FIELD INSTRUMENTATION DETECTION SENSITIVITY

This appendix describes the detection sensitivities for field instrumentation used during the characterization of the New Haven Depot. This includes instruments used for gamma walkover surveys (GWS) of land areas, and instruments used for detection of contamination on building and/or structure surfaces through surface activity scans and direct measurements.

The RCOPCs at the New Haven Depot are discussed in Section 1 of the Characterization Survey Work Plan. As indicated, the RCOPCs are natural thorium and uranium. Since both were present in unprocessed ore the natural thorium and natural uranium chains remained in secular equilibrium with the parent radionuclide, as they were in nature.

The parent radionuclides in the natural thorium and natural uranium decay chains, thorium-232 (^{232}Th), uranium-238 (^{238}U) and uranium-235 (^{235}U), emit alpha particles. The daughter products in both chains decay by emission of alpha or beta particles, some with accompanying emission of gamma rays. The decay schemes for both the natural thorium and natural uranium chains are very well documented, and this knowledge is used in the design of the characterization surveys and selection of appropriate survey instruments and analysis methods.

As presented in the following sections, the NaI gamma walkover survey minimum detectable concentrations (MDCs) for natural thorium and natural uranium plus progeny in soil are:

Natural thorium: **1.3 pCi/g**

Natural uranium: **19.7 pCi/g**

Integrated or static measurement MDCs and the MDC for smear analysis are also presented in the following sections.

Gamma Walkover Survey (GWS) Detection Sensitivity

The GWS will be performed using a Ludlum 44-10 (2"x 2" NaI scintillation detector) or equivalent detector. The GWS is accomplished by a walking speed (1.5 ft/sec) walkover by the surveyor at a detector height of approximately 2-4 inches above the ground surfaces. Results are recorded in units of counts per minute (cpm).

The NaI detection sensitivities, i.e., MDC in soil, for the two RCOPCs are presented below. This evaluation assumes the RCOPCs are in the upper 15 cm layer of soil with an area of 56 cm for modeling and calculation purposes.

GWS Minimum Detectable Concentration For Natural Thorium in Soil

The methodology used to determine the NaI scintillation detector scan MDC is based on NRC NUREG –1507, *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions*, December 1997. Factors included in this analysis are the surveyor scan efficiency, index of sensitivity, the natural background of the surveyed area, scan rate, detector to source geometry, aerial extent of the contamination, and energy and yield of gamma emissions.

The computer code Microshield was used to model the presence of a normalized 1 pCi/g total thorium with its 50-year decay progeny in soil with the further assumption that the activity is uniformly distributed to a depth of 15 cm and spread over a disk shaped area with a diameter of 56 cm. The uncontaminated soil cover thickness has zero thickness (contamination on the surface) and there is a 0.051 cm aluminum shield simulating the cover of the NaI detector to complete the model source term. This model is consistent with the NUREG-1507 methodology and provides for a count rate to exposure rate ratio (cpm/μR/hr) to be calculated.

The following sections provide tabulated data based upon the NUREG-1507 methodology as applied to NaI scintillation detector used in this survey, zero thickness soil cover, and a 56 cm diameter soil uniformly contaminated to a 15 cm thickness. The dose point is centered over the contaminated disk of soil.

Fluence Rate to Exposure Rate (FRER, no units)

The fluence rate to exposure rate (FRER) may be approximated by:

$$\mathrm{FRER} \sim (1\ \mu\mathrm{R/hr})/(E_\gamma)(\mu_{en}/\rho)_{air}$$

Where,

E_γ = energy of the gamma photon of concern, keV

$(\mu_{en}/\rho)_{air}$ = the mass energy absorption coefficient for air, cm^2/g

The FRER over a 40 keV to 3 MeV gamma energy range is provided in Table 1.

Table 1: Fluence Rate to Exposure Rate (FRER)

Energy$_\gamma$, keV	$(\mu_{en}/\rho)_{air}$, cm^2/g	FRER
40	0.064	0.3906
60	0.0292	0.5708
80	0.0236	0.5297
100	0.0231	0.4329
150	0.0251	0.2656
200	0.0268	0.1866
300	0.0288	0.1157
400	0.0296	0.0845
500	0.0297	0.0673
600	0.0296	0.0563
800	0.0289	0.0433
1,000	0.0280	0.0357
1,500	0.0255	0.0261
2,000	0.0234	0.0214
3,000	0.0205	0.0163

Probability of Interaction (P) Through Detector End for a Given Energy

The probability, P, of a gamma ray interaction in the NaI scintillation crystal entering through the end of the crystal is given by:

$$\text{Probability (P)} = 1\text{-}e^{-(\mu/\rho)NaI(X)(\rho NaI)}$$

Where:

$(\mu/\rho)_{NaI}$ = the mass attenuation coefficient for NaI

X = the thickness through the bottom edge (end facing the soil) of the Ludlum 44-10 2”x2” NaI crystal, 5.1 cm

ρ = the density of the NaI crystal, 3.67 g/cm^3

The probability of interaction in the NaI detector over the same gamma energy range is provided in Table 2.

Table 2: NaI Probability of Interaction (P)

Energy$_\gamma$, keV	$(\mu/\rho)_{NaI}$, cm^2/g	P
40	18.3	1.00
60	6.23	1.00
80	2.86	1.00
100	1.58	1.00
150	0.566	1.00
200	0.302	1.00
300	0.153	0.94
400	0.11	0.87
500	0.0904	0.82
600	0.079	0.77
800	0.0657	0.71
1,000	0.0576	0.66
1,500	0.0464	0.58
2,000	0.0412	0.54
3,000	0.0367	0.50

Relative Detector Response (RDR)

The Relative Detector Response (RDR) by energy is determined by multiplying the FRER by the probability (P) of an interaction and is given by:

$$RDR = FRER \times P$$

The RDR for a NaI detector over the same gamma energy range is provided in Table 3.

Table 3: Relative Detector Response

Energy$_\gamma$, keV	FRER	P	RDR
40	0.3906	1.00	0.3906
60	0.5708	1.00	0.5708
80	0.5297	1.00	0.5297
100	0.4329	1.00	0.4329
150	0.2656	1.00	0.2656
200	0.1866	1.00	0.1859
300	0.1157	0.94	0.1091
400	0.0845	0.87	0.0737
500	0.0673	0.82	0.0549
600	0.0563	0.77	0.0435
800	0.0433	0.71	0.0306
1,000	0.0357	0.66	0.0236
1,500	0.0214	0.58	0.0124
2,000	0.0214	0.54	0.0115
3,000	0.0163	0.50	0.0081

Determination of Count Rate per μR/hr as a Function of Energy

The equivalent FRER, P, and finally RDR may be calculated for a NaI Scintillation detector at the cesium-137 energy of 662 keV. Manufacturers of this equipment typically provide an instrument response in terms of count rate and μR/hr at the cesium-137 energy. This point allows determination of the count rate per μR/hr and ultimately activity concentration and minimum detection sensitivity level in terms of pCi/g.

Based on measured counts in a known field it is estimated that a typical Ludlum 44-10 NaI response is 900 cpm/μR/hr and using the same methodology as shown in the tables above, the FRER, P and RDR are calculated. The mass energy absorption coefficient for air and the mass attenuation coefficient for NaI are interpolated from tables in the *Radiological Health Handbook*, Revised Edition January 1970, pages 139, and 140. These values for Cs-137 are provided in Table 4.

Table 4: NaI FRER, P and RDR For Cs-137 Gamma Energy (Ba-137m)

$Energy_\gamma$, keV	FRER	$(\mu_{en}/\rho)_{air}$, cm^2/g	$(\mu/\rho)_{NaI}$, cm^2/g	P	RDR
662	0.0514	0.0294	0.0749	0.75	0.0387

The detector response (cpm) to any other gamma energy is based upon the ratio of the RDR at that energy to the known Cs-137 energy RDR as shown in the following equation.

$$\text{cpm}/\mu\text{R/hr}, E_i = (\text{cpm}_{\text{Cs-137}}) \times (\text{RDR}_{\text{Ei}}) / (\text{RDR}_{\text{Cs-137}})$$

$$= (900) \times (\text{RDR}_{\text{Ei}}) / (\text{RDR}_{\text{Cs-137}})$$

The NaI count rate over the same range of gamma energies presented previously is provided in Table 5.

Table 5: NaI cpm/μR/hr, E_i

Energy$_\gamma$, keV	RDR$_{Ei}$	NaI Detector, E_i, cpm per μR/hr
40	0.3906	9078
60	0.5708	13264
80	0.5297	12309
100	0.4329	10060
150	0.2656	6172
200	0.1859	4320
300	0.1091	2536
400	0.0737	1712
500	0.0549	1277
600	0.0435	1010
662	0.0387	900
800	0.0306	711
1,000	0.0236	548
1,500	0.0124	288
2,000	0.0115	267
3,000	0.0081	188

Finally, the count rate to exposure rate ratio for natural thorium and daughters in secular equilibrium and the contribution to the total exposure rate are determined using the output of the Microshield runs and the count rate to exposure rate ratios from Table 5. The weighted cpm/μR/hr over the same energy range in previous tables is presented in Table 6.

Table 6: NaI Weighted cpm/μR/hr For Natural Thorium and Decay Products

keV	MicroShield Exposure Rate (with buildup) for 1 pCi/g ^{232}Th, μR/hr	cpm/μR/hr	Weighted cpm/μR/hr
40	3.957E-05	9078	0
60	6.309E-05	13264	1
80	7.110E-03	12309	91
100	1.815E-03	10060	19
150	2.134E-03	6172	14
200	4.142E-02	4320	187
300	3.261E-02	2536	86
400	4.042E-03	1712	7
500	2.979E-02	1277	40
600	8.114E-02	1010	85
800	1.058E-01	711	78
1000	2.360E-01	548	135
1500	7.559E-02	288	23
2000	2.136E-03	267	1
3000	3.396E-01	188	66
Total	**9.593E-01**		**833**

The scan MDC is calculated using the NUREG-1507 methodology where:

The average number of background counts in a one second interval, b_i = background cpm/60

For the Ludlum 2” x 2” NaI scintillation detector and the measured background count rate of 4600 cpm the calculated background counts in a one second measurement interval is:

$$b_i = (4600 \text{ cpm}) / 60 = 77 \text{ counts}$$

The minimum detectable count rate, MDCR is

$$MDCR = (d') \times (b_i)^{0.5} \times (60 \text{ seconds}/1 \text{ minute})$$

Where d', equal to 1.38 from NUREG-1507, Table 6.1, represents the rate of detections at a 95% true positive proportion with a false positive proportion of 60%, b_i, is the background counts in the interval determined above.

$$MDCR = (1.38) \times 8.8 \times (60 \text{ seconds}/1 \text{ min}) = 725 \text{ cpm}$$

The Minimum Detectable Count Rate for the surveyor is given as

$$MDCR_{surveyor} = MDCR/(p)^{0.5}$$

Where

p = Surveyor Efficiency, equal to 0.75 to 0.5 as given by NUREG-1507 (0.5 is chosen as a conservative choice).

$$MDCR_{surveyor} = 725/0.707 = 1025 \text{ cpm}$$

The Minimum Detectable Exposure Rate (MDER_ for the surveyor is obtained from the $MDCR_{surveyor}$ divided by the Table 6 weighted count rate to exposure rate value of 833 cpm/μR/hr for natural thorium, including decay progeny in secular equilibrium, is:

$$(1025 \text{ cpm}) /(833 \text{ cpm}/\mu R/hr) = 1.23 \ \mu R/hr$$

The scan MDC is then equal to the ratio of the MDER in the field to the exposure rate determined for the normalized 1 pCi/g concentration of natural thorium in soil as follows:

$$\text{Scan MDC} = (\text{Normalized Th}_{\text{Total Conc}}) \times (\text{Exposure Rate}_{\text{Surveyor}})/(\text{Exposure Rate}_{\text{normalized Th conc}})$$

Natural Thorium Scan MDC = (1 pCi/g) x (1.23 μR/hr)/(9.593E-1 μR/hr) = **1.28 pCi/g**

<u>GWS Minimum Detectable Concentration for Natural Uranium plus progeny in Soil</u>

The MDC for natural uranium (^{238}U and ^{235}U plus decay products in secular equilibrium) is determined in the same manner. The weighted count rate ratio to exposure rate (cpm/μR/hr) is presented in Table 7.

Table 7: NaI Weighted cpm/μR/hr For Natural Uranium (U-Nat) and Decay Products

keV	MicroShield Exposure Rate (with buildup) for 1 pCi/g U-Nat, μR/hr	cpm/μR/hr	Weighted cpm/μR/hr
40	7.03E-8	9078	0
60	3.40E-5	13264	8
80	3.59E-4	12309	75
100	1.61E-4	10060	28
150	5.70E-5	6172	6
200	9.09E-4	4320	67
300	2.43E-3	2536	105
400	5.61E-3	1712	164
500	3.27E-4	1277	7
600	1.03E-2	1010	177
800	2.77E-3	711	34
1000	1.10E-2	548	102
1500	8.99E-3	288	44
2000	1.58E-2	267	72
Total	**5.87E-2**		**889**

The scan MDC is calculated using the background counts in the measurement interval (77 counts), $MDCR_{surveyor}$ (1025 cpm), MDER equation and scan MDC equation from the determination of natural thorium scan MDC presented previously.

The MDER is obtained from the $MDCR_{surveyor}$ divided by the Table 7 weighted count rate to exposure rate value of 889 cpm/μR/hr for natural uranium, including decay progeny in secular equilibrium is:

$$(1025 \text{ cpm}) / (889 \text{ cpm/}\mu\text{R/hr}) = 1.15 \ \mu\text{R/hr}$$

The scan MDC is then equal to the ratio of the MDER in the field to the exposure rate determined for the normalized 1 pCi/g concentration of natural uranium plus progeny in soil as follows:

$$\text{Scan MDC} = (\text{Normalized } U_{\text{Total Conc}}) \times (\text{Exposure Rate}_{\text{Surveyor}})/(\text{Exposure Rate}_{\text{normalized U conc}})$$

$$\text{Natural Uranium Scan MDC} = (1 \text{ pCi/g}) \times (1.15\ \mu\text{R/hr})/(5.87\text{E-}2\ \mu\text{R/hr}) = \mathbf{19.7\ pCi/g}$$

Building Surface and/or Structure Surface Scan, Static Measurements and Smear Analysis Minimum Detectable Concentration

As indicated in Section 6 of the Characterization Survey Work Plan, building and/or structure surfaces will be surveyed for alpha contamination using direct surface scan and static measurement techniques. Surveys will be performed in accordance with CABRERA standard operating procedures. These surveys may be performed using a Ludlum Model 43-37 floor monitor, Ludlum Model 43-68 gas flow proportional detector, or Ludlum Model 43-89 ZnS scintillation detector. The alpha surface scan MDC for each of these detectors is provided in the following sections.

General Information on Alpha Scan MDC

Scan MDCs for alpha emitters must be derived differently than scanning for beta and gamma emitters. *MARSSIM* contains formulas and probability concepts for alpha scans in Appendix J, which provides a complete derivation of the formulas used to determine the probability of observing a count when performing an alpha scan. Additional information on various material background, detector efficiencies, surface material effects, etc. may be found in NUREG-1507.

In general, when performing an alpha scan, once a count has been recorded and the surveyor stops, the surveyor should wait a sufficient period of time such that if the guideline level (or action level) of contamination is present, the probability of getting another count is at least 90%. For low background areas (alpha background of 0 to 3 cpm), it is assumed that a single count is sufficient to cause a surveyor to stop and investigate. For higher background areas or when using larger area detectors resulting in a higher background count rates such as the Ludlum Model 43-37 floor monitor (alpha background up to 10 cpm), the surveyor will usually need to get at least 2 counts while passing over the source area before stopping for further investigation.

For the purpose of determining alpha scan MDCs, the source activity, G in the following equations, is assumed to be slightly less than 50% of the natural thorium surface activity action level presented in the Characterization Survey Work Plan, Table 3-1, i.e., 100 dpm/100 cm^2.

The assumptions pertaining to scan speeds, background, efficiency, dwell times, etc. used in the evaluation of alpha scan MDCs (probability of detection) are provided in Table 8. The probabilities of detection calculated using the equations below are also presented in Table 8. These calculations indicate that the under the conditions presented in the assumptions, the design objective of 90% probability is achieved when scanning surfaces contaminated to 100 dpm/100 cm^2 when using the indicated detectors.

Table 8: Alpha Surface Scan Assumptions

Model No.	Probe Area (cm^2)	Probe Width (cm)	α Efficiency (cpm /dpm)	α Bkgrd (cpm)	Scan Speed (cm/sec)	Pause Time (sec)	P(n>=1)	P(n>=2)
43-37	582	15	0.15*	10	6	2.5	NA	0.91
43-89 & 43-68	126	9	0.15*	3	1	7.3	0.90	NA

cm = centimeters
cm^2 = square centimeters
cpm = counts per minute
dpm = disintegrations per minute
sec = second
cm/sec = centimeters per second

* Manufacturer's stated 4π alpha efficiencies for these detectors have a range of 15 to 20%. For this evaluation, 15% is chosen as a conservative approach.

Ludlum Model 43-37 Scan MDC

The Ludlum Model 43-37 gas proportional detector is a large area detector (active area of 582 cm^2) with a higher background count rate compared to smaller area detectors, such as the Ludlum Model 43-68 or Ludlum Model 43-89. Using *MARSSIM* Equation J-7, the probability of two or more alpha counts during the scan survey of a surface is determined as follows:

$$P(n \geq 2) = 1 - P(n = 0) - P(n = 1) \quad (\textit{MARSSIM} \text{ Equation J-7})$$

$$= 1 - \left(e^{-A}\right) \times \left(1 + A\right)$$

$$\text{for } A = \frac{(GE + B)t}{60}$$

Where:

$P(n \geq 2)$ = Probability of getting 2 or more counts during the time interval t

$P(n = 0)$ = Probability of not getting any counts during the time interval t

$P(n = 1)$ = Probability of getting 1 count during the time interval t

G = Source activity (100 dpm/100 cm^2)

E = Detector efficiency (4π)

B = Background count rate (cpm)

t = Dwell time over source (seconds)

Scans will be performed by moving the active area of the detector over the surface of interest at or below the given scan speed in Table 8. If two or more counts occur over the indicated observation interval, a one-minute integrated or static measurement will be performed at that location prior to resuming the scan survey. For Class 3 survey units, if the result of the static measurement is in excess of 100 dpm/100 cm2 (slightly less than 50% of the natural thorium action level), the area will be marked for biased measurements and investigated further.

Ludlum Model 43-89 and Ludlum Model 43-68 Scan MDC

If the Ludlum Model 43-89 alpha scintillation detector or Ludlum Model 43-68 gas proportional detector is used, then *MARSSIM* Equation J-5 and the assumptions listed in Table 8, with a probability of at least one count occurring while surveying an area of contamination equal to the 100 dpm/100 cm^2 surface scan action level $P(n \geq 1)$, will be implemented instead of *MARSSIM* Equation J-7. The Model 43-89 and Model 43-68 are similar in active area and efficiency. Scans are performed the same (scan speed and dwell time) for both detectors.

Although, the background may be slightly different for the two detector types, for this evaluation, they are assumed to be the same.

Using *MARSSIM* Equation J-5 and the assumptions listed in Table 8 (scan speeds, background, efficiency, dwell times, etc), the probability that a single count is sufficient to cause a surveyor to stop and investigate further is derived as follows:

$$P(n \geq 1) = 1 - P(n = 0) = 1 - e^{-A} \qquad \text{(MARSSIM J-5)}$$

$$\text{for } A = \frac{GEd}{60v}$$

Where:

$P(n \geq 1)$ = Probability of getting 1 or more counts during the time interval t

$P(n = 0)$ = Probability of not getting any counts during the time interval t

G = Source activity (100 dpm/100 cm^2)

E = Detector efficiency (4π)

d = Width of the detector in the direction of scan (cm)

v = Scan speed (cm/s)

Alpha scans will be performed using the Ludlum Model 43-89 or Ludlum Model 43-68 detector by moving the active area of the detector over the surface of interest at the scan speed shown in Table 8. Whenever a count is detected during the scan, the detector will be held in place over the location where the count was detected for the indicated pause time (approximately 7-8 seconds). If a second count is detected over this location during the pause time, a one minute integrated count will be performed. For Class 3 survey units, if the result of the static measurement is in excess of 100 dpm/100 cm2 (slightly less than 50% of the natural thorium action level), the area will be marked for biased measurements and investigated further.

Integrated Direct Surface Measurements and Smear Analysis

Integrated direct measurements (i.e., static measurements) of surface alpha contamination will be performed to compare contaminant concentrations at discrete sampling locations to the appropriate action level. Smear samples will be collected at biased building surface locations, as appropriate, to quantify transferable surface alpha contamination.

Integrated alpha activity measurements will be performed using a Ludlum Model 43-37 gas proportional detector, Ludlum Model 43-68 gas proportional detector, Ludlum Model 43-89 handheld scintillation detector, or equivalent. Again, the parameters and static measurement requirements are very similar for the Ludlum Model 43-68 and Ludlum Model 43-89 detectors. For the purpose of this evaluation, the same parameters are used for both detectors. Smears will be analyzed using a Ludlum Model 43-10-1 smear count detector attached to a Ludlum Model 2929 ratemeter, or equivalent. The static measurement and smear analysis MDC and assumptions used for each of the detectors are presented in Table 9. The MDC was determined using Equation 3-11 of *NUREG 1507*. For comparison, the action levels applicable to the New Haven Depot are presented in Table 3-1 of the Characterization Survey Work Plan.

Table 9: Static Survey and Smear Analysis MDC and Assumptions

Model No.	Count Time (min)	Bkg Count Time (min)	Probe Area (cm^2)	α Efficiency (cpm/dpm)	α Bkg (cpm)	α Static MDC (dpm/100 cm^2)
43-37	1	1	582	0.15*	10	20
43-89 & 43-68	1	1	126	0.15*	3	60
2929	4	20	Smear	0.39	2	8

min = minutes
cm^2 = square centimeters
cpm = counts per minute
dpm = disintegrations per minute

* Manufacturer's stated 4π alpha efficiencies for these detectors have a range of 15 to 20%. For this evaluation, 15% is chosen as a conservative approach.

Summary

GWS, scan survey, static measurement and smear analysis MDCs have been calculated for each instrument to be used during the New Haven Depot characterization. Calculation of MDCs for each instrument ensures that direct measurements are performed using radiation survey instrumentation sufficient to evaluate radiological conditions in accordance with the requirements of the Characterization Survey Work Plan. Due to the potential variations of conditions in the field, parameters such as static measurement and smear count times may be adjusted onsite with the permission of the CABRERA project health physicist.