Dade Moeller & Associates, Inc.

Technical Report

TECHNICAL BASIS FOR THE ACCEPTANCE OF OIL PRODUCTION PIPING AND EQUIPMENT CONTAINING RADIOACTIVE PIPE SCALE AT THE DEER TRAIL LANDFILL

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EXECUTIVE SUMMARY

Naturally Occurring Radioactive Materials (NORM), in the form of radium containing pipe scale, is commonly found in the oil production industry. Oil field waste, largely surplus pipe and equipment, is candidate for disposal at the Deer Trail landfill because of its radioactive properties. However, to ensure safe disposal within the Deer Trail radioactive materials license conditions, Standard Operating Procedures (SOPs) are needed for radiation surveys prior to shipment (by the waste generator) and upon receipt (by Deer Trail personnel). This report establishes the relationship between external exposure rates and the average radionuclide concentrations per waste shipment, in a conservative manner, so that external exposure rate measurements can be used as the basis of the SOPs. Modeling results, using the MicroShield computer program and an empirical equation from the literature, are compared and used to establish the exposure rate/radionuclide concentration relationship. The analysis considers the potential variability encountered from pipes of selected diameters and schedules, ^{226}Ra to ^{228}Ra pipe scale ratios, and single pipe versus multiple pipe configurations. The Wilcoxon Rank Sum (WRS) test is used to establish the number of exposure rate measurements that are required to statistically characterize the average exposure rate from a shipment of oil field pipe and equipment. The analysis considers the potential radon post-closure impacts from receiving radium containing oil field waste. From the results of this analysis, a conservative basis for the SOPs is recommended.

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1. INTRODUCTION

The purpose of this report is to develop a technical basis for Standard Operating Procedures (SOPs) for radiation surveys prior to shipment (by the waste generator) and upon receipt (by Deer Trail personnel) of oil field pipe and equipment containing radium-contaminated pipe scale. The goal of this analysis is to determine the relationship between external exposure rates and average radionuclide concentrations per waste shipment in a conservative manner, so that external exposure rate measurements can be used as the basis of SOPs. The overall approach is to compare modeling exposure rate results, using MicroShield (Grove 2009) and an empirical formula from the literature (API 1997) for various pipe diameters, schedules, and scale thicknesses. From this comparison, the exposure rates are correlated with internal pipe scale concentrations so that measurements can be used to determine if the Deer Trail waste acceptance criteria are met for specific shipments of oil field pipe and equipment. Using MicroShield, sensitivity studies are conducted to determine the potential variability encountered from various ^{226}Ra to ^{228}Ra ratios on measured radiation exposure rates, and the variability from stacks or jumbles of pipe and equipment with various scale concentrations on waste acceptance decisions. A statistical evaluation is conducted to determine the number of exposure rate measurements required per shipment to implement the SOPs and reduce uncertainty. Finally, an evaluation of potential long-term radon concerns following closure is conducted. From the results, a conservative basis for the SOPs is recommended.

1.1 Background Information – The Nature of Radium Pipe Scale

Naturally occurring radioactive material (NORM) has been detected in pipe scale associated with the oil and gas industry. Radium is preferentially soluble in brine solutions (often common to oil production) compared to relatively insoluble uranium and thorium. Under certain conditions, the dissolved minerals in the brine solution lead to the formation of pipe scale. NORM pipe scale is produced when radium is co-precipitated with silicates, sulfates, or carbonates. The concentration of radium in oil field pipe scale is a function of the underlying geology and age of the well; more brine solution is typically recovered from older wells as oil production decreases. The scale can buildup in the pipe to thicknesses of up to several centimeters, depending on the pipe diameter, the total time the pipe is in service, and the total brine production. As a result, the concentration and quantity of radium in pipe scale can vary over a wide range. It has been reported that radium scale can vary in concentration from background to 410,000 picoCuries per gram (pCi/g) radium (EPA 1993), with a reported average of 480 pCi/g. The scale will typically contain predominantly ^{226}Ra and ^{228}Ra and their associated decay chains in equilibrium. Although the concentration ratio of ^{226}Ra to ^{228}Ra is highly variable, a typical ratio of 3:1 has been reported and used in previous assessments (Smith et al. 1996).

1.2 Radium Decay Chains

As part of the ^{238}U decay series, separated ^{226}Ra has eight radioactive decay chain products for a total of nine radionuclides. These include:

^{226}Ra (half-life ~ 1,660 years) decays by alpha/gamma radiation to:
^{222}Rn (half-life ~ 3.8 days) decays by alpha/gamma radiation to:
^{218}Po (half-life ~ 3.1 minutes) decays by alpha radiation to:

^{214}Pb (half-life 27 minutes) decays by beta/gamma radiation to:
^{214}Bi (half-life ~ 20 minutes) decays by beta/gamma radiation to:
^{214}Po (half-life ~ 160 microseconds) decays by alpha/gamma radiation to:
^{210}Pb (half-life ~ 22 years) decays by beta/gamma radiation to:
^{210}Bi (half-life ~ 5 days) decays by beta radiation to:
^{210}Po (half-life ~140 days) decays by alpha/gamma radiation to Stable ^{206}Pb

To meet the 2,000 pCi/g Deer Trail license limit, this means that, for a pure ^{226}Ra decay chain mixture, each member of the ^{226}Ra decay chain can have only one ninth (1/9th) of the total activity, or 220 pCi/g. As part of the ^{232}Th decay series, separated ^{228}Ra has nine radioactive decay chain products for a total of ten radionuclides. These include:

^{228}Ra (half-life ~ 5.8 years) decays by beta radiation to:
^{228}At (half-life ~ 6.1 hours) decays by beta/gamma radiation to:
^{228}Th (half-life ~ 1.9 years) decays by alpha/gamma radiation to:
^{224}Ra (half-life ~ 3.6 days) decays by alpha/gamma radiation to:
^{220}Rn (half-life ~ 55 seconds) decays by alpha/gamma radiation to:
^{216}Po (half-life ~ 0.15 seconds) decays by alpha radiation to:
^{212}Pb (half-life ~ 11 hours) decays by beta/gamma radiation to:
^{212}Bi (half-life ~ 5 days) decays 64% of the time by beta/gamma radiation to:
^{212}Po (half-life ~ 300 nanoseconds) decays to Stable ^{208}Pb
Or: ^{212}Bi (half-life ~ 5 days) decays 36% of the time by alpha/gamma radiation to:
^{208}Tl (half-life ~3.1 minutes) decays by beta/gamma radiation to Stable ^{206}Pb

Again, to meet the 2,000 pCi/g limit, this means that, for a pure ^{228}Ra decay chain mixture, each member of the ^{228}Ra decay chain can have only one tenth (1/10th) of the total activity, or 200 pCi/g.

As shown in **bold** in the decay chains above, each chain contains a noble gas member, radon. If radon is released from the scale, the subsequent radionuclides in each chain may not be in equilibrium with the parent radium radionuclides. The literature reports average radon emanation fraction of 0.001 to 0.002, which means that it can be assumed that equilibrium conditions exist between all decay chain members (Wilson 1994).

2. MODELS AND DATA

This section describes the modeling approaches, data, and assumptions used to determine the average radioactive contamination per shipment per unit mass based on external exposure rates in contact with pipe or equipment. Models are also described for statistical methods for determining the number of measurements required to characterize a pipe shipment and reduce uncertainty, and for evaluating potential post closure radon emanation rates. The results of the analyses are provided and discussed in Section 3.0, and overall recommendations are provided in Section 4.

2.1 Average Radium Concentrations

The radioactive concentration per shipment of contaminated oil field pipe is a function of the total quantity of radium in the pipe scale and the total weight of the pipe in a shipment. Relevant to this report is the concentration of total radioactivity averaged in each pipe or waste shipment (pipe scale plus pipe), not the concentration of radium in pipe scale alone. That is, the pCi/g of radium averaged between the scale and pipe, for each load of waste. The current Deer Trail waste acceptance criteria receipt of NORM waste that is less than 2,000 pCi/g.

Oil field pipe scale can vary in density over a wide range, and has been reported to vary from 1.7 to 3.5 g/cm^3 (API 1997). For this analysis, it is assumed that the average density of pipe scale is 2.6 g/cm^3. Steel pipe is assumed to have a density of 7.8 g/cm^3. The weight of pipe is a function of the pipe internal diameter and the pipe schedule, which determines the pipe wall thickness. Information from the American National Standards Institute (ANSI) for steel pipes of selected diameters and schedules is shown in Table 2-1 in units of pounds per foot for pipe weight, and inches for wall thickness (ANSI 2009).

Table 2-1. Steel pipe weights and wall thicknesses for selected pipe diameters.

Pipe Size (I.D. inches)	Schedule 40 (lb/ft)	Wall Thickness (inches)	Schedule 80 (lb/ft)	Wall Thickness (inches)	Schedule 160 (lb/ft)	Wall Thickness (inches)
2	3.653	0.154	5.022	0.218	7.462	0.344
3	7.576	0.216	10.25	0.3	14.32	0.437
6	18.97	0.28	28.57	0.432	45.3	0.718
8	28.55	0.322	43.39	0.5	74.69	0.906
10	40.48	0.365	64.33	0.593	115.7	1.125
12	49.56	0.375	88.51	0.687	160.3	1.312

The calculation of average radium activity simply accounts for the mass of scale (for selected scale thicknesses) and the mass of pipe (for selected pipe diameters and schedules). The resulting average concentrations are used as input for the modeling analyses to estimate radiation exposure rates in contact with single or multiple pipe configurations. The details of the analysis conducted using simple spreadsheets are provided in Appendix A.

The relationship between scale activity and total activity to equal 220 pCi/g for selected pipe diameters and schedules, for ^{226}Ra plus its decay chain members is shown in Figure 2-1. As is shown Figure 2-1, when the pipe diameter increases, the total activity needed to equal 220 pCi/g total (pipe plus scale) for ^{226}Ra increases because of the additional pipe mass encountered. In a similar manner, as the pipe schedule increases, so does the total activity to equal 220 pCi/g total for ^{226}Ra, again because of the increased pipe mass with increased pipe wall thickness.

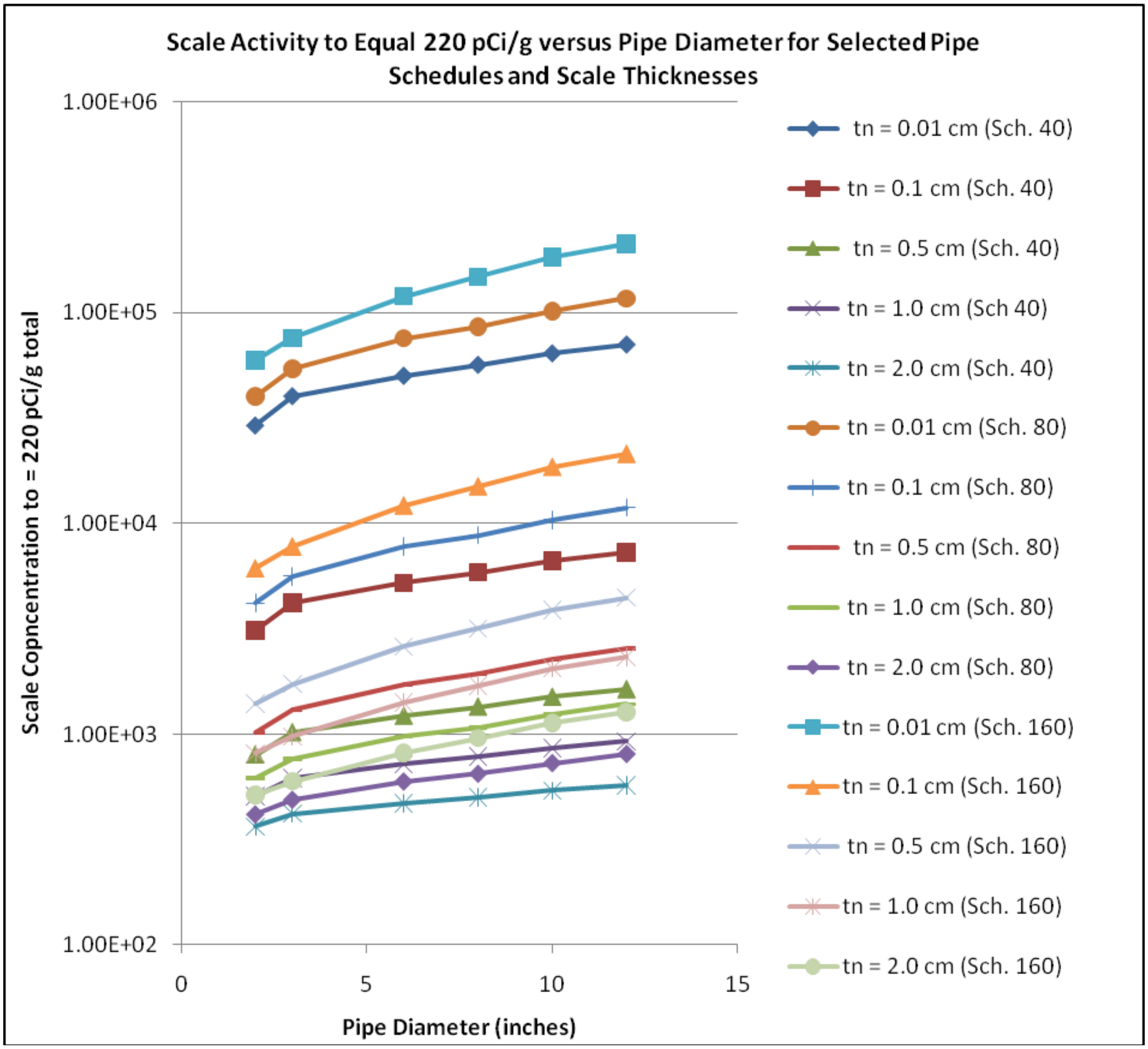

Figure 2-1. Scale activity to equal 220 pCi/g total pipe plus scale activity for selected pipe diameters and schedules: ^{226}Ra.

2.2 Estimated Radiation Exposure Rates

Radiation surveys for the shipment and receipt of oil field pipe and equipment containing radium-contaminated pipe scale for the Deer Trail landfill must rely on external radiation measurements made in the field to confirm that the concentrations encountered meet the waste acceptance criteria. The exposure rate results from two modeling methods are compared to determine the best approach for establishing the external exposure rate to pipe scale radium concentration relationship. The first applies the MicroShield (Grove 2009) computer program, and the second applies an empirical formula derived by the American Petroleum Institute (API 1997) based on measured data.

2.2.1 Modeling Estimates of External Exposure Rates Using MicroShield

Radiation exposure rates are estimated using the MicroShield (Grove 2009) computer program. MicroShield is a widely used and comprehensive photon/gamma-ray shielding and exposure assessment program for designing shields, estimating source strength from radiation measurements, minimizing exposure to people, and as a tool for teaching shielding principles. The program uses a point-kernel calculation with integration parameters to define the size of each source, and takes that amount of activity at that location along with the line of sight distance to the receptors to calculate the receptor dose. The program uses buildup and reduction factors based on the intervening (shield) materials.

MicroShield features include:

Sixteen defined geometries are provided to accommodate offset dose points and as many as 10 standard shields as well as source self-shielding and cylinder cladding.

- Dimensional data are accepted in meters, centimeters, feet, or inches with a rotatable three-dimensional display for viewing and printing;
- Sources can be created, saved, and moved among cases as radionuclides or photon energies, as either individual concentrations or mixture totals. Several photon-grouping methods are provided including user-defined custom groupings.
- Source decay can be calculated with progeny in-growth.
- As many as 25 energy groups ranging from 15 keV to 10 MeV can be used; input can be individual concentrations or mixture totals.
- Sensitivity of exposure rate to time, source dimension, shield thickness, or distance can be investigated.
- Up to six receptors or dose points can be defined for a single case for most geometries.

The standard geometry consisted of a 30 cm length of pipe (cylindrical geometry) with the exposure point 0.1 cm from the midpoint of the pipe (to approximate surface contact exposure rates). The analysis considered the various combinations of pipe diameter, pipe schedule (pipe wall thickness), and scale thickness.

2.2.2 Modeling Estimates of External Exposure Rates Using an Empirical Equation

In November 1997, the American Petroleum Institute (API) published a report entitled *Methods for Measuring Naturally Occurring Radioactive Materials (NORM) in Petroleum Production Equipment* (API 1997). In response to industry concerns regarding the potential concentrations of NORM radionuclides in oil and gas production equipment, the API developed a correlation between radium concentrations in scales and sludge and the external radiation measured with scintillation detectors and Geiger- Mueller (GM) tubes. Their correlation (an empirical equation) was validated with field measurements, and was used to estimate the lowest limits of detection of radium in piping and equipment. The report provided commentary and experimental data for the characteristics of the field-survey instruments and the NORM distributions that may be encountered. The report recognized that correlations were needed to quantitatively relate survey readings. The correlations were dependent on the NORM scale density, volume, thickness, radionuclide composition, detector efficiency, and geometric efficiency (measurement position). They also depend on the thickness of the equipment wall (i.e., pipe schedule). Actual NORM scale sources from oil fields, and surrogates sources using uranium tailings, were used to obtain measured data to serve as the empirical basis of the correlations. Although separate correlations were developed for thin scales in gas plant equipment and for NORM contamination in exposed surface soils, only the evaluations relevant to oil field piping are considered in this analysis.

The API study benchmarked 159 field-measured data points and recommended the following correlation between measured external radiation and internal NORM concentration for oil field equipment and pipe:

$$C = (0.031/\ t_n\ \rho_n)\ (1 + st_n/4 + 2t_w)\ D$$

Where: t_n = NORM scale thickness
ρ_n = NORM density
s = 2.6 for dense scales
t_w = pipe wall thickness
D = gamma detector count rate (counts/minute).

The detector used in the API study was a 1 by 1 inch sodium iodine (NaI) detector. Solving for D the equation becomes:

$$D = (t_n\ \rho_n/0.031)\ (4 + 2t_w/1 + st_n)\ C$$

The solution for this equation, using the previously calculated values of C (equal to 220 pCi/g total pipe plus scale, derived in Appendix A), are shown in Appendix B. The empirical results are in terms of the detector response in units of counts per minute using a NaI detector. The API study concluded that, although there will be variability in scale distributions and radium concentrations, external measurements represent averages over significant areas (API 1997). They further concluded that external radiation measurements give as accurate an estimate of the average radium concentration compared with a single grab sample (API 1997).

2.3 Evaluation of Multiple Pipe Configurations

The modeling conducted thus far consider exposure rates from a single pipe with radium-contaminated inner scale. The potential importance of multiple pipes on the measured exposure rate for a multiple pipe shipment received at Deer Trail is evaluated using a MicroShield analysis. First, the relative contribution from adjacent contaminated pipes is evaluated for small diameter (two inch) and larger diameter (six inch) pipes, schedule 80, for ^{226}Ra contaminated pipe scale. This analysis was conducted by modeling each adjacent pipe, then summing the contributions of each pipe in the array, with consideration of the shield afforded by the pipe walls between each pipe and the instrument location. The analysis was conducted using a configuration of 28, two inch internal diameter, schedule 80 pipes, and a configuration of 21 six inch internal diameter, schedule 80 pipes, intended to determine the difference between small and large diameter pipes.

2.4 Statistical Determination of the Required Number of Exposure Rate Measurements

Several sources of parameter and measurement variability that lead to uncertainty in the measured exposure rates have been identified, including:

- Variability of scale layers and distributions within a pipe shipment,
- Variability in the gamma attenuation factors for steel pipe across the incident energy groups,
- Geometric measurement efficiency,
- Variation cause by the instrumentation and the detector efficiency, and
- Measurement variability and errors.

However, the uncertainty produced can be managed my making multiple measurements, and using the average of those measurements in making decisions regarding waste acceptance. Thus, in addition to determining a defensible exposure rate, a sufficient number of measurements must be made for each multiple-pipe shipment to assure that statistically-defendable decisions are made about the average radionuclide concentrations encountered, consistent with the Deer Trail radioactive materials license. A determination of how many measurements are required can be derived through a statistical analysis. The problem of determining average concentrations per shipment, and the number of measurements required to make that determination, is parallel to making release decisions for contaminated property using the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) (EPA 2000). Specifically, the exposure rate is comparable to the MARSSIM Derived Concentration Guideline Level (DCGL). The exposure rate is the measurement of the activity/exposure rate relationship corresponding to the Deer Trail waste acceptance criteria. When the specific radionuclide activity is present in background (such as NORM), the Wilcoxon Rank Sum (WRS) test is used. The WRS evaluation is provided in Appendix C. The WRS test relies on managing two types of decision errors: Type I, or α (in our case, accepting waste that exceeds the waste acceptance criteria) and Type II, or β (in our case, rejecting waste that meets the waste acceptance criteria).

2.5 Post Closure Radon Concerns

Finally, an evaluation of potential post-closure radon emanation rates is conducted. Radon flux rate calculations can be made for up to eight different soil and sub-soil layers using the Uranium Mill Tailings Cover Calculator (Wise Uranium Project 2004). For this analysis, the following assumptions are made:

- The waste layer is 4 m thick, with a concentration of 220 pCi/g of ^{226}Ra. This is a conservative concentration since it does not account for the presence of other non-NORM waste or daily soil cover materials that would reduce the average concentration of ^{226}Ra in the waste layer.

- The waste is assumed to have a dry weight porosity of 0.44%, moisture content of 11%, and diffusion coefficient of 2.6 x 10^{-6} m^2/second (based on ranges of literature values).

- The radon emanation fraction from scale is assumed to be 0.1 (a factor of 100 higher than literature estimates) (Wilson 1994). Note, for pipe scale, diffusion would only occur at the ends of the pipe, which would greatly reduce the average emanation fraction.

- The cover layer thicknesses and properties are consistent with typical RCRA closure designs: 0.15 m of clay, 0.91 m of compressed fill material, and 0.2 m of cover soil.

- The assumed radium concentration in the cover materials (2 pCi/g) is consistent with average soil concentrations in the U.S. (NCRP 2009, Table 3.4).

3. RESULTS AND DISCUSSION

The results of applying the models described in Section 2 for the analysis of exposure rates from oil field pipe and equipment containing radium-bearing pipe scale, using the average scale plus pipe concentrations reported in Appendix A, are presented in this section.

3.1 Single Pipe MicroShield Results

A summary of the MicroShield exposure rate results for the single pipe analysis are shown graphically in Figure 3-1 for selected pipe internal diameters, schedules, and scale thicknesses for ^{226}Ra and ^{228}Ra, using the average concentrations reported in Appendix A. Note that there is a linear relationship between the exposure rate and the radium concentration in scale; that is, an increase in scale concentration will result in a similar, linear increase in the measured exposure rate.

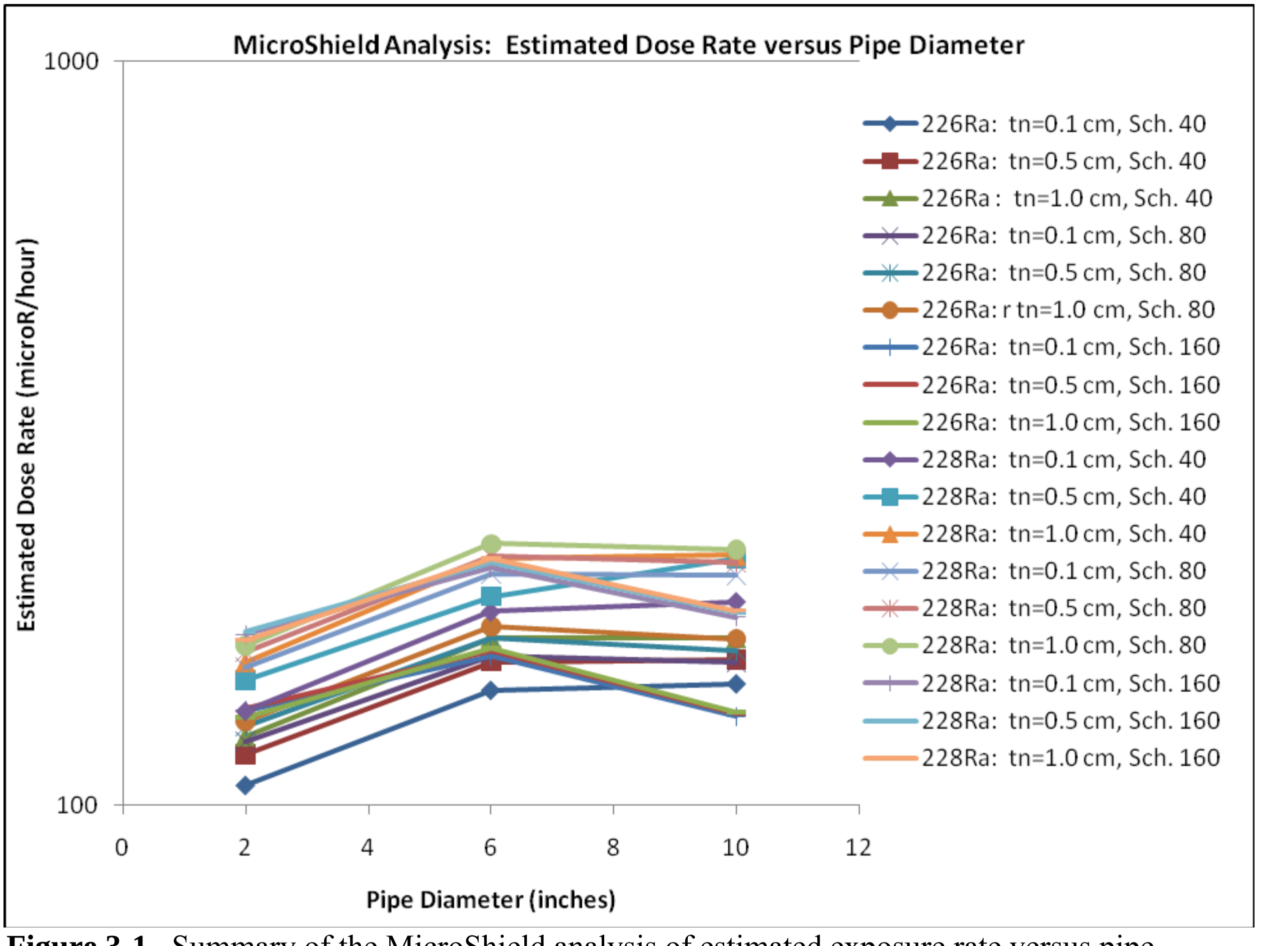

Figure 3-1. Summary of the MicroShield analysis of estimated exposure rate versus pipe diameter for selected pipe diameters, pipe schedules, and scale thicknesses.

This figure shows several features:

- All of the exposure rate results, across pipe diameters, pipe schedules, scale thicknesses, and decay chains are within about a factor of 2; this is close agreement for modeling results,

- Since the activity concentrations for each of these estimates (scale plus pipe) is the same, the theoretical external exposure rates from all pipe scale/pipe combinations should be roughly the same, with some variation induced by geometry effects associated with the pipe diameter and wall thickness,

- For a given pipe diameter the results across all schedules are in close agreement (within about 50%),

- The results for the ^{228}Ra decay chain produce radiation exposures that are about a factor of two greater than comparable exposures for the ^{226}Ra decay chain, and

- For the larger pipe diameters, the estimated exposure rate at a point on the surface at the pipe centerline for the higher pipe schedules decreases, reflecting the geometry effect of additional shielding by the thicker steel walls compared to the increased radius on the modeling results.

3.2 Single Pipe Empirical Equation Results

The empirical equation results obtained from the API study equation, using the detector response (D) values calculated in Appendix B, are next converted to the detector response in terms of exposure rate (µR/hour). The API study indicates that the background count rate for the one-inch NaI detector is 1,504 counts per minute for background, with a background exposure rate of 15 µR/hour. Figure 3-2 shows the empirical exposure rates produced by converting the count rates in Appendix B to exposure rates.

This figure includes the following features:

- For a given pipe diameter the results across all schedules are in close agreement (within about 30%); however, there seems to be some sensitivity to pipe diameter, especially for the lower pipe schedules, and

- The empirical equation includes a mixture of roughly 66% ^{226}Ra decay chain members and 33% % ^{228}Ra decay chain members.

3.3 Multiple Pipe Results

The MicroShield exposure rate modeling results for the 28 pipe configuration of two inch internal diameter, schedule 80 pipes, is shown in Figure 3-3. The relative contribution of each pipe to the exposure rate at the instrument location (at the centerline of the middle pipe on the top row) is shown within each pipe.

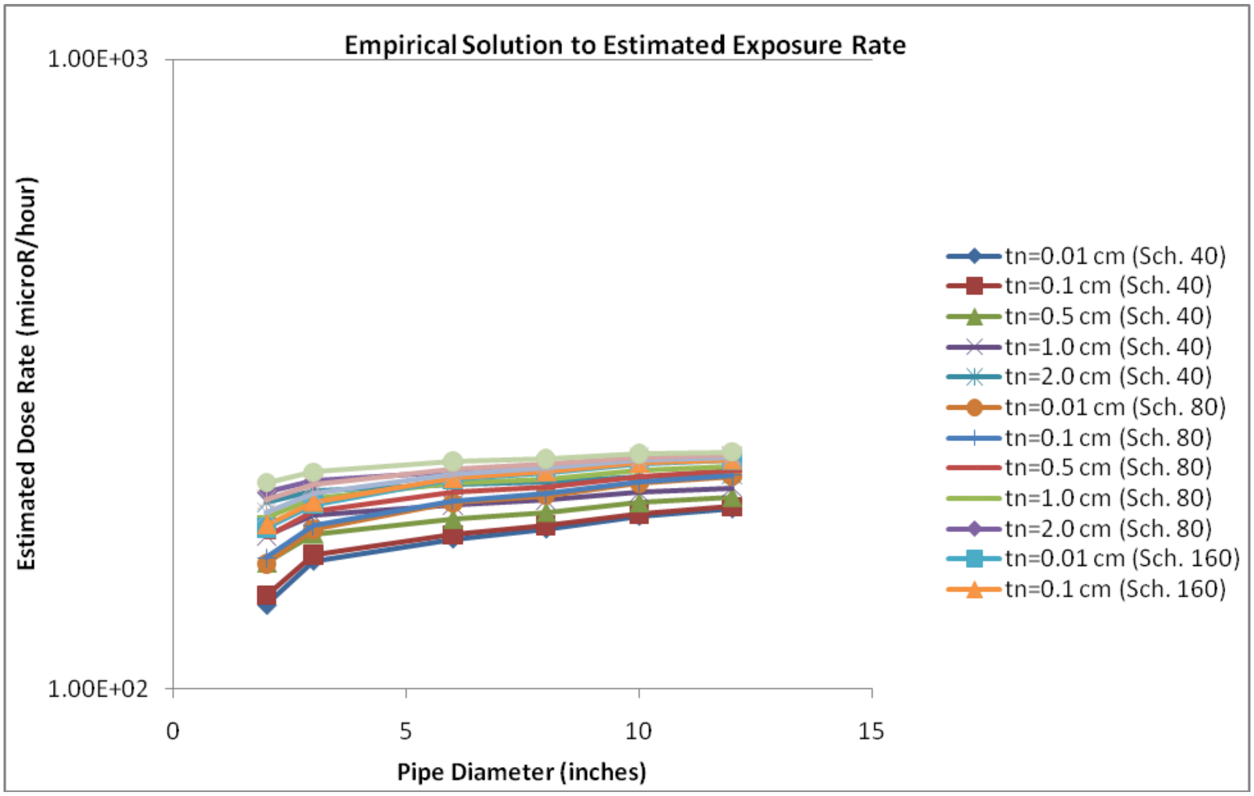

Figure 3-2. Empirical exposure rates for selected pipe diameters, pipe schedules, and scale thicknesses.

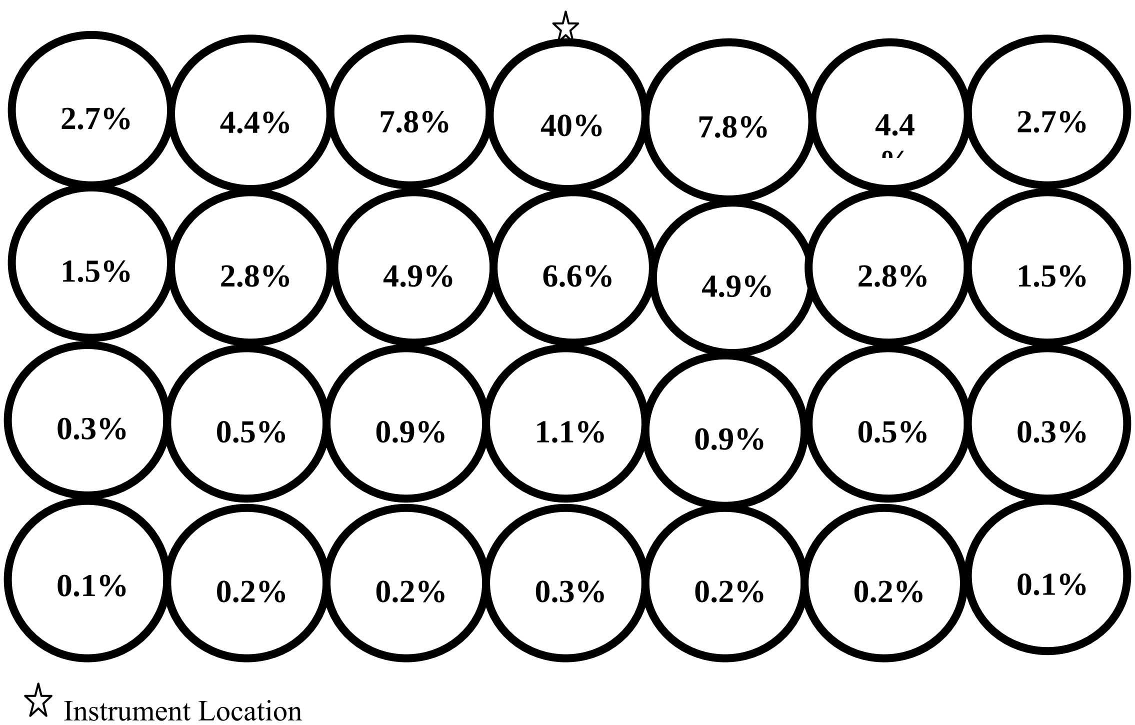

Figure 3-3. Relative contribution to the exposure rate from two inch, Schedule 80 adjacent pipes to the instrument location: ^{226}Ra contaminated pipe scale.

As this figure shows, pipes further away from the instrument location contribute less to the measured exposure rate than closer pipes. It also shows that the instrument reading would need to be increased by 40% to meet the 220 pCi/g criterion if all pipes in the array were uniformly contaminated. Assuming 30 foot lengths of pipe, using the information in Table 1-1, a shipment of 28 pipes would weigh about 2 tons. This analysis was repeated for six inch diameter pipe, using a configuration of 21 pipes, as shown in Figure 3-4.

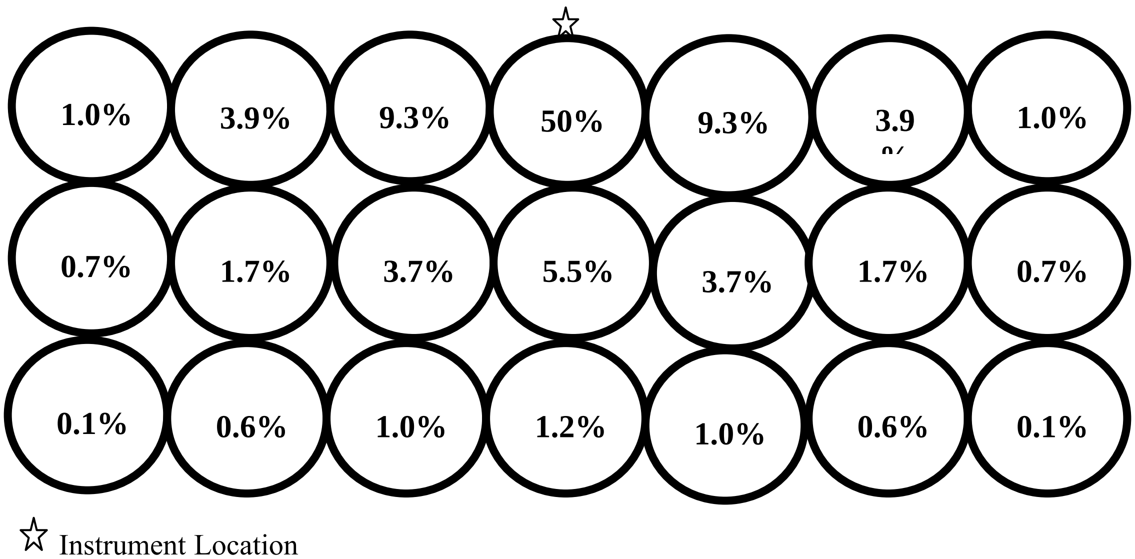

Figure 3-4. Relative contribution to the exposure rate from six inch, Schedule 80 adjacent pipes to the instrument location: ^{226}Ra contaminated pipe scale.

This figure again shows pipes further away from the instrument location contribute less to the measured exposure rate than closer pipes. It also shows that the instrument reading would need to be increased by 50% to meet the 220 pCi/g criterion if all pipes in the array were uniformly contaminated. Assuming 30 foot lengths of pipe, using the information in Table 1-1, a shipment of 21 pipes would weigh about 9 tons.

3.4 Statistical Results for Determining the Number of Measurements Required for a Multiple-Pipe Configuration

The API study concluded that the gamma measurements of pipe and equipment (valves) in the laboratory predicted radium concentrations that averaged within 20-50 percent of the reference values. Although this is an excellent single measurement result, the uncertainty can be reduced by making a number of measurements, and using the average of the results to determine compliance with the waste acceptance criteria (i.e., acceptable exposure rate).

The Wilcoxon Rank Sum (WRS) test was applied, as described in Appendix C, to determine the number of measurements required for a multiple-pipe configuration so that the mean concentration in the survey unit (a shipment of contaminated oil field pipe or equipment) is less than the identified exposure rate. This result would then indicate that the shipment is in compliance with the waste acceptance criteria. The WRS test relies on managing two types of decision errors: Type I, or α (in this case, accepting waste that exceeds the waste acceptance criteria) and Type II, or β (in this case, rejecting waste that meets the waste acceptance criteria). For this analysis, α and β were selected to be 0.05 (or selecting a 95% confidence limit). The estimate of the mean concentration is the arithmetic average of a set of randomly selected locations for the multiple-pipe shipment. The results of the analysis indicated that 15 total number of measurements (N = measurements for pipe shipment plus background measurements) would be required. However, to assure sufficient data points to attain the desired power level (95% confidence limit) with statistical tests and to allow for possible unusable data, MARSSIM recommends increasing the number of points by 20%, making the calculated value of N equal to 18. Since N equals the number of measurements of the pipe shipment and background, the number for the shipment is one half of the total, or nine (rounding up to the nearest measurement). Thus, the average of nine exposure rate measurements per shipment, compared with the waste acceptance criteria exposure rate limit, provide a statistical basis for characterizing the multiple-pipe configuration for oilfield pipe and equipment.

3.5 Post Closure Radon Concerns

The input/output generated by the Uranium Mill Tailings cover Calculator is shown as:

Uranium Mill Tailings Cover Calculator Input/Output

---------------- Input Parameters ----------------
Number of Layers: 4
Radon Flux into Layer 1: 0 pCi/m2s
Surface Radon Concentration: 0 pCi/L
Bare Source Flux (Jo) from Layer 1: 77.61 pCi/m^2s
Specific Bare Source Flux from Layer 1: 0.353 pCi/m^2s per pCi_Ra-226/g

Layer No.	Thickness [m]	Ra-226 [pCi/g]	Emanation Fraction	Porosity [dry wt %]	Moisture	Diffusion Coefficient [m^2/s]
1	4	220	0.1	0.44	11	2.600E-6
2	0.15	2	0.3	0.37	8	220.0E-9
3	0.91	2	0.3	0.37	6.3	5.000E-6
4	0.2	2	0.3	0.37	8	1.700E-6

-------- Results of Radon Diffusion Calculation --------

Layer No.	Thickness [m]	Exit Flux [pCi/m^2s]	Exit Concentration [pCi/L]	MIC
1	4	23.83	52.39E3	0.720
2	0.15	20.37	12.93E3	0.728
3	0.91	15.63	5.351E3	0.786
4	0.2	15.68	0E0	0.728

Total cover radon retention: 79.80%

The results indicate a radon exit flux rate of about 16 pCi/m^2s, compared with the EPA uranium mill tailings limit of 20 pCi/m^2s. Again, this result is considered to be conservative since it did not account for mixing of the pipe scale waste with non-NORM waste or with the daily soil cover, and the limited radon diffusion that would occur only at the ends of pipe. This result indicates that there should be no difficulty from receiving oil field piping and equipment containing radium scale. However, measurements of the radon flux above the cell prior to cell closure will confirm these results, or define the need for a thicker cover to provide an extra diffusion barrier to limit radon emissions.

3.6 Comparison of Results and Discussion

Figure 3-5 shows a comparison of the MicroShield (for ^{226}Ra and ^{228}Ra decay chain members) and empirical equation modeling exposure rate results for each scale thickness and each pipe schedule. For this figure, average exposure rate values were obtained across all internal diameters to show the potential effects of scale thickness and pipe schedule on the results.

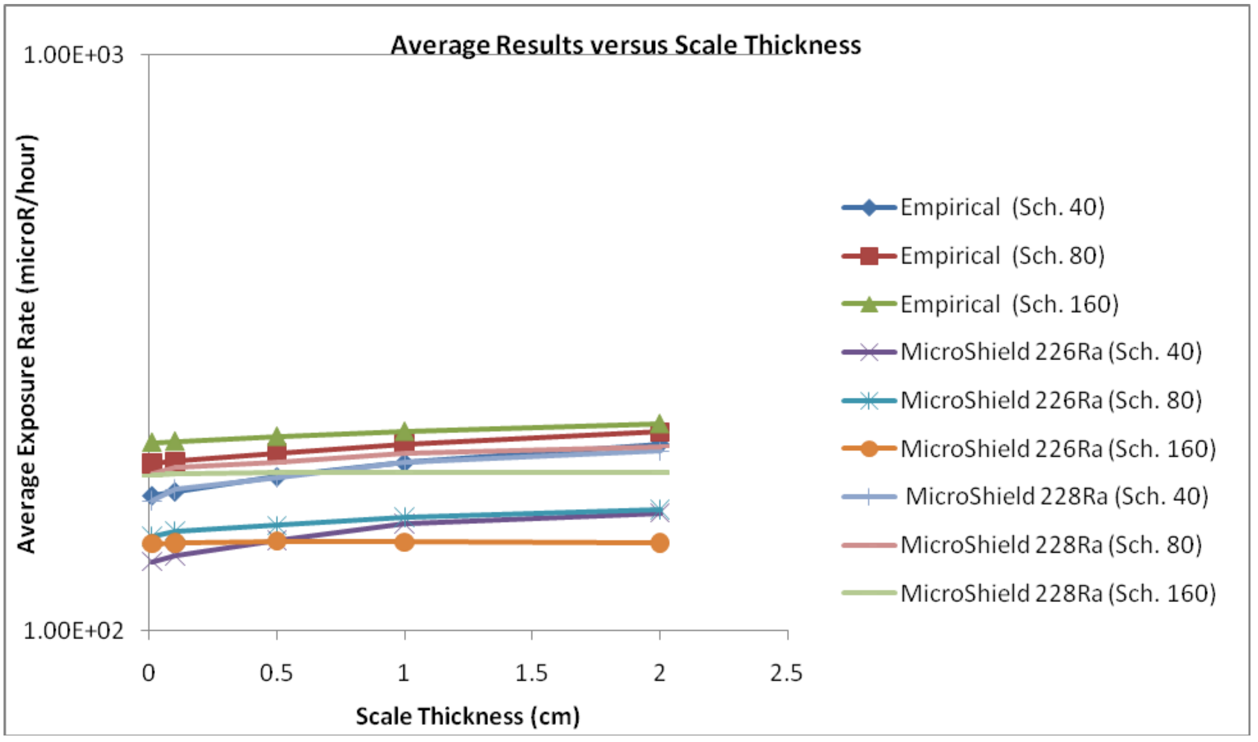

Figure 3-5. Average modeling exposure rate results comparison.

This figure shows the following features:

- All of the modeling exposure rate results are in close agreement, and are generally within about a factor of 1.6, independent of pipe schedule, indicating that scale thickness and pipe schedule are less significant than pipe diameter in estimating external exposures,

- All of the modeling exposure rate results are consistent across all scale thicknesses considered, and

- The empirical modeling exposure rate results are slightly larger than the MicroShield ^{226}Ra results, but almost equal to the MicroShield ^{228}Ra results – this partially reflects the inclusion of ^{228}Ra in the empirical results.

This comparison indicates that there is less variation in estimated exposure rate across scale thickness and pipe schedule compared with the variation produced across the selected pipe diameters (as shown in figures 3-1 and 3-2). The API study also concluded that, based on gamma measurements, the dependence of the scale thickness was low.

4. COMMENTARY AND RECOMMENDATIONS

The purpose of this report is to develop a technical basis for SOPs for radiation surveys prior to shipment and upon receipt of oil field pipe and equipment containing radium-contaminated pipe scale. The goal of this analysis is to determine the relationship between external exposure rates and average radionuclide concentrations per waste shipment in a conservative manner, so that external exposure rate measurements can be used as the basis of the SOPs. The overall approach is to compare modeling exposure rate results, using MicroShield (Grove 2009) and an empirical formula from the literature (API 1997) for selected pipe diameters, schedules, and scale thicknesses. From this comparison, the exposure rates are correlated with internal pipe scale concentrations so that measurements can be used to determine if the Deer Trail waste acceptance criteria are met for specific shipments of oil field pipe and equipment. As previously described, there was close agreement between the MicroShield and empirical modeling contact exposure rate results, which were well within a factor of two for all pipe sizes, schedules, and scale thicknesses. The results also quantified the difference between measurements made on single pipes versus multiple pipes for small and large diameter pipes. The following paragraphs provide final commentary and recommendations for the development of the Deer Trail oil field pipe and equipment SOPs.

4.1 Commentary

The following topics identified during this analysis require further commentary:

- Overall Ranges. The overall ranges of the estimated contact exposure rates for small and large pipes are summarized in Table 4-1 for both the MicroShield and empirical models, on a per pipe basis.

Table 4-1. Summary of estimated exposure rates for small and large oil field pipes containing radium scale.

Modeling Method	Small Pipe Exposure Rate Range[a] (μR/hour)	Large Pipe Exposure Rate Range[b] (μR/hour)
Empirical – $^{226}Ra/^{228}Ra$ mixture	140 – 220	173 – 240
MicroShield – ^{226}Ra	106 – 131	140 – 160
MicroShield – ^{228}Ra	130 – 170	170 – 250

a. Pipes with internal diameters < 4 inches.
b. Pipes with internal diameters > 4 inches.

These single pipe results can be thought of as the exposure rate per the same average radium concentration in pipe (scale plus pipe). Although all of these results show relatively close agreement, the empirical model exposure rate results are somewhat higher than the results produced by MicroShield. This means that it would be conservative to select the MicroShield model exposure rates as the basis for the SOPs since they would not underestimate the radium concentrations in pipe compared to the empirical results. Also, since actual pipe scale has both ^{226}Ra and ^{228}Ra, it would not be as appropriate to use the most conservative ^{226}Ra results as the sole basis for the SOPs since this value may underestimate the radium concentration when the contamination contains a good proportion of ^{228}Ra (total scale activity is typically about one fourth ^{228}Ra). Based on these considerations, it is concluded that the following external exposure rates would conservatively indicate pipe scale concentrations of less than the Deer Trail waste acceptance limits: 120 μR/hour for small pipes less than four inches internal diameter (roughly the midpoint of the small pipe MicroShield exposure rate range for ^{226}Ra) and 150 μR/hour for large pipes greater than four inches internal diameter (roughly the midpoint of the MicroShield large pipe exposure rater range for ^{226}Ra). Again, note that there is a linear relationship between the exposure rate and the radium concentration in scale; that is, an increase in scale concentration will result in a similar, linear increase in the measured exposure rate.

- Multiple Pipes. As has been shown, when multiple pipes or equipment and pipes are encountered, the measured exposure rates increase, for the same scale concentration, because of the contributions of the scale in adjacent pipes. This means that for multiple pipe configurations, the small diameter pipe value can be increased by 1.4 times (to 170 μR/hour), and the large diameter pipe value can be increased by 1.5 times (to 230 μR/hour). All measured exposure rates would be exclusive of background. Based on practical considerations for measurements in the field, single pipe measurements would be appropriate for the waste generator to assure that the waste acceptance criteria are met, while multiple pipe measurements would be appropriate for waste received at Deer Trail. A summary of the final technical basis for the Deer Trail SOPs is shown in Table 4-2.

Table 4-2. External exposure rates to meet the Deer Trail Waste acceptance criteria for oil field pipe and equipment.

Measurement Location and Type	Pipe I.D. < 4 inches (μR/hr at Contact)	Pipe I.D. > 4 inches (μR/hr at Contact)
Generator – Single Pipe	120	150
Receipt – Multiple Pipe	170	230

- "Junk" Shipments. It is most probable that the shipments will resemble shipments of "junk," that is random jumbles of various sizes of pipe, random valves, tanks, and or other equipment. For this situation, it would be appropriate to apply the small diameter pipe exposure rate criteria instead of the large diameter pipe criteria to assure that the waste acceptance criteria are not exceeded.

4.2 Recommendations

Based on the preceding analysis and commentary, the following recommendations are made for the development of the Deer Trail oil field pipe and equipment SOPs:

- The SOPs must account for shipments of small and large diameter pipe, and "junk" shipments of randomly sized and shaped mixtures of pipe and equipment.

- The SOPs must account for both multiple and single pipe or equipment exposure rate measurements as may be encountered in the field.

- For multiple small pipes less than four inches internal diameter, the average of nine exposure rate measurements in contact with the pipe evenly distributed across the shipment must be less than 170 μR/hour. The use of nine measurements would provide

95% confidence that the average radium concentrations for a shipment are less than 2,000 pCi/g.

- For multiple large pipes greater than four inches internal diameter, the average of nine exposure rate measurements in contact with the pipe evenly distributed across the shipment must be less than 230 μR/hour. The use of nine measurements would provide 95% confidence that the average radium concentrations for a shipment are less than 2,000 pCi/g.

- For shipments of junk (a mixture of randomly sized and shaped pipe and equipment), the average multiple small pipe exposure rate measurements in contact with the pipe must be less than 170 μR/hour. The use of nine measurements would provide 95% confidence that the average radium concentrations for a shipment are less than 2,000 pCi/g.

- For single small diameter pipes less than four inches internal diameter, the exposure rate in contact with the pipe must not exceed 120 μR/hour.

- For single large diameter pipes or equipment (valves, tanks, or other equipment) greater than for inches, the exposure rate in contact with the pipe must not exceed 150 μR/hour.

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APPENDIX A: DETERMINATION OF AVERAGE RADIUM CONCENTRATIONS

The estimated scale activity to equal 220 pCi/g total (scale plus pipe), for ^{226}Ra, and for selected pipe diameters, scale thicknesses, and pipe schedules is shown in Tables A-1 through A-3. The estimated scale activity to equal 200 pCi/g total for scale plus pipe, for ^{228}Ra, and for selected pipe diameters, scale thicknesses, and pipe schedules is shown in Tables A-4 through A-6.

Table A-1. ^{226}Ra activity to equal 220 pCi/g total for selected Schedule 40 pipe diameters.

Pipe Size (I.D. inches), Schedule 40	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	2.91E+04	3.11E+03	7.98E+02	5.09E+02	3.64E+02
3	4.02E+04	4.21E+03	1.02E+03	6.19E+02	4.20E+02
6	5.02E+04	5.22E+03	1.22E+03	7.20E+02	4.70E+02
8	5.67E+04	5.86E+03	1.35E+03	7.84E+02	5.02E+02
10	6.42E+04	6.62E+03	1.50E+03	8.60E+02	5.40E+02
12	7.08E+04	7.27E+03	1.63E+03	9.25E+02	5.73E+02

Table A-2. ^{226}Ra activity to equal 220 pCi/g total for selected Schedule 80 pipe diameters.

Pipe Size (I.D. inches), Schedule 80	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	3.99E+04	4.19E+03	1.01E+03	6.17E+02	4.19E+02
3	5.42E+04	5.62E+03	1.30E+03	7.60E+02	4.90E+02
6	7.55E+04	7.75E+03	1.73E+03	9.73E+02	5.96E+02
8	8.60E+04	8.80E+03	1.94E+03	1.08E+03	6.49E+02
10	1.02E+05	1.04E+04	2.25E+03	1.24E+03	7.29E+02
12	1.17E+05	1.19E+04	2.55E+03	1.39E+03	8.03E+02

Table A-3. ^{226}Ra scale activity to equal 220 pCi/g total for selected Schedule 160 pipe diameters.

Pipe Size (I.D. inches), Schedule 160	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	5.92E+04	6.12E+03	1.40E+03	8.10E+02	5.15E+02
3	7.57E+04	7.77E+03	1.73E+03	9.75E+02	5.97E+02
6	1.20E+05	1.22E+04	2.61E+03	1.41E+03	8.17E+02
8	1.48E+05	1.50E+04	3.17E+03	1.70E+03	9.58E+02
10	1.83E+05	1.85E+04	3.88E+03	2.05E+03	1.13E+03
12	2.11E+05	2.13E+04	4.44E+03	2.33E+03	1.28E+03

Table A-4. ^{228}Ra activity to equal 200 pCi/g total for selected Schedule 40 pipe diameters.

Pipe Size (I.D. inches), Schedule 40	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	2.62E+04	2.80E+03	7.18E+02	4.58E+02	3.28E+02
3	3.61E+04	3.79E+03	9.17E+02	5.57E+02	3.78E+02
6	4.52E+04	4.70E+03	1.10E+03	6.48E+02	4.23E+02
8	5.10E+04	5.28E+03	1.21E+03	7.06E+02	4.52E+02
10	5.78E+04	5.96E+03	1.35E+03	7.74E+02	4.86E+02
12	6.37E+04	6.55E+03	1.47E+03	8.33E+02	5.15E+02

Table A-5. ^{228}Ra activity to equal 200 pCi/g total for selected Schedule 80 pipe diameters.

Pipe Size (I.D. inches), Schedule 80	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	3.59E+04	3.77E+03	9.13E+02	5.55E+02	3.77E+02
3	4.88E+04	5.06E+03	1.17E+03	6.84E+02	4.41E+02
6	6.80E+04	6.97E+03	1.55E+03	8.76E+02	5.37E+02
8	7.74E+04	7.92E+03	1.74E+03	9.70E+02	5.84E+02
10	9.18E+04	9.35E+03	2.03E+03	1.11E+03	6.56E+02
12	1.05E+05	1.07E+04	2.30E+03	1.25E+03	7.23E+02

Table A-6. ^{228}Ra activity to equal 200 pCi/g total for selected Schedule 160 pipe diameters.

Pipe Size (I.D. inches), Schedule 160	Scale Thickness = 0.01 cm (pCi/g in Scale)	Scale Thickness = 0.1 cm (pCi/g in Scale)	Scale Thickness = 0.5 cm (pCi/g in Scale)	Scale Thickness = 1.0 cm (pCi/g in Scale)	Scale Thickness = 2.0 cm (pCi/g in Scale)
2	5.33E+04	5.51E+03	1.26E+03	7.29E+02	4.64E+02
3	6.81E+04	6.99E+03	1.56E+03	8.77E+02	5.38E+02
6	1.08E+05	1.09E+04	2.35E+03	1.27E+03	7.35E+02
8	1.33E+05	1.35E+04	2.86E+03	1.53E+03	8.62E+02
10	1.65E+05	1.67E+04	3.49E+03	1.84E+03	1.02E+03
12	1.90E+05	1.92E+04	4.00E+03	2.10E+03	1.15E+03

APPENDIX B: EMPIRICAL ESTIMATES OF INSTRUMENT RESPONSE

Solving the API empirical equation discussed in Section 2.2.2 for the detector response (D in counts/minute), produces the results in Tables B-1 through B-3 for selected pipe diameters, scale thicknesses, and pipe schedules.

Table B-1. Analytical solution for counts per minute (D) for selected pipe diameters and scale thicknesses – Schedule 40.

Sch. 40 Pipe Diameter (I.D. inches)	D (counts/minute) for t_n=0.01 cm	D (counts/minute) for t_n=0.1 cm	D (counts/minute) for t_n=0.5 cm	D (counts/minute) for t_n=1.0 cm	D (counts/minute) for t_n=2.0 cm
2	1.37E+04	1.41E+04	1.59E+04	1.76E+04	1.98E+04
3	1.60E+04	1.64E+04	1.77E+04	1.89E+04	2.07E+04
6	1.74E+04	1.76E+04	1.87E+04	1.97E+04	2.12E+04
8	1.80E+04	1.82E+04	1.91E+04	2.01E+04	2.14E+04
10	1.89E+04	1.91E+04	1.98E+04	2.06E+04	2.18E+04
12	1.94E+04	1.95E+04	2.02E+04	2.09E+04	2.20E+04

Table B-2. Analytical solution for counts per minute (D) for selected pipe diameters and scale thicknesses – Schedule 80.

Sch. 80 Pipe Diameter (I.D. inches)	D (counts/minute) for t_n=0.01 cm	D (counts/minute) for t_n=0.1 cm	D (counts/minute) for t_n=0.5 cm	D (counts/minute) for t_n=1.0 cm	D (counts/minute) for t_n=2.0 cm
2	1.59E+04	1.62E+04	1.75E+04	1.88E+04	2.06E+04
3	1.80E+04	1.83E+04	1.92E+04	2.01E+04	2.15E+04
6	1.98E+04	2.00E+04	2.06E+04	2.13E+04	2.23E+04
8	2.04E+04	2.05E+04	2.10E+04	2.16E+04	2.25E+04
10	2.13E+04	2.14E+04	2.18E+04	2.23E+04	2.30E+04
12	2.18E+04	2.19E+04	2.23E+04	2.27E+04	2.33E+04

Table B-3. Analytical solution for counts per minute (D) for selected pipe diameters and scale thicknesses – Schedule 160.

Sch. 160 Pipe Diameter (I.D. inches)	D (counts/minute) for t_n=0.01 cm	D (counts/minute) for t_n=0.1 cm	D (counts/minute) for t_n=0.5 cm	D (counts/minute) for t_n=1.0 cm	D (counts/minute) for t_n=2.0 cm
2	1.81E+04	1.83E+04	1.91E+04	2.00E+04	2.13E+04
3	1.97E+04	1.99E+04	2.05E+04	2.12E+04	2.22E+04
6	2.16E+04	2.17E+04	2.20E+04	2.24E+04	2.30E+04
8	2.22E+04	2.22E+04	2.25E+04	2.28E+04	2.33E+04
10	2.29E+04	2.29E+04	2.32E+04	2.34E+04	2.38E+04
12	2.32E+04	2.32E+04	2.34E+04	2.36E+04	2.39E+04

APPENDIX C: STATISTICAL DETERMINATION OF THE NUMBER OF MEASUREMENTS REQUIRED TO CHARACTERIZE RADIONUCLIDE CONCENTRATIONS IN OIL FIELD PIPE AND EQUIPMENT

When the specific radionuclide activity is present in background (such as NORM), the Wilcoxon Rank Sum (WRS) test is used. The WRS evaluation is provided in Appendix C. The WRS test relies on managing two types of decision errors: Type I, or α (in this case, accepting waste that exceeds the waste acceptance criteria) and Type II, or β (in this case, rejecting waste that meets the waste acceptance criteria). First, Data Quality Objectives (DQOs) are set for this measurement situation. The DOQ process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing appropriate survey designs. Early in the process, DQOs are qualitative and quantitative statements derived from the DQO process that clarify the objective, define the most appropriate type of data to collect, determine the most appropriate conditions for data collection, and specify limits on decision errors used as the basis for establishing the quantity and quality of data needed to support the decision. The simple decision rule is: if the mean concentration in the survey unit (a shipment of contaminated oil field pipe or equipment) is less than the identified exposure rate, then the shipment is in compliance with the waste acceptance criteria. The estimate of the mean concentration is the arithmetic average of a set of randomly selected locations. At this point, the “null hypothesis,” or baseline condition that is assumed to be true in the absence of strong contradictory evidence, is established. For this problem, the null hypothesis is that the pipe shipment does not meet the waste acceptance criteria (i.e., an unacceptable exposure rate).

The decision based on the survey results can be simplified to a choice between “yes” and “no” as to whether the shipment meets the waste acceptance criteria. There are also two types of errors in this decision given the null hypothesis that the pipe shipment does not meet waste acceptance criteria: 1) incorrectly deciding that the answer is yes (deciding that the waste acceptance criteria is met), when the answer is actually no (a false positive or acceptance of contamination in excess of the waste acceptance criteria, or Type I decision error), and 2) incorrectly deciding that the answer is no (or deciding that the waste acceptance criteria is not met), when the answer is actually yes (a false negative or not accepting a shipment when in fact the levels meet the waste acceptance criteria, or Type II decision error). While the possibility of a decision error cannot be totally eliminated, it can be statistically controlled.

The number of total data points, N (reference plus survey area), for the WRS test is obtained for each reference area/survey unit pair (i.e., measurement/background pair) using the following equation:

$$N = (Z_{1-\alpha} + Z_{1-\beta})^2/3(P_r-0.5)^2$$

Where:
- $Z_{1-\alpha}$ = percentile represented by the selected decision error level α (Type I Error),
- $Z_{1-\beta}$ = percentile represented by the selected decision error level β (Type II error), and
- P_r = the probability that a measurement performed at a random location in the survey unit is larger than a random background measurement.

Inherent to this statistical determination is the grey region; or more specifically, the lower bound of the grey region, or LBGR. It is necessary to specify a grey region because variability in the parameter of interest and unavoidable imprecision in the measurement system combine to produce variability in the data so that a decision may be very difficult when the true but unknown value of the parameter is very near the waste acceptance criteria. For this situation, the LBGR is a exposure rate that is less than the exposure rate waste acceptance criteria, and is chosen to be easily distinguishable from the criteria. The grey region lies between the LBGR and the waste acceptance criteria in which only Type II decision errors occur (i.e., a false negative or not accepting a shipment when in fact the levels meet the waste acceptance criteria). The width of the grey region, or the difference between the waste acceptance criteria and the lower bound of the grey area of the decision, is referred to as the shift, or Δ. For this analysis the lower bound of the grey area is assumed to be half of the total waste acceptance criteria exposure rate, or 63 μR/hour; a reading that should be easily distinguished from the waste acceptance criteria. The shift and the estimated standard deviation of the measures of the exposure rate (σ) are used to calculate the relative shift (Δ/σ). For this analysis, the total contact exposure rate is 125 (source plus background) μR/hour, and background is 15 μR/hour. As indicated in Section 5.5.2.2 of MARSSIM (2000), when preliminary measurements are not available, it may be reasonable to assume a relative standard deviation on the order of 30%, based on experience. For this analysis, the estimated standard deviation of the survey measurement is taken as 30%. Thus,

$$\Delta/\sigma = (125\text{-}63)/(63 \text{ x } 0.3) = 62/19 = 3.28$$

From Table 5.1 of MARSSIM, when $\Delta/\sigma \sim 3.3$, $P_r \sim 0.99$. Solving for N, using $Z_{1-\alpha}$ ($\alpha = 0.05$; 5% decision error) = 1.645, and $Z_{1-\beta}$ ($\beta = 0.05$; 5% decision error) = 1.645, and assuming $P_r = 0.99$:

$$N = (1.645 + 1.645)^2/3(P_r\text{-}0.5)^2$$
$$N = (1.645+1.645)^2/3(0.99\text{-}0.5)^2 = 10.8/0.72 = 15$$

To assure sufficient data points to attain the desired power level with statistical tests and to allow for possible unusable data, MARSSIM recommends increasing the number of points by 20%, making the calculated value of N equal to 18. Since N equals the number of measurements of the shipment and background, the number for the shipment is one half of the total, or nine (rounding up to the nearest measurement). Thus, the average of nine exposure rate measurements, compared with the waste acceptance criteria exposure rate limit, will be used in the SOP for oilfield pipe and equipment.