B-1.0 MINIMUM DETECTABLE CONCENTRATIONS

NUREG-1507, *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions* (NRC 1998), and NUREG-1575, MARSSIM (DOD 2000), provide methodology for calculation of MDCs. The approach for calculating site-specific MDCs for individual instruments used in the FSS process at Southeast is as follows. The MDCs provided in this appendix were calculated using specific instrument data gathered at Southeast during the 2010, 2011, and 2012 field sampling events.

MARSSIM Section 6.2.2.6 states, "Scanning and direct measurement techniques should be capable of measuring levels below the established DCGLs – detection limits of 10-50 percent of the DCGL should be the target..." (DOD 2000).

The steps utilized for calculating MDCs for Southeast follow the approach detailed in NUREG-1507. The steps include:

1. Calculating the MDCR by selecting a given level of performance, scan speed, and background level of the detector; and
2. Selecting a surveyor efficiency, if applicable.

The scan MDCs for structure surfaces may be calculated as follows:

The observation interval (i) is defined as the width of the probe divided by the time that 25 percent of the probe is over a 4"×4" area of interest (scan speed).

$$i = \text{(probe width)} / \text{(scan speed)}$$

or

$$i = \frac{w}{s}$$

i = observation interval (second)
w = probe width (inches)

The observable background counts (b_i) is defined as is the number of background counts that occur during an observation interval.

$$b_i = (B) \times (i/60)$$

B = background count rate (cpm)

The minimum detectable number of net source counts in the interval is given by s_i. Therefore, for an ideal observer, the number of source counts required for a specified level of performance can be arrived at by multiplying the square root of the number of background counts by the detectability value associated with the desired performance (d'), as shown below:

$$s_i = d'\sqrt{b_i}$$

or

$$s_i = d'\sqrt{B(\frac{i}{60})}$$

s_i = minimum detectable number of net source counts
d' = Index of detectability
B = background count rate (cpm)

The MDCR is defined as the increase above background recognizable during a survey in a given period of time. The variable, *d*', is defined as the index of sensitivity and is dependent on the selected decision errors for Type I (alpha) and Type II (beta) errors. A true positive error (1–β) of 95 percent and a false positive error (alpha) of 60 percent were selected to be consistent with NUREG-1507. The value of 1.38 was obtained from Table 6.1 in NUREG-1507 (Table 6.5 in MARSSIM).

$$\mathrm{MDCR} = s_i \times (60/i) = \mathrm{cpm}$$

Finally, the scan MDCs for structure surfaces may be calculated:

$$MDC = \frac{MDCR}{\left(\sqrt{p}\right)(\varepsilon_s)(\varepsilon_i)\left(\frac{probe\ area}{100\ cm^2}\right)}$$

MDCR = minimum detectable count rate
ε_s = surface efficiency
ε_i = instrument efficiency
p = surveyor efficiency

The static MDC for structure surfaces may be calculated as follows:

$$MDC = \frac{\left(3 + 3.29\sqrt{(B)(T_g)(1 + \frac{T_g}{T_b})}\right)}{(\varepsilon_s)(\varepsilon_i)\left(\frac{probe\ area}{100\ cm^2}\right)(T_g)}$$

B = background count rate (cpm)
ε_s = surface efficiency
ε_i = instrument efficiency
T_g = sample count time (minutes)
T_b = background count time (minutes)

For alpha survey instrumentation with a background of approximately 1 to 3 counts per minute, a single count will give a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha emitting radionuclides can be calculated by use of Poisson summation statistics. Derivation of this equation can be found in Appendix J of MARSSIM.

The alpha scan probability for structure surfaces may be calculated as follows:

$$P\ (n\ \geq 1) = 1 - e^{\frac{(-G)(\varepsilon_i)(d)}{(60)(v)}}$$

$P(n \geq 1)$ = probability of getting greater than or equal to 1 count during the time interval t
G = Investigation Level (dpm/100 cm^2)
ε_i = instrument efficiency (cpm/dpm)
v = scan speed (inches/second)
d = Probe width (inches)

The MDC results are presented in dpm/100 cm^2 for comparison purposes. Thus, the MDC calculation was corrected using total efficiency and probe area.

Examples of this calculation using site-specific data for each type of instrument are shown below; all other information regarding the calculation of additional instrument MDCs is listed in Table B-1.

B-1.1 LUDLUM 2224-1 WITH LUDLUM MODEL Model 43-89A DETECTOR

The alpha static MDC for Ludlum Model 43-89A can be calculated as follows:

B = 0.5 cpm
T_b = 1 minute
T_g = 1 minute
ε_s = 0.25
ε_i = 0.214 cpm/dpm
probe area = 125 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(0.5)(1)(1 + \frac{1}{1})}\right)}{(1)(0.25)(0.214)\left(\frac{125}{100\ cm^2}\right)} = 94\ dpm/100\ cm^2$$

Note: Alpha instrument efficiency (e.g., 0.214) is instrument specific and ranged from 0.214 to 0.259 for the instruments used for definitive evaluations. Similarly, alpha background varied from 0.3 cpm to 0.6 cpm among the instruments used.

The alpha scan probability for the 43-89A can be calculated as follows:

G = 580 dpm/100 cm^2
ε_i = 0.214 cpm/dpm
v = 1 inch/second
d = 4 inches

$$P\ (n\ \geq 1) = 1 - e^{\frac{(-580)(0.214)(4)}{(60)(1)}} = 0.99$$

The alpha scan MDC for the 43-89A can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 0.5 cpm
i = 4 seconds

$$MDCR = 1.38\left(\sqrt{(0.5)\frac{4}{60}}\right)\left(\frac{60}{4}\right) = 3.8 \text{ cpm}$$

MDCR = 5.3 cpm
$\varepsilon_s = 0.25$
$\varepsilon_i = 0.214$
p = 0.5
probe area = 125 cm^2

$$MDC = \frac{3.8}{\left(\sqrt{0.5}\right)(0.25)(0.214)\left(\frac{125}{100\ cm^2}\right)} = 80\ dpm/100\ \ cm^2$$

The beta static MDC for the 43-89A can be calculated as follows:

B = 153 cpm
T_b = 1 minute
T_g = 1 minute
$\varepsilon_s = 0.25$
ε_i = 0.312 cpm/dpm
probe area = 125 cm

$$MDC = \frac{\left(3 + 3.29\sqrt{(153)(1)(1+\frac{1}{1})}\right)}{(1)(0.25)(0.312)\left(\frac{125}{100\ \ cm^2}\right)} = 621\ dpm/100\ \ cm^2$$

Note: Beta instrument efficiency (e.g., 0.312) is instrument specific and ranged from 0.282 to 0.371 for the instruments used for definitive evaluations. Similarly, beta background varied from 153 cpm to 236 cpm among the instruments used.

The beta scan MDC for the 43-89A can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 153 cpm
i = 4 seconds

$$MDCR = 1.38\left(\sqrt{(153)\frac{4}{60}}\right)\left(\frac{60}{4}\right) = 66 \text{ cpm}$$

MDCR = 66 cpm
$\varepsilon_s = 0.25$
$\varepsilon_i = 0.312$
$p = 0.5$
probe area = 125 cm^2

$$MDC = \frac{66}{\left(\sqrt{0.5}\right)(0.25)(0.312)\left(\frac{125}{100\ cm^2}\right)} = 957\ dpm/100\ \ cm^2$$

B-1.2 LUDLUM 2224-1 WITH A 43-10-1B DETECTOR

The alpha static MDC for the 43-10-1B can be calculated as follows:

B = 0.1 cpm
T_b = 10 minute
T_g = 1 minute
$\varepsilon_s = 0.25$
ε_i = 0.366 cpm/dpm
probe area = 100 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(0.1)(1)(1 + \frac{1}{10})}\right)}{(1)(1)(0.366)\left(\frac{100}{100\ cm^2}\right)} = 11\ dpm/100\ \ cm^2$$

The beta static MDC for the 43-10-1B can be calculated as follows:

B = 40.0 cpm
T_b = 10 minute
T_g = 1 minute
$\varepsilon_s = 1$
ε_i = 0.342 cpm/dpm
probe area = 100 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(40)(1)(1 + \frac{1}{10})}\right)}{(1)(1)(0.342)\left(\frac{100}{100\ cm^2}\right)} = 73\ dpm/100\ \ cm^2$$

B-1.3 LUDLUM 2224-1 WITH A 43-93A DETECTOR

The alpha static MDC for the 43-93A can be calculated as follows:

B = 0.9 cpm
T_b = 1 minute

T_g = 1 minute
ε_s = 0.25
ε_i = 0.300 cpm/dpm
probe area = 100 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(0.9)(1)(1+\frac{1}{1})}\right)}{(1)(0.25)(0.300)\left(\frac{100}{100\ \ cm^2}\right)} = 99\ dpm/100\ \ cm^2$$

The alpha scan probability for the 43-93A can be calculated as follows:

G = 580 dpm/100 cm^2
ε_i = 0.300 cpm/dpm
v = 1 inch/second
d = 4 inches

$$P\ (n\ \geq 1) = \ 1 - e^{\frac{(-580)(0.300)(4)}{(60)(1)}} = 0.99$$

The alpha scan MDC for the 43-93A can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 0.9 cpm
i = 4 seconds

$$MDCR = \ 1.38\left(\sqrt{(0.9)\frac{4}{60}}\right)(\frac{60}{4}) = 5.1 \text{ cpm}$$

MDCR = 5.1 cpm
ε_s = 0.25
ε_i = 0.300
p = 0.5
probe area = 100 cm^2

$$MDC = \frac{5.1}{\left(\sqrt{0.5}\right)(0.25)(0.300)\left(\frac{100}{100\ \ cm^2}\right)} = 96\ dpm/100\ \ cm^2$$

The beta static MDC for the 43-93A can be calculated as follows:

B = 250 cpm
T_b = 1 minute
T_g = 1 minute
ε_s = 0.25

ε_i = 0.382 cpm/dpm
probe area = 125 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(250)(1)(1+\frac{1}{1})}\right)}{(1)(0.25)(0.382)\left(\frac{100}{100\ \ cm^2}\right)} = 801\ dpm/100\ \ cm^2$$

The beta scan MDC for the 43-93A can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 250 cpm
i = 4 seconds

$$MDCR = \ 1.38\ \left(\sqrt{(250)\,\frac{4}{60}}\right)(\tfrac{60}{4}) = 85 \text{ cpm}$$

MDCR = 85 cpm
ε_s = 0.25
ε_i = 0.382
p = 0.5
probe area = 125 cm^2

$$MDC = \frac{85}{\left(\sqrt{0.5}\right)(0.25)(0.382)\left(\frac{100}{100\ \ cm^2}\right)} = 1258\ dpm/100\ \ cm^2$$

B-1.4 LUDLUM 2224-1 WITH A 43-37 DETECTOR

The alpha static MDC for the 43-37 can be calculated as follows:

B = 4.1 cpm
T_b = 1 minute
T_g = 1 minute
ε_s = 0.25
ε_i = 0.232 cpm/dpm
probe area = 100 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(4.1)(1)(1+\frac{1}{1})}\right)}{(1)(0.25)(0.232)\left(\frac{584}{100\ \ cm^2}\right)} = 26\ dpm/100\ \ cm^2$$

The alpha scan probability for the 43-37 can be calculated as follows:

G = 580 dpm/100 cm^2
ε_i = 0.232 cpm/dpm
v = 1 inch/second
d = 4 inches

$$P\ (n\ \geq 1) = \ 1 - e^{\frac{(-580)(0.232)(4)}{(60)(1)}} = 0.99$$

The alpha scan MDC for the 43-37 can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 0.9 cpm
i = 4 seconds

$$MDCR = \ 1.38\left(\sqrt{(4.1)\frac{4}{60}}\right)\left(\frac{60}{4}\right) 10.8 \text{ cpm}$$

MDCR = 10.8 cpm
ε_s = 0.25
ε_i = 0.232
p = 0.5
probe area = 100 cm^2

$$MDC = \frac{10.8}{\left(\sqrt{0.5}\right)(0.25)(0.232)\left(\frac{584}{100\ \ cm^2}\right)} = 45\ dpm/100\ \ cm^2$$

The beta static MDC for the 43-37 can be calculated as follows:

B = 361 cpm
T_b = 1 minute
T_g = 1 minute
ε_s = 0.25
ε_i = 0.18 cpm/dpm
probe area = 125 cm^2

$$MDC = \frac{\left(3 + 3.29\sqrt{(361)(1)(1 + \frac{1}{1})}\right)}{(1)(0.25)(0.18)\left(\frac{584}{100\ \ cm^2}\right)} = 194\ dpm/100\ \ cm^2$$

The beta scan MDC for the 43-37 can be calculated as follows:

w = 4 inches
s = 1 inch/second

$$i = \frac{4}{1} = 4 \text{ second}$$

d' = 1.38
B = 361 cpm
i = 4 seconds

$$MDCR = 1.38\left(\sqrt{(361)\frac{4}{60}}\right)\left(\frac{60}{4}\right) = 101.5 \text{ cpm}$$

MDCR = 101.5 cpm
$\varepsilon_s = 0.25$
$\varepsilon_i = 0.18$
$p = 0.5$
probe area = 125 cm^2

$$MDC = \frac{101.5}{\left(\sqrt{0.5}\right)(0.25)(0.18)\left(\frac{584}{100\ cm^2}\right)} = 546\ dpm/100\ cm^2$$

Table B-1. Instruments MDCs

Detector Model	Radiation of Interest	Background (cpm)		2 π Instrument Efficiency (cpm/dpm)		Count time		Scan MDC (dpm/100 cm^2)		Static MDC (dpm/100 cm^2)		Scan Probability
		Beta	Alpha	Beta	Alpha	Sample	Background	Beta	Alpha	Beta	Alpha	Alpha
Ludlum 43-89 Instrument A	Alpha/Beta	153	0.5	31.2	21.4	1	1	957	80	621	94	99
Ludlum 43-10-1 Instrument B	Alpha/Beta	40	0.1	34.2	36.6	1	10	N/A	N/A	73	11	N/A
Ludlum 43-93 Instrument A	Alpha/Beta	250	0.9	38.2	30.0	1	1	1,258	96	801	99	99
Ludlum 43-37	Alpha/Beta	361	4.1	18.0	23.2	1	1	546	45	194	26	99

N/A – Not Applicable

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B-2.0 TOTAL PROPAGATED UNCERTAINTY FOR THE USE OF FIELD RADIATION INSTRUMENTATION

B-2.1 LUDLUM MODEL 43-89 ALPHA-BETA SCINTILLATION DETECTORS WITH MODEL 2360 SCALER/RATEMETER

Total propagated uncertainty (TPU) of gross alpha/gross beta fixed-point measurements is addressed below. The uncertainties used for these calculations are at the 1σ level.

$$TPU = \sqrt{(B)^2 + (CA)^2 + (A)^2 + (\varepsilon_s)^2 + (E)^2 + (R)^2 + (CT)^2}$$

Where:

B = background uncertainty (dependent on cosmogenic and terrestrial variability as well as variability among construction materials used in a given structure). A value of 30 percent is used herein to include both the uncertainty associated with the statistical nature of radiation inherently variable and variability associated with differing construction materials.

CA = instrument calibration accuracy, estimated at ±10 percent, consistent with the instrument certificate of calibration and inclusive of uncertainty of 3 percent to 10 percent in calibration source activity.

Uncertainty for a given measurement includes the:

A = activity variability inherent in emissions of radioactive materials with the standard deviation determined by taking the square root of the number of counts divided by the counting time (Cember 1983). For the purposes of this estimate, a standard deviation of 10 percent is used.

ε_s = variability with respect to source efficiency. (Source [or surface] efficiency, ε_s, is corrected for by the use of a factor of 0.5 for maximum beta energies of 0.4 MeV and for alpha emitters and lower energy beta emitters with a factor of 0.25. Uncertainty with respect to source efficiency is assumed to be 26 percent based on Table 5.5, NUREG-1507.)

E = energy response variability. Two-pi alpha efficiency commonly varies from approximately 28 to 38 percent, or by about 30 percent, while beta efficiency varies from about 4 percent for C-14 to 17 percent (or more) for clorine (Cl)-36 or Sr-Y-90. Given that energy response uncertainty is isotope-specific, TPU must be determined on an isotope-specific basis. For this calculation, a value of 20 percent is used.

R = Instrument response varies across the face of the detector at up to 10 percent of the average reading.

CT = Cross talk from the alpha channel to the beta channel and from the beta channel to the alpha channel occurs at a rate of up to 10 percent and 1 percent, respectively. As such, the actual uncertainty will vary with the isotopic mixture present. For this estimate, a value of 2 percent is used.

Multiple other sources of uncertainty exist. These include uncertainty with respect to timing a fixed-point count and variability with respect to the physical probe size. These factors are generally relatively minor contributors to uncertainty and are, therefore, not included. Additional uncertainties, such as scan rate and source-to-detector distance, apply to scan measurements.

$$TPU = \sqrt{(0.3)^2 + (0.1)^2 + (0.1)^2 + (0.26)^2 + (0.2)^2 + (0.1)^2 + (0.02)^2} = 0.48$$

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