants at the Weldon Spring site are shallow (generally not more than 60 cm deep), and show a decreasing concentration gradient with depth. Therefore, post-remediation soils as high as the action level should be very shallow, and with few exceptions, residual Ra-226 concentrations in soils at depth are expected to be less than 2 pCi/g. Background concentrations of other uranium and thorium series radionuclides were assumed to be present (12, 13, 14).
- Site-specific parameters were used whenever possible, and included soil stratigraphy and properties, meteorological data, and hydrological data (15,16). Where measured values or estimates were not available, RESRAD default parameters were used. Inhalation rates and dietary parameters were taken from the U.S. Environmental Protection Agency (EPA) risk-assessment guidance (17). It was conservatively assumed that all water for drinking, irrigation, and livestock was from groundwater.
- Committed dose rates resulting from indoor radon concentrations were estimated from soil concentrations. Depths of above-background concentrations were taken to be the same as those previously specified for RESRAD, and weighted average concentrations, W, were computed over a 240 cm (8 ft.) depth, which corresponds to a typical basement depth. Committed dose rates (CDR) were then computed according to Eq. (4):

$$CDR = A \times \frac{16\,h}{d} \times \frac{365\,d}{y} \times \frac{1\,month}{170h} \times W(pCi/g) \times B \quad \text{(Eq. 4)}$$

TABLE III

Dose Rates From Indoor Radon

Action Level (pci/g)	Weighted Average Concentration, W (pCi/g)	Incremental Dose Rate[a] (mrem/y)
6.2	0.58	78
5	0.50	68
4	0.44	59
3	0.38	51
2	0.31	42

[a] - Incremental dose rate is the background-subtracted dose rate.

where

A = 0.0041 WL per pCi/g (18)

and

B = 1,000 mrem/y per WLM/y (19)

Results of the computation versus action level are provided in Table III.

The doses from background were subtracted from the results obtained from RESRAD. The radon doses determined from equation (4) were then added. The corresponding incremental risk was calculated on the basis of a 30-year lifetime exposure (17) to the doses (50-year committed effective dose equivalents) calculated above and a risk coefficient of 6×10^{-7} per mrem (20). Table II provides a summary of the risk assessment findings. Figure 2-5 is a plot of remediation costs and incremental risks versus action level. Note that excavation costs vs. action level are approximately linear from 4 pCi/g to 6.2 pCi/g, but are nonlinear (approaching exponential) for concentrations below 4 pCi/g. In the meantime, incremental risks are linear over the entire range, barely changing by a factor of two*. The escalation in cost, relative to risk, occurs at the lower action levels for two reasons. First, the areal extent of contamination increases. This occurs because

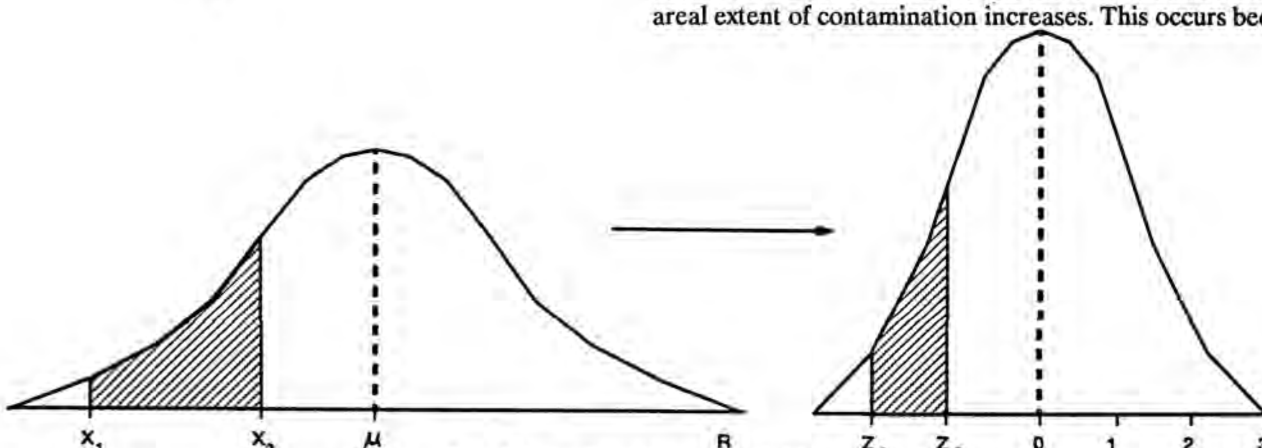

Fig. 2. Transformation of variables.

* Although the incremental risk is zero at 1 pCi/g, the line shown in Fig. 4 does not extrapolate to zero along the same slope. This is an artifact of the soil profile chosen to estimate residual risk; the contaminated soil profile is not uniform with depth, but the background soil profile is.

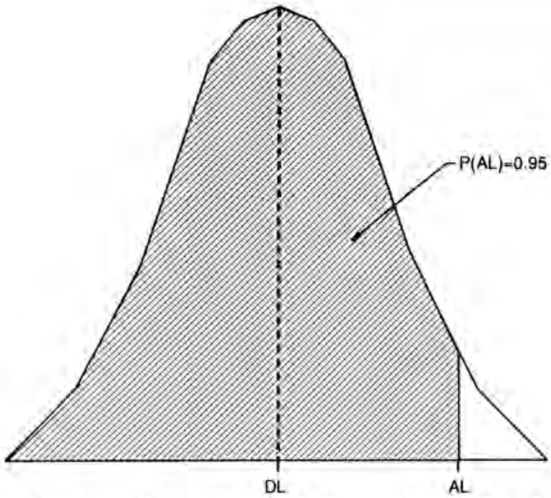

Fig. 3. Soil sampling error analysis: action level (AL) and decision level (DL).

soil concentrations surrounding some spills and dump sites decrease gradually with distance from the point of highest concentration, due to environmental transport. Also, sites that are below criteria at the higher action levels must be remediated at the lower action levels. Second, the escalation in cost at lower action levels occurs because some fraction of the excavation volume is background soil. Using the background Ra-226 distribution (1.005 ± 0.26 at 1 standard deviation), which was found to be normally distributed, and the sample error analysis results provided in Table I, it is possible to estimate the background fraction using transformation of variables and Eq. (2). Figure 5 shows the overlapping distributions.

The endpoints of the region where the distributions overlap occur at x_1 and x_2, which can be rewritten in general as*:

$$x_1 = \mu_B + 3.4\,\sigma_B$$

$$X_2 = \mu_A + 3.4\,\sigma_A$$

If these values are substituted into Eq. (2), the following expressions are obtained:

$$z_1 = \frac{(\mu_B + 3.4\,\sigma_B) - \mu_A}{\sigma_A}$$

$$z_2 = \frac{(\mu_A + 3.4\,\sigma_A) - \mu_B}{\sigma_B}$$

$$*n_d = \left(\frac{Z_{1-\beta} + Z_{1-\alpha}}{\tau^2}\right)^2$$

where

$$\tau = \left(\frac{\mu_A - \mu_B}{\sigma}\right)$$

and

$Z_{1-\beta}$ is the critical value corresponding to 90%

$Z_{1-\alpha}$ is the critical value corresponding to 95%

The area to the left of z_1, $P(z_1)$, corresponds to the probability that the values ranging from x_1 to x_2 occur in the sample distribution. Similarly, the area to the right of z_2, denoted 1 - $P(z_2)$, corresponds to the probability that the values ranging from x_1 to x_2 occur in the background distribution. For statistically independent events, the probability that both A and B will occur is defined to be the product of the unconditional probabilities of each (21):

$$P(A\&B) = P(A)\,P(B)$$

In other words, the fraction of the time that sample distribution values from x_1 to x_2 also occur in the background distribution is:

$$P(BKG) = P(z_1)\,(1 - P(z_2))$$

The background fractions, P(BKG), vs. action level are provided in Table II. They were computed from the background Ra-226 distribution and from Table I results. So for example, if the average Ra-226 concentration in an area of soil is 2 pCi/g, then 49% of that soil may be considered to belong within the background distribution. This means that if it is falsely concluded that such an area requires further remediation, then nearly half of all soils removed will be background soils.

The results of the above analyses can now be used to propose an ALARA cleanup standard. In considering this issue, two additional points should be advanced. First, the EPA's target range of 10^{-6} to 10^{-4} for post-remediation incremental risk cannot be achieved at any action level with the foregoing assumptions used in the resident farmer scenario, as evidenced in the incremental risk column of Table II. Note, however, if other assumptions are used, incremental risks will still be linear over the range of action levels, so the ALARA analysis conclusions will be the same. Second, it is not possible to identify with certainty the various action levels in the field with portable instrumentation. It is possible to observe a relative change as concentrations increase or decrease, but as the concentration approaches background, field instrumentation may not be able to distinguish between background and slightly elevated concentrations. This occurs at about 2 pCi/g to 3 pCi/g. Although the cost-impact due to additional requirements for soil sampling and construction delays at these action levels was not calculated, it is certain that costs would increase at a steeper rate than is shown in Fig. 4 for action levels below 4 pCi/g.

With these facts and the above analyses in mind, refer again to Fig. 4. The 2 pCi/g and 3 pCi/g action levels are not suitable candidates for an ALARA cleanup standard because (1) it is not reasonable to remove substantial amounts of clean soils and (2) costs increase much faster than risks decrease for the action levels at 2 pCi/g and 3 pCi/g. This leaves 6.2, 5, and 4 pCi/g as potential cleanup standards. Recall that the decision level will be 1 pCi/g below the cleanup standard. As a result, 5 pCi/g, including background, is proposed as the ALARA cleanup standard because the use of the decision level implies that the average post-remediation concentration will be 4 pCi/g, including background. This is the lowest concentration that can be reasonably achieved without excavating significant quantities of clean soils and without incurring costs that are disproportionately high for the corresponding risk reduction.

* The standard deviation may be expressed as sigma because the calculated sample size, n_d, necessary to achieve 90% power and 95% confidence in the comparison of action level to background was less than 24 (number of background samples). The necessary sample size was calculated from (6):

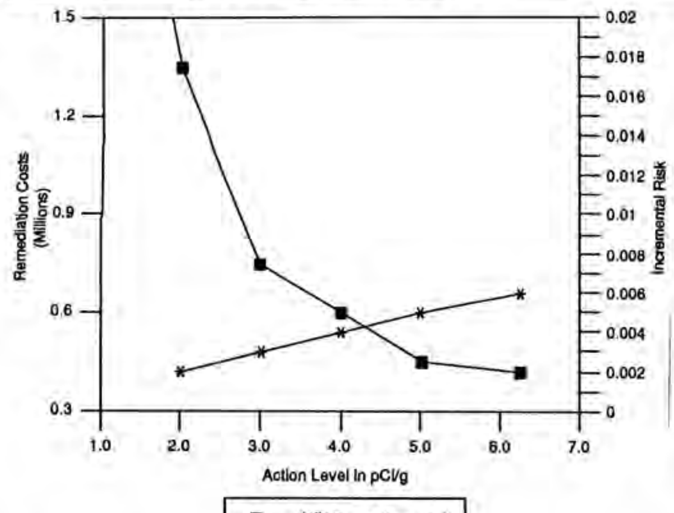

Fig. 4. Remediation costs and incremental risks as a function of action level.

SUBSURFACE REMEDIAL ACTION STANDARD FOR Ra-226

The Ra-226 standard cited in the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) and DOE Order 5400.5 for each successive soil layer more than 15 cm (6 in.) below the surface is 15 pCi/g above background. Site characterization data was again evaluated with respect to as low as reasonably achievable (ALARA) objectives. In the specific case of the Weldon Spring site, the radiological contamination is very shallow, and in cases where it is deep, it almost always exceeds the standard. There is only one boring where Ra-226 is (1) more than 60 cm (2 ft.) deep and (2) less than 15 pCi/g above background. Using the methods described above to estimate volumes, this amounts to about 500 cu. yds. of material. When that amount is compared to the volume that would be excavated in remediating Ra-226 to 5 pCi/g, including background, to any depth, it represents only a 6% increase in the estimated Ra-226 soil volume. This is less than 0.1% of the total waste volume at the Weldon Spring site (WSS), which is currently estimated to be about 1,000,000 cu. yd. (22). Further, in reviewing characterization data for all site radionuclides, there are fewer than 10 borings out of 321 where contamination more than 60 cm deep is not significant. To meet ALARA objectives at the Weldon Spring site, it is therefore proposed that subsurface contaminated soils be removed; i.e., that the proposed surface cleanup standard for Ra-226 be applied to all depths and that supplemental remedial action criteria for soils at depth be waived.

THORIUM

Thorium-232

Cleanup standards for Th-232 can be determined by reviewing the RESRAD outputs generated as a result of the investigations discussed above, and by reviewing site characterization data.

One of the RESRAD runs assumed all natural uranium and Th-232 series radionuclides were present in background concentrations to a depth of 300 cm (10 ft.). The results indicated that the principal exposure pathways for the resident farmer scenario were external gamma exposure and ingestion. Namely, the majority of the dose, excluding radon, was from external exposure to Ra-226, Th-228, and Ra-228 gammas and from ingestion of Pb-210. The external exposure doses for the thorium series, as compared to Ra-226 and its daughters, were comparable: Ra-226 and its daughters contributed about 55% of the dose, and Th-232 and its daughters contributed about 40% of the dose. It is, therefore, possible to conservatively adopt the Ra-226 cleanup standard for Th-232.

Characterization data show that there are only four borings with concentrations greater than 5 pCi/g, including background, where Th-232 is the principal contaminant. The maximum depth of contamination is 15 cm. (0.5 ft.), and using methods previously described, the estimated contaminated volume of soils is less than 1,000 cu. yd., which again is a very small fraction of the total waste volume.

Since the risk from external exposure is comparable to that of Ra-226 and its daughters, and because the volume of soils where Th-232 is the principal contaminant is small, it is suggested that the proposed Ra-226 cleanup standard be used for Th-232 as well.

Thorium-230

Site characterization data indicate that there are 11 borings where Th-230 is the principal contaminant. The depth of contamination is 30 cm (1 ft.) in nine of the borings, and 60 cm (2 ft.) in the remainder. The maximum concentration is 17.6 pCi/g, including background, and extends to a depth of 30 cm (1 ft.). Applying the erosion rate chosen for the WSS and used in the RESRAD code (3.8×10^{-4} m/y), approximately 800 years would be required for a soil interval of one foot to erode away. During that time, ingrowth of Ra-226 from Th-230 decay would result in surface Ra-226 concentrations exceeding the proposed cleanup standard.

It is, therefore, suggested that the proposed Ra-226 cleanup standard be adopted for Th-230.

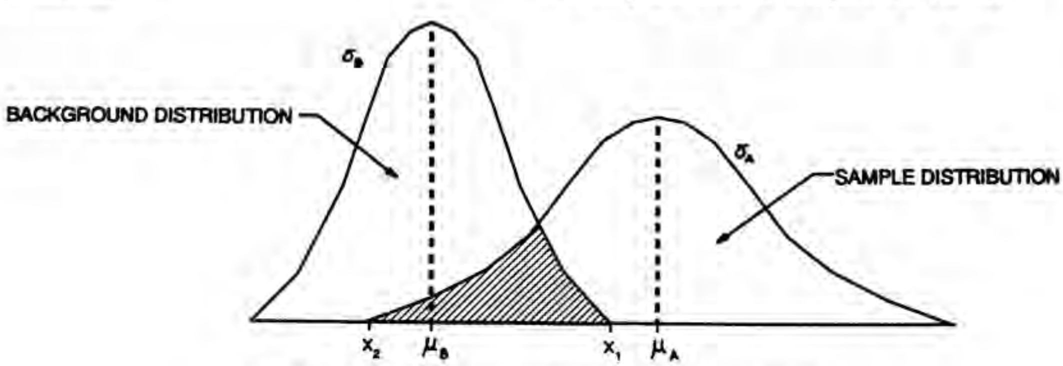

Fig. 5. Determination of background fraction in soils.

CONCLUSIONS

In developing technical support information for radiological cleanup standards for the Weldon Spring site, DOE Order 5400.5, the National Contingency Plan (NCP), the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), and the Uranium Mill Tailings Radiation Control Act (UMTRCA) standard for cleanup of residual radioactive materials from processing sites were evaluated. As a result, a Ra-226 remedial action standard of 5 pCi/g, including background, is proposed. This standard meets the requirements of 40 CFR 192, DOE Order 5400.5, and as low as reasonably achievable (ALARA) objectives.

Because the majority of radiological contamination at the Weldon Spring site is shallow, it is believed that supplemental cleanup standards for contamination at depth are not warranted. It does not appear that the NCP target post-remediation risk range of 10^{-6} to 10^{-4} can be achieved at any action level, given the assumptions presented above. Finally, because of the higher relative risk of Ra-226 and its daughters, and because of ingrowth of Ra-226 from Th-230, it is suggested that the Ra-226 cleanup standard be adopted for Th-232 and its daughters and for Th-230.

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MKES, see MK Environmental Services.
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EPA, see U.S. Environmental Protection Agency.