TECHNICAL MEMORANDUM

SCANNING CAPABILITY ASSESSMENT
OF GANGED LUDLUM 44-20**s** FOR DISCRETE Ra-226 IN SOIL

Claude Wiblin, CHP

September 2013

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

$(\mu/\rho)_{NaI}$	mass attenuation coefficient for NaI
μR/hr	microReontgen per hour
%	percent
^{226}Ra	Radium-226
^{137}Cs	Cesium-137
bgs	below ground surface
cm	centimeter
COC	contaminant of concern
cpm	counts per minute
Eff_{total}	Total detector efficiency
FRER	fluence rate to exposure rate
GPS	global positioning system
GWS	gamma walkover survey
m	meter
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MDC	minimum detectable concentration
MDCR	Minimum detectable count rate
Micro*Shield*	Software manufactured by Grove Engineering
NaI	Sodium iodide
P	Probability
RDR	Relative Detector Response

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1.0 INTRODUCTION

For the scanning activities described in this Technical Memo, the Ludlum 44-20 NaI detector will be used. Calculation data is in accordance with Provisional US Patent No. 16505188, *Method and Apparatus for Improved Radiation Detection in Radiation Scanning Systems of Surfaces With Multiple Sequencing of Detectors*.

The goal of this Technical Memo is to determine:

- The radiation levels from a 10 mCi ^{226}Ra artifact or source buried three feet in the ground.
- The minimum detectable count rate (MDCR) for a NaI 3X3 detector in a variable background of 4 - 9 µR/hour with an average of 7 µR/hour.
- The appropriate height above ground of the detector.
- The scanning speed to maintain reasonable assurance that MDCRs are met.
- The optimal path width.

Scan surveys are planned using ganged sets of NaI 3X3 detectors coupled with a rate-meter/scaler that is configured to output directly to a Global Positioning System (GPS) unit. The basic method for performing a gamma driveover survey is to drive along a path with the detector bottom at a set distance and a set speed. The GPS will provide high quality, precision geospatial positioning data to support data verification, and remediation. The rate-meter/scalars used for this work will be configured to output directly to the GPS unit. The GPS unit will perform data logging functions. An example setup of two two-ganged detectors, meters, GPS and computer is shown in Figure 1.

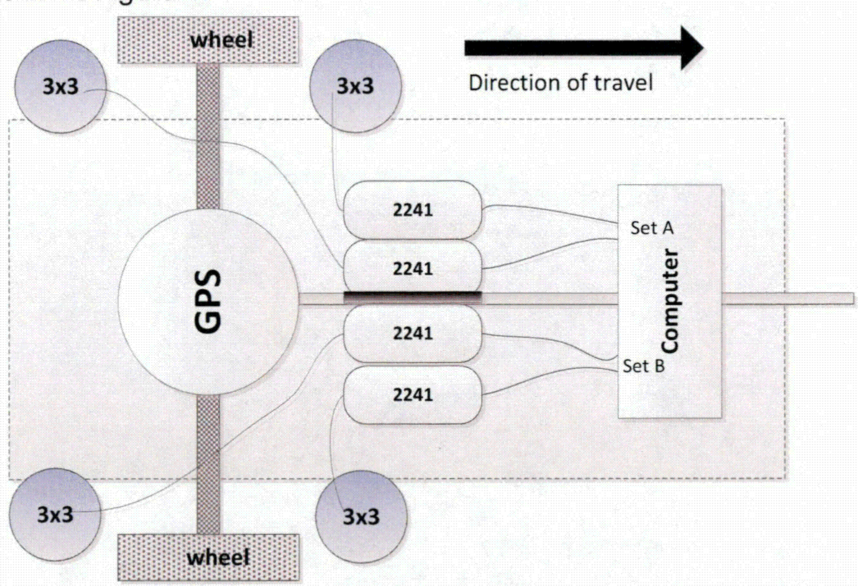

Figure 1. Example Setup of Scan Device

2.0 MINIMUM DETECTABLE COUNT RATE

Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) Section 6.7.2.1 describes the methodology used to calculate the Scan Minimum Detectable Concentrations (MDCs) for land areas that are delineated in MARSSIM Table 6.7.

The minimum detectable number of net source counts in the interval is given by s_i. For walkover gamma surveys, 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 (as reflected in *d'*) as shown in MARSSIM Equation 6-8 which parallels the MARSSIM page 6-45 analysis as follows:

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

For driveover and walkover gamma surveys, d' is set equal to 1.38 as this index of sensitivity is independent of human factors. The value of d' is from Table 6.5 of MARSSIM and the required true positive proportion is 0.95 and the false positive rate of 0.60 will be tolerated.

The manufacturer gives the detector a sensitivity value of 2300 cpm/µR/h (^{137}Cs). As background exposure rates vary but are typically between 4-9 µR/hr, the range of b_i value may need to be adjusted to actual field conditions and the impact is reviewed as follows.

The Minimum Detectable Count Rate (MDCR) as cpm is calculated as:

$$MDCR = (1.38)(b_i)^{0.5}(60/i)$$

For a given time interval, the Minimum Detectable Counts (MDC) is the MDCR converted to seconds times the length of the interval:

$$MDC = [MDCR/60]*(i)$$

However, MARSSIM does not strictly apply to this application as all measurements will be recorded every second and reviewed through mapping; thus, a value for surveyor efficiency will not be applied. Per the Provisional Patent, for in-sequence detectors, the minimum detectable number of net source counts in a specific time interval in a specific time period for two detectors is given by $s_{in\text{-}sequence}$.

$$s_{in-sequence} = d'\sqrt{n \times b_i}$$

The minimum detectable source count rate (*MDCR*), in cpm, for multiple in-sequence detectors may be calculated by:

$$MDCR_{multiple} = s_{in-sequence} \times (60/(n \times i))$$

Again, with a value of d' of 1.38, the equation is reduced to:

$$MDCR_{multiple} = 1.38\sqrt{2 \times b_i} \times (60/(2 \times i))$$

Table 1 illustrates the differences between a single 3x3 versus a ganged set of 2- 3x3s.

Table 1. MDCRs for One and 2-Ganged Detectors for 1s Interval in Varying Backgrounds

Background (µR/hr)	Background (cpm)	MDCR 1 Detector	MDCR 2 Detectors
9	20700	1538	1087
8	18400	1450	1025
7	16100	1356	959
6	13800	1256	888
5	11500	1146	811
4	9200	1025	725

Calculations of MDCR for a 2-Ganged set for time intervals from 0.5 s to 1.5 s in increments of 0.5 are presented in Table 2 and presented graphically in Figure 2.

Table 2. MDCRs for 2-Ganged Detectors for Various Observation Intervals in 7µR/hr

i (s)	MDCR (cpm)
0.5	1356
1	959
1.5	783
2	678
2.5	607
3	554

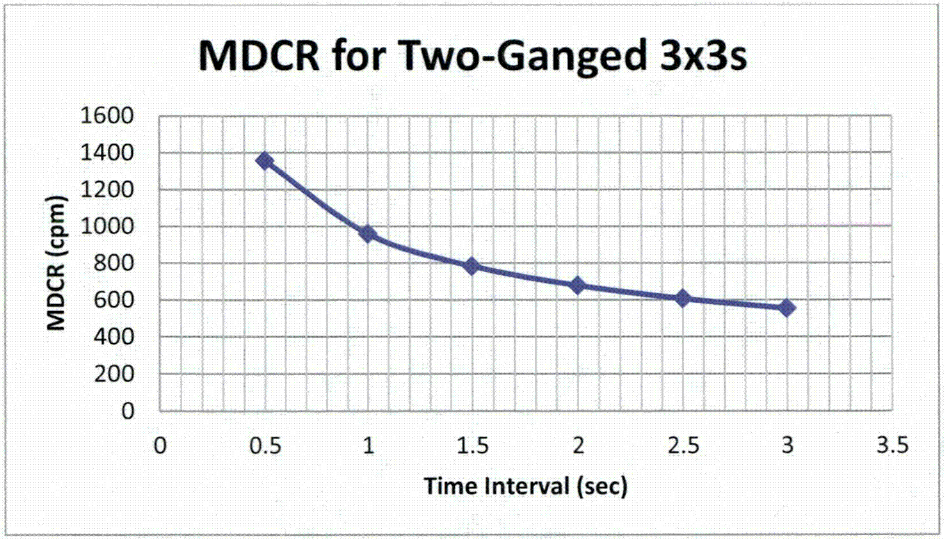

Figure 2. MDCR for Two-Ganged 3x3s

MARSSIM develops the time interval for small surface areas versus the geometry described here for a point source 3' bgs. The time interval may be arranged for a desired MDCR as shown in Figure 3. The overall field of view for detectability is a circle but the observation interval (t_{obs}) for the time that a source is detectable between points a and b is determined by:

$$t_{obs} = 2r\cos\theta/v$$

Where v is the velocity of the detector and r is the radius of the circle. The closer the source is to the top of the circle in Figure 3, the shorter the observation interval versus the longest at the equator.

The distance from b to c is the actual scan path width and will be calculated:

$$Path\ Width = 2r\sin\theta$$

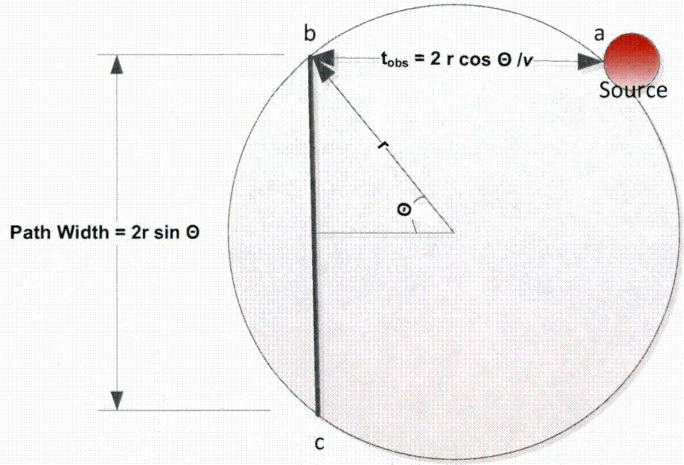

Figure 3. Observation Interval and Path Width Error! Bookmark not defined.

3.0 HEIGHT OF DETECTOR

The computer code Microshield® was used to model the presence of a 10 mCi of ^{226}Ra in soil with the assumption that the activity was a point source. This is consistent with the MARSSIM methodology and permits a count rate to exposure ratio (cpm/μR/hr) to be calculated. Immediately above the source, the exposure rate is highest at the ground surface but this is not always true when geometry considerations are made for lateral distances. The maximum exposure rate is anticipated to increase and peak at some distance from the ground surface and this was evaluated for the following parameters:

- depth of the point source is three feet,
- dose points are 0.5, 1, 2, 3, 4, 5, 6, and 8 feet above the surface,
- lateral distances considered are 4, 5, 6, and 8 feet, and
- density of soil is 1.6 g/cm^3.

Activity must be entered into Microshield in units of curies with considerations for decay and soil density. Therefore, a activity concentration for ^{226}Ra was entered into Microshield as 0.01 curies (10 mCi) with 65 years of decay time and soil composition from the Federal Guidance Report 12 at a density of 1.6 g/cc.

Microshield presents an output in units of mR/hour with buildup for each standard energy indice. The Microshield exposure rate outputs are included as an attachment. Table 3 lists the total exposure determined from a buried 10 mCi ^{226}Ra source. The height for the maximum exposure rate is different for each lateral distance and is shown graphically in Figure 4.

Table 3. Exposure Rates from 10 mCi of Ra-226 for Varying Detector Heights and Laterals

Height (ft)	Exposure Rate (μR/hour)			
	4' Lateral	5' Lateral	6' Lateral	8' Lateral
0.5	0.56	0.11	0.02	0.00
1	0.93	0.23	0.05	0.00
2	1.65	0.60	0.20	0.02
3	2.10	0.97	0.41	0.06
4	2.28	1.25	0.63	0.14
5	2.27	1.40	0.81	0.23
6	2.16	1.46	0.93	0.33
7	2.01	1.45	0.99	0.41

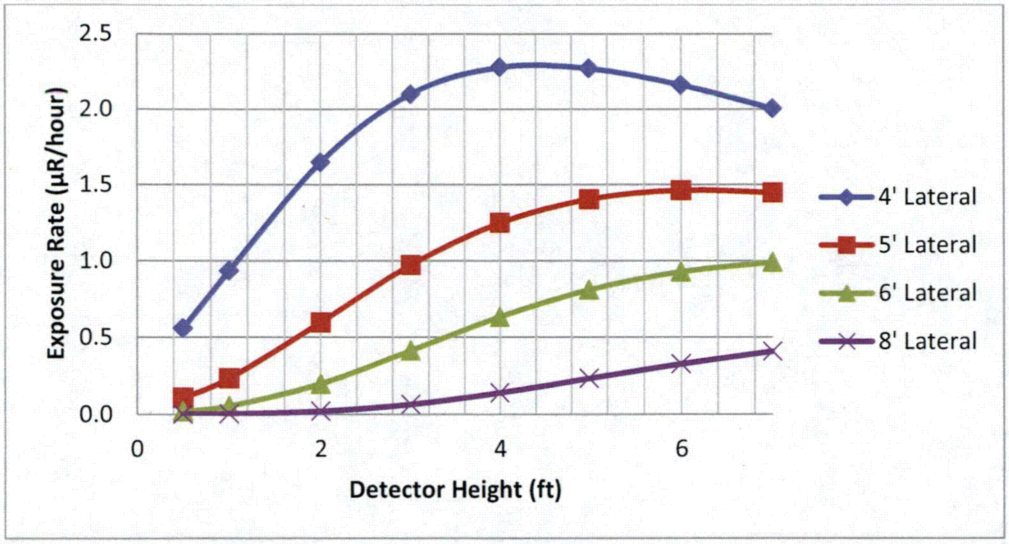

Figure 4. Exposure Rates from 10 mCi Ra-226 for Varying Detector Heights and Laterals

As an example, interpolation shows approximately 0.6 µR/hour rate for a five foot lateral distance at a detector height of 2 feet above ground surface. This height also assures that exposure would also be greater than 0.6 µR/hour for shorter lateral distances.

4.0 DETERMINATION OF EFFICIENCY

The manufacturer indicates that the sensitivity of the detector is 2300 cpm per μR/hour. However, the detector crystal sensitivity cpm/ μ/hour is not constant for all gamma energies and this must be accounted for.

This document utilizes the methodology and approach documented in MARSSIM but modified for point sources and the geometries described earlier. MARSSIM calculations are based on NRC NUREG-1507, *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions* (NRC 1997). MARSSIM Table 6.7 does not provide scan MDCs for a point source buried three feet in the ground; thus scan MDCs are derived using MARSSIM/NUREG-1507 methods. Factors included in this analysis are the natural background of the surveyed area, scan rate, detector to source geometry, areal extent of the potential hot spot(s), and energy and yield of gamma emissions. A factors not included in this analysis is the surveyor scan efficiency.

Modeling (using Microshield® Version 8.02) of a 10 mCi ^{226}Ra source buried three feet under the ground is used to determine the net exposure rate produced for a five foot lateral at a distances 2 feet above the above the ground surface. This position is selected as reasonable from the example presented in Section 3. The objective is to establish that exposure rates at the selected distances exceed the minimum detectable exposure rate. These concepts are shown in Figure 5.

4.1 Micro*Shield* Calculations

The computer code Microshield® was used to model the presence of a nominal 10 mCi of ^{226}Ra in soil with the assumption that the activity was a point source. This is consistent with the MARSSIM methodology and allows a count rate to exposure ratio (cpm/μR/hr) to be calculated.

Activity must be entered into Microshield in units of curies with considerations for decay and soil density. Therefore, a activity concentration for ^{226}Ra was entered into Microshield as 0.01 curies with 65 years of decay time and soil composition from the Federal Guidance Report 12 at a density of 1.6 g/cc.

Microshield presents an output in units of mR/hour with buildup for each standard energy indice. The Microshield exposure rate outputs are shown in Table 4.

There are several steps to converting these outputs into cpm anticipated on the detector. These steps follow and are performed for each of the geometries above.

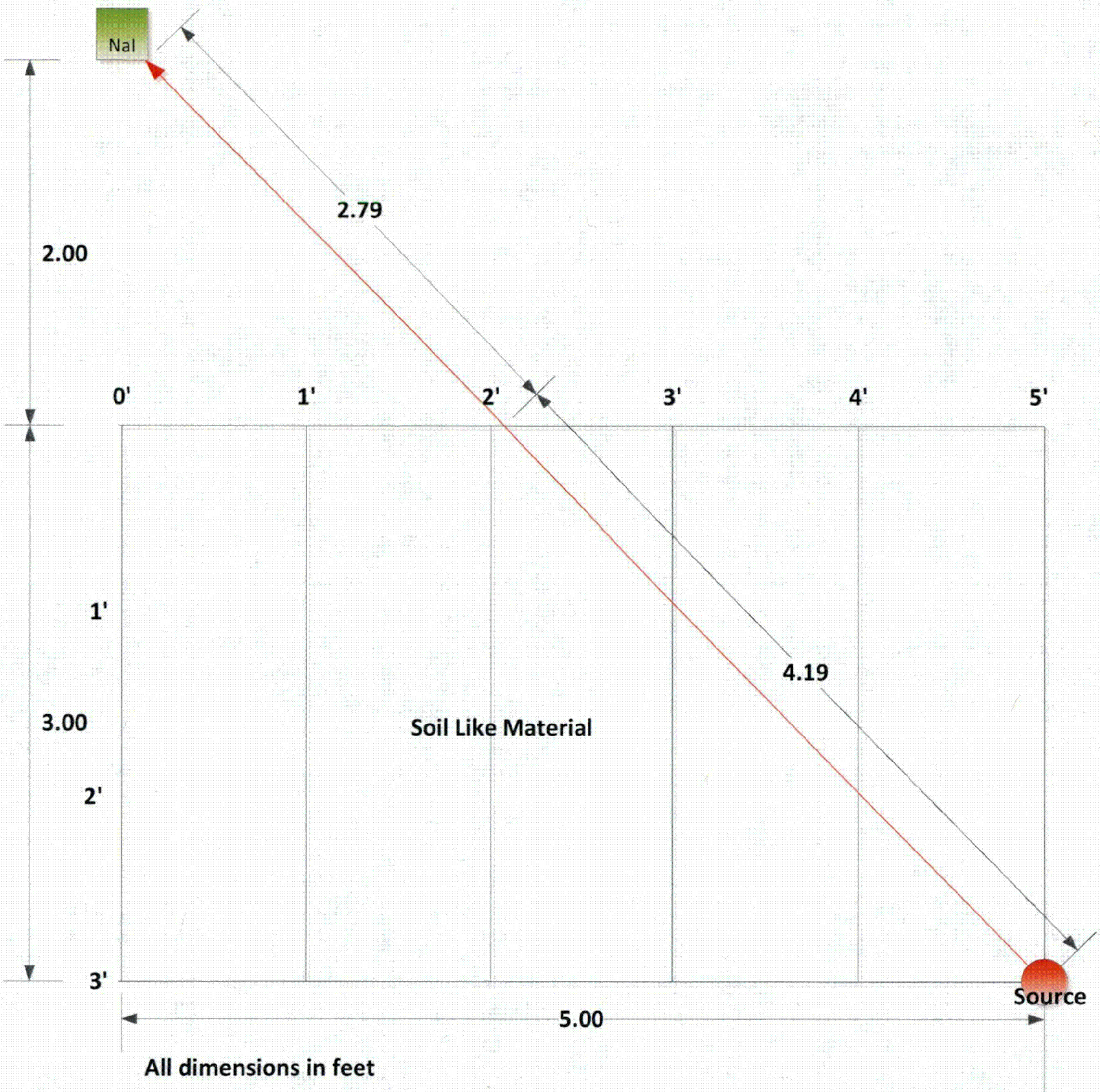

Figure 5. Illustration of Source to Detector Configuration

4.1.1 Fluence Rate to Exposure Rate (FRER)

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

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

Where:

E_γ = energy of the gamma photon of concern, keV

(μ_{en}/ρ) = the mass energy absorption coefficient for air, cm^2/g

This can be represented in tabular form, as in Table 4.

4.1.2 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:

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

Where:

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

X = the thickness through the end of the NaI crystal, 7.62 cm

(ρ_{NaI}) = the density of the NaI crystal, 3.67 g/cm^3

This can be represented in tabular form, as in Table 4.

4.1.3 Relative Detector Response (RDR)

The Relative Detector Response (RDR) as a function of energy is determined by multiplying the relative fluence rate to exposure rate (FRER) by the probability (P) of an interaction and is given by:

$$RDR = (FRER)(P)$$

This can be represented in tabular form, as in Table 4.

4.1.4 Determination of cpm per μR/hr as a Function of Energy

The equivalent FRER, P, and finally RDR may be calculated for the NaI scintillation detector at the Cesium-137 (^{137}Cs) energy of 662 keV. The manufacturer lists 2300 cpm/μR/hr for the

Model 44-20. This point allows one to determine the cpm per μR/hr and ultimately activity concentration and minimum detection sensitivity level in terms of cpm for a specific instrument.

Based on the manufacturer's response specification, 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 similar to the technique used in NUREG-1507.

FRER = 0.0514

$Energy_\gamma$, keV = 662

$(\mu_{en}/\rho)_{air}$, cm^2/g = 0.0294

$(\mu_{en}/\rho)_{NaI}$, cm^2/g = 0.0780

P = 0.89

Cs-137 RDR (662 keV) = 0.0456

The detector response (cpm) to another energy is based upon the ratio of the RDR at a specific energy to the known Cs-137 energy RDR:

$$CPM/\mu R/hr, E_i = \frac{(CPM/\mu R/hr_{Cs-137})(RDR_{E_i})}{(RDR_{Cs-137})}$$

This can be represented in tabular form, as in Table 4.

The energy indices from Microshield show that several indices are required for ^{226}Ra. The Microshield runs and the weighted cpm per μR/h for ^{226}Ra buried in three feet of are summarized in Table 4. As expected, more than 99% of anticipated responses fall above the 600 keV energy indexes which reflect the emergency abundance of the gamma emissions.

Table 4. Computed Values for a Detector 2' above Ground – 5' Lateral

Energy (keV)	Mass Attenuation Coefficient - Air (cm^2/g)	FRER	Mass Attenuation Coefficient - NaI (cm^2/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.29	0.0517	47.4	1.00	0.0517	2608	3.18E-24	0
50	0.0384	0.5208	10.7	1.00	0.5208	26282	1.56E-24	0
80	0.0236	0.5297	3.12	1.00	0.5297	26727	1.60E-21	0
100	0.0231	0.4329	1.72	1.00	0.4329	21845	7.62E-18	0
200	0.0268	0.1866	0.334	1.00	0.1866	9414	1.93E-08	0
300	0.0288	0.1157	0.167	0.99	0.1147	5786	2.99E-06	0
400	0.0296	0.0845	0.117	0.96	0.0813	4100	6.04E-05	0
500	0.0297	0.0673	0.0955	0.93	0.0627	3163	1.41E-05	0
600	0.0296	0.0563	0.0826	0.90	0.0507	2559	1.33E-03	6
662	0.0294	0.0514	0.078	0.89	0.0456	2300	0.00E+00	
800	0.0289	0.0433	0.0676	0.85	0.0367	1853	1.55E-03	5
1000	0.028	0.0357	0.0586	0.81	0.0288	1452	1.87E-02	45
1500	0.0255	0.0261	0.0469	0.73	0.0191	964	9.41E-02	152
2000	0.0234	0.0214	0.0413	0.68	0.0146	739	4.80E-01	595
					Total		5.96E-01	**804**

5. CONCLUSIONS

It is recognized that the resulting gamma energy spectrum incident on the NaI detector (both primary and scattered gamma radiation) should be accounted for. The MicroShield® modeling code only considered primary gamma energies when evaluating the buildup from scattered photons. The NaI detector response will be greater during field applications as compared to the calculated detector response because the detector is more efficient at detecting lower energy scattered photons. Assumptions in this document are anticipated to yield a conservative determination of the detector response and resulting scan MDCR.

A sequencing of two detectors, each surveying the same area, effectively doubles the observation interval. The observational interval in the example given was determined to be about 1.4 seconds for the cpm rate to exceed the MDCR. There is no front-to-back spacing requirement between the detectors but the time each is over a specified area must be determined by GPS locations per measurement and times of the measurement. In other words, the detectors can immediately follow each other or be separated by any practical distance.

Except for the instances of being immediately over or very close to a zero lateral distance, the exposure rates increase and then decrease the higher the detector is placed. For the 10 mCi source, the maximum detector height for an 8' lateral distance was approaching 7 feet. This physical process is related to shielding by the soil and varying line of sight to the source. Although larger distances are mathematically possible, the detector height and lateral distance were reduced to be on the fringe of standard practices. An actual prove-out may be required prior to industry acceptance of all concepts in this document.

For the example provided of a 5' lateral distance and a 2' detector height, the exposure rate is 0.6 μR/hour and a total of 804 cpm, see Table 4. For 804 cpm to be the MDCR, the time interval from Figure 1 is 1.4 sec. Accepting the sensitivity as 1340 cpm per μR/hour for Ra-226, the MDERs are shown in Table 5 for the various observation intervals. Again, about a 1.4 sec time interval is required.

Table 5. MDCRs and MDERs for 2-Ganged Detectors for Various Observation Intervals in 7μR/hr

i (s)	MDCR (cpm)	MDER (μR/hour)
0.5	1356	1.01
1	959	0.72
1.5	783	0.58
2	678	0.51
2.5	607	0.45
3	554	0.41

If the detector were raised to 2'5", the observation interval is reduced to 1 sec for the 5' lateral distance. This seems contrary to routine distance calculations for radiation but is correct for lateral geometry consideration.

An arbitrary decision is made to set the path width at 8' (2' less than the diameter for a 5' lateral) as shown in Figure 6. As the cosine Θ is adjacent length/hypotenuse length, a 0.6 value is determined. The observation interval is calculated from:

$$t_{obs} = 2r\cos\theta/v$$

$$t_{obs} = 2 \text{ x } 5' \text{ x } \tfrac{3}{5}/v$$

For a path width of 8', the observation interval will be the numerator result of 6'divided by the selected velocity.

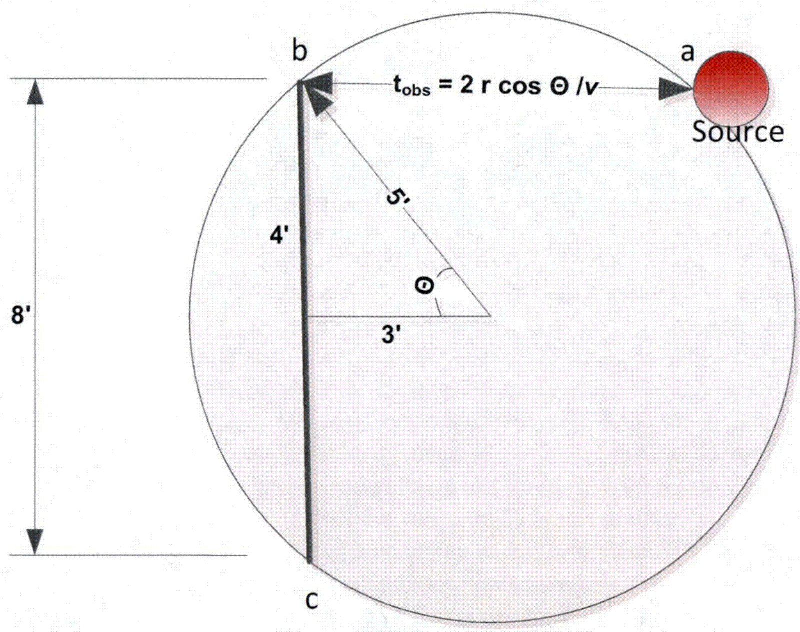

Figure 6. Geometry for Arbitrary Path Width for 5' Lateral

For this example and for a 5' radius (10' diameter)) and a desired observation interval of 1.4 sec (0.0233 min), the speed is determined from the following formulas as 257 ft/min or about 2.9 mph.

$$v = 2 \text{ x } 5' \text{ x } \tfrac{3}{5}/t_{obs}$$

$$v = \frac{6'}{0.0233\, min}$$

The area covered per second is the *actual* path width of 8' times the velocity of 4.3 fps or about 34.4 ft^2 per sec. Per setup of ganged sequential detectors with an arbitary path width of 8' and an observation interval of 1.4 seconds, the survey rate is 5.9 acres per hour at a speed of 4.9 mph. With two sets of two detectors separated by 8', the survey rate is about 11.8 acres per hour at the same speed. In an eight hour survey day, ninety-four acres could be anticipated. Practical experience indicates that at about 50% time is lost to curves, difficult terrain, and realignment of driving paths; a practical claim would be 25 acres per day for one set of two-ganged detectors and 50 acres per day for two two-ganged sets of detectors.

There are several variables which can be changed to meet an MDCR for a 10 mCi Ra-226 source 3' bgs. These choices include the survey speed, the lateral distance desired, and the corresponding height of the detector. Should terrain permit a wider trailer; a third set of two-ganged detectors could be deployed. Alternatively, a human pull-cart arrangement for one ganged set is shown in Figure 7.

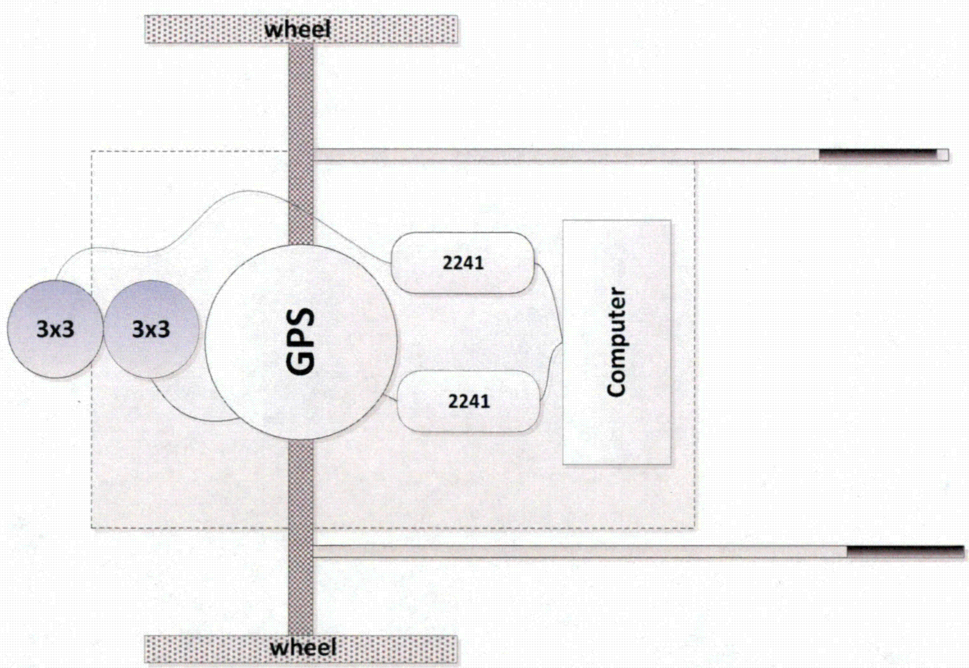

Figure 7. Example Setup for One Ganged Set

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^{137}Cs	Cesium-137
bgs	below ground surface
cm	centimeter
COC	contaminant of concern
cpm	counts per minute
Eff_{total}	Total detector efficiency
FRER	fluence rate to exposure rate
GPS	global positioning system
GWS	gamma walkover survey
m	meter
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MDC	minimum detectable concentration
MDCR	Minimum detectable count rate
Micro*Shield*	Software manufactured by Grove Engineering
NaI	Sodium iodide
P	Probability
RDR	Relative Detector Response

SCANNING CAPABILITY ASSESSMENT
OF LUDLUM 44-20s FOR DISCRETE RA-226 IN SOIL

1.0 INTRODUCTION

The goal of this Technical Memo is to determine:

- The radiation levels from mCi activities of ^{226}Ra buried three feet in the ground.
- The minimum detectable count rate (MDCR) for a NaI 3X3 detector in a variable background of 4 - 9 μR/hour with an average of 7 μR/hour.
- The detectable field of view or path width.

Scan surveys are performed using a NaI 3X3 detector coupled with a rate-meter/scaler that is configured to output directly to a Global Positioning System (GPS) unit. The basic method for performing a gamma walkover survey is to walk along a path with the detector bottom at a set distance and a set speed while swinging the detector in a serpentine motion. The GPS will provide high quality, precision geospatial positioning data to support data verification, and remediation. The rate-meter/scalars used for this work will be configured to output directly to the GPS unit. The GPS unit will perform data logging functions.

2.0 MINIMUM DETECTABLE COUNT RATE

Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) Section 6.7.2.1 describes the methodology used to calculate the Scan Minimum Detectable Concentrations (MDCs) for land areas that are delineated in MARSSIM Table 6.7.

The minimum detectable number of net source counts in the interval is given by s_i. For walkover gamma surveys, 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 (as reflected in d') as shown in MARSSIM Equation 6-8 which parallels the MARSSIM page 6-45 analysis as follows:

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

For walkover gamma surveys, d' is set equal to 1.38 as this index of sensitivity is independent of human factors. The value of d' is from Table 6.5 of MARSSIM and the required true positive proportion is 0.95 and the false positive rate of 0.60 will be tolerated.

The manufacturer gives the detector a sensitivity value of 2300 cpm/μR/h (^{137}Cs). As background exposure rates vary but are typically between 4-9 μR/hr with an average of 7 μR/hr, the range of b_i value may need to be adjusted to actual field conditions and the impact is reviewed as follows.

The Minimum Detectable Count Rate (MDCR) as cpm is calculated as:

$$MDCR = (1.38)(b_i)^{0.5}(60/i)$$

However, MARSSIM does not strictly apply to this application as all measurements will be recorded every second and reviewed through mapping; thus, a value for surveyor efficiency will not be applied. Table 1 illustrates the differences for the MDCR and the Minimum Detectable Exposure Rate (MDER) for the various background rates at Great Kills Park (GKP).

Table 1. MDCRs for a One Second Observation Interval in Varying Backgrounds

Background (μR/hr)	Background (cpm)	MDCR (cpm)	MDER as Cs-137 (μR/h)
9	20700	1538	0.67
8	18400	1450	0.63
7	16100	1356	0.59
6	13800	1256	0.55
5	11500	1146	0.50
4	9200	1025	0.45

3.0 MICROSHIELD SIMULATIONS

This document utilizes the methodology and approach documented in MARSSIM but modified for point sources and the geometries described earlier. MARSSIM calculations are based on NRC NUREG-1507, *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions* (NRC 1997). MARSSIM Table 6.7 does not provide scan MDCs for a point source buried three feet in the ground ; thus scan MDCs must be derived using MARSSIM/NUREG-1507 methods. Factors included in this analysis are the natural background of the surveyed area, scan rate, detector to source geometry, areal extent of the potential hot spot(s), and energy and yield of gamma emissions. A factor not included in this analysis is the surveyor scan efficiency as all data is recorded and reviewed post survey.

Modeling (using Microshield® Version 8.02) of a one millicurie ^{226}Ra source buried three feet under the ground is used to determine the net exposure rate produced at a height of four inches above ground surface and lateral distances of 0, 0.25, 0.5, 0.75, 1 and 1.25 m. The height position is selected because it relates to the average height of the NaI(Tl) scintillation detector above the ground during scanning and is suggested by MARSSIM. The objective is to determine the radionuclide concentration that is correlated to the minimum detectable net exposure rate.

The computer code Microshield® was used to model the presence of a 1 mCi of ^{226}Ra in soil with the assumption that the activity was a point source and that decay products of 75 years was present. This is consistent with the MARSSIM methodology and provides for a count rate to exposure ratio (cpm/μR/hr) to be calculated:

- depth of the 1 mCi point source is three feet,
- the detector bottom is 10 cm above the ground (standard MARSSIM height),
- dose points are 0, 0.25, 0.5, 0.75, 1.00, and 1.25 m as lateral distances, and
- the density of soil is 1.6 g/cm^3.

Activity must be entered into Microshield in units of curies with considerations for decay and soil density. Therefore, an activity concentration for ^{226}Ra was entered into Microshield as 0.001

curies including 65 years of decay time and soil composition from the Federal Guidance Report 12.

Microshield presents an output in units of mR/hour with buildup for each standard energy indice. The Microshield exposure rate outputs are included as an attachment. An illustration of the MicroShield configuration is presented in Figure 1 where the green dot at the Y location is the point source; blue represents the shielding soil, and the orange dots represent the detector lateral distance.

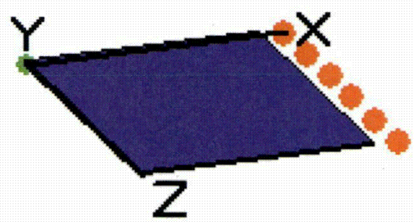


Figure 1. MicroShield Configuration

Table 2. Exposure Rates at Lateral Distances

Lateral Distance (m)	0	0.25	0.5	0.75	1	1.25
Exposure Rate with Buildup (μR/hour)	3.4	2.7	1.3	0.5	0.14	0.04

4.0 DETERMINATION OF PATH THROUGH NaI CRYSTAL

For simplicity, MARSSIM determinations assume that all gamma rays enter the detector at a right angle into the bottom. This is not the best configuration for field-of view calculations and a scale drawing was made to determine the distances that gamma rays would have to pass through (soil, air and the crystal) and these are shown in Figure 1. The bottom of the detector was placed at 4 inches above the ground surface; note that distances used in Microshield were determined by MicroShield and this drawing was only applied for distance traveled through the crystal. Table 3 summarized the estimated distances.

Figure 2. Distances Used for Survey Path Calculations

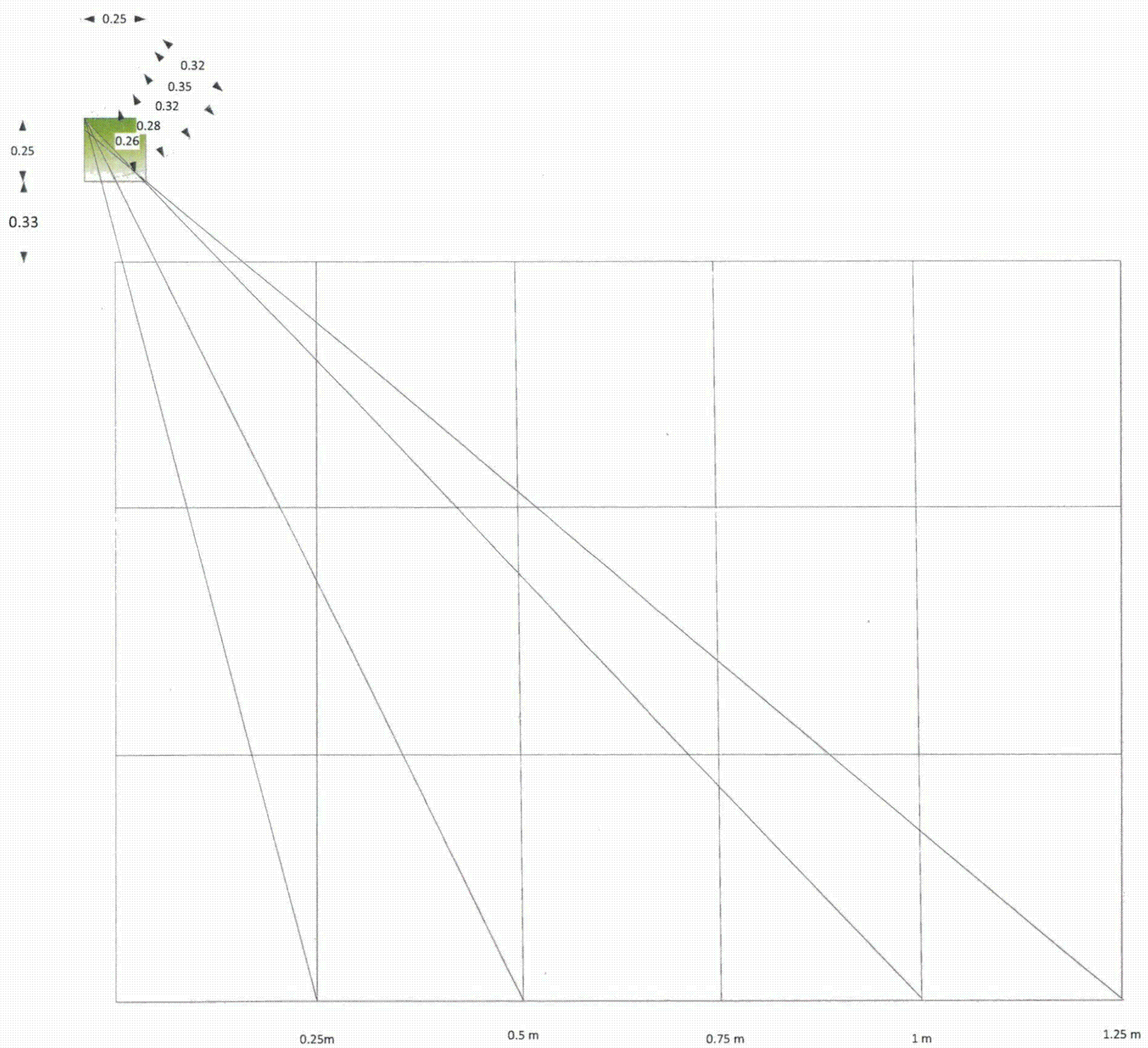


Table 3. Estimated Pathway Distance Through NaI Crystal.

Lateral Distance (m)	0	0.25	0.5	0.75	1	1.25
Path Through Crystal (cm)	7.62	7.93	8.54	9.76	10.7	9.76

5.0 DETERMINATION OF EFFICIENCY

MicroShield computations described in Section 2 provide an output in units of mR/hour with buildup for each standard energy indice. The Microshield exposure rate outputs are included as an attachment.

There are several steps to converting these outputs into cpm anticipated on the detector. These steps follow and are performed for each of the geometries above.

5.1 Fluence Rate to Exposure Rate (FRER)

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

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

Where:

E_γ = energy of the gamma photon of concern, keV

(μ_{en}/ρ) = the mass energy absorption coefficient for air, cm^2/g

This can be represented in tabular form, as in Tables 4 to 9.

5.2 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:

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

Where:

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

X = the thickness through the end of the NaI crystal, 7.62 cm

(ρ_{NaI}) = the density of the NaI crystal, 3.67 g/cm^3

This can be represented in tabular form, as in Tables 4 to 9.

5.3 Relative Detector Response (RDR)

The Relative Detector Response (RDR) as a function of energy is determined by multiplying the relative fluence rate to exposure rate (FRER) by the probability (P) of an interaction and is given by:

$$RDR = (FRER)(P)$$

This can be represented in tabular form, as in Tables 4 to 9.

5.4 Determination of cpm per μR/hr as a Function of Energy

The equivalent FRER, P, and finally RDR may be calculated for the NaI scintillation detector at the Cesium-137 (^{137}Cs) energy of 662 keV. The manufacturer lists 2300 cpm/μR/hr for the Model 44-20. This point allows one to determine the cpm per μR/hr and ultimately activity concentration and minimum detection sensitivity level in terms of cpm for a specific instrument.

Based on the manufacturer's response specification, 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 similar to the technique used in NUREG-1507.

FRER = 0.0514

$Energy_{\gamma}$, keV = 662

$(\mu_{en}/\rho)_{air}$, cm^2/g = 0.0294

$(\mu_{en}/\rho)_{NaI}$, cm^2/g = 0.0780

P = 0.89

Cs-137 RDR (662 keV) = 0.0456

The detector response (cpm) to another energy is based upon the ratio of the RDR at a specific energy to the known Cs-137 energy RDR:

$$CPM/\mu R/hr, E_i = \frac{(CPM/\mu R/hr_{Cs-137})(RDR_{E_i})}{(RDR_{Cs-137})}$$

This can be represented in tabular form, as in Tables 4 to 9.

The energy indices from Microshield show that several indices are required for ^{226}Ra. The Microshield runs and the weighted cpm per μR/h for ^{226}Ra buried in three feet of are summarized in Tables 4 to 9. As expected, more than 99% of anticipated responses fall above the 600 keV energy indexes which reflect the emergency abundance of the gamma emissions.

Table 4. Computed Values for Zero Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm²/g)	FRER	Mass Attenuation Coefficient - NaI (cm²/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.04998	47.4	1.00	0.0500	2526	1.43E-24	0
50	0.04098	0.48804	10.5	1.00	0.4880	24673	3.69E-22	0
80	0.02407	0.51932	3	1.00	0.5193	26254	7.83E-15	0
100	0.02305	0.43384	1.67	1.00	0.4338	21933	7.09E-13	0
200	0.02672	0.18713	0.328	1.00	0.1871	9459	1.20E-05	0
300	0.02872	0.11606	0.166	0.99	0.1149	5811	5.14E-04	1
400	0.02949	0.08477	0.117	0.96	0.0816	4124	5.08E-03	6
500	0.02966	0.06743	0.095	0.93	0.0627	3170	7.36E-04	1
600	0.02953	0.05644	0.0822	0.90	0.0508	2567	4.73E-02	36
662	0.02931	0.05154	0.0766	0.88	0.0455	2300		
800	0.02882	0.04337	0.0675	0.85	0.0368	1861	3.20E-02	18
1000	0.02789	0.03586	0.0588	0.81	0.0289	1463	2.59E-01	112
1500	0.02547	0.02617	0.047	0.73	0.0191	968	6.81E-01	195
2000	0.02345	0.02132	0.0415	0.69	0.0146	740	2.36E+00	516
					Total		**3.39E+00**	**884**

Table 5. Computed cpm Values for a 0.25 m Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm^2/g)	FRER	Mass Attenuation Coefficient - NaI (cm^2/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.0500	47.4	1.00	0.0500	2499	1.35E-24	0
50	0.04098	0.4880	10.5	1.00	0.4880	24406	7.14E-23	0
80	0.02407	0.5193	3	1.00	0.5193	25971	2.33E-15	0
100	0.02305	0.4338	1.67	1.00	0.4338	21696	2.80E-13	0
200	0.02672	0.1871	0.328	1.00	0.1871	9357	6.78E-06	0
300	0.02872	0.1161	0.166	0.99	0.1151	5758	3.19E-04	1
400	0.02949	0.0848	0.117	0.97	0.0820	4099	3.32E-03	5
500	0.02966	0.0674	0.095	0.94	0.0632	3160	4.97E-04	1
600	0.02953	0.0564	0.0822	0.91	0.0513	2564	3.28E-02	32
662	0.02931	0.0515	0.0766	0.89	0.0460	2300		
800	0.02882	0.0434	0.0675	0.86	0.0373	1865	2.31E-02	16
1000	0.02789	0.0359	0.0588	0.82	0.0294	1469	1.92E-01	106
1500	0.02547	0.0262	0.047	0.75	0.0195	976	5.28E-01	193
2000	0.02345	0.0213	0.0415	0.70	0.0149	748	1.88E+00	529
					Total		**2.66E+00**	**882**

Table 6. Computed Values for a 0.5 m Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm^2/g)	FRER	Mass Attenuation Coefficient - NaI (cm^2/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.0500	47.4	1.00	0.0500	2453	1.15E-24	0
50	0.04098	0.4880	10.5	1.00	0.4880	23951	6.70E-25	0
80	0.02407	0.5193	3	1.00	0.5193	25486	7.42E-17	0
100	0.02305	0.4338	1.67	1.00	0.4338	21291	1.99E-14	0
200	0.02672	0.1871	0.328	1.00	0.1871	9183	1.34E-06	0
300	0.02872	0.1161	0.166	0.99	0.1154	5665	8.20E-05	0
400	0.02949	0.0848	0.117	0.97	0.0826	4054	9.86E-04	3
500	0.02966	0.0674	0.095	0.95	0.0640	3141	1.63E-04	0
600	0.02953	0.0564	0.0822	0.92	0.0521	2559	1.16E-02	22
662	0.02931	0.0515	0.0766	0.91	0.0469	2300		
800	0.02882	0.0434	0.0675	0.88	0.0381	1872	9.12E-03	13
1000	0.02789	0.0359	0.0588	0.84	0.0302	1481	8.21E-02	90
1500	0.02547	0.0262	0.047	0.77	0.0202	990	2.58E-01	188
2000	0.02345	0.0213	0.0415	0.73	0.0155	761	9.93E-01	558
					Total		**1.35E+00**	**874**

Table 7. Computed Values for a 0.75 m Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm^2/g)	FRER	Mass Attenuation Coefficient - NaI (cm^2/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.0500	47.4	1.00	0.0500	2384	9.25E-25	0
50	0.04098	0.4880	10.5	1.00	0.4880	23278	4.55E-25	0
80	0.02407	0.5193	3	1.00	0.5193	24769	3.98E-19	0
100	0.02305	0.4338	1.67	1.00	0.4338	20692	3.63E-16	0
200	0.02672	0.1871	0.328	1.00	0.1871	8925	1.16E-07	0
300	0.02872	0.1161	0.166	1.00	0.1158	5521	1.05E-05	0
400	0.02949	0.0848	0.117	0.98	0.0835	3982	1.58E-04	1
500	0.02966	0.0674	0.095	0.97	0.0652	3109	3.02E-05	0
600	0.02953	0.0564	0.0822	0.95	0.0535	2550	2.42E-03	12
662	0.02931	0.0515	0.0766	0.94	0.0482	2300		
800	0.02882	0.0434	0.0675	0.91	0.0395	1884	2.25E-03	9
1000	0.02789	0.0359	0.0588	0.88	0.0315	1502	2.29E-02	69
1500	0.02547	0.0262	0.047	0.81	0.0213	1017	8.78E-02	180
2000	0.02345	0.0213	0.0415	0.77	0.0165	787	3.82E-01	604
					Total		4.97E-01	**875**

Table 8. Computed Values for a 1 m Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm^2/g)	FRER	Mass Attenuation Coefficient - NaI (cm^2/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.0500	47.4	1.00	0.0500	2347	7.26E-25	0
50	0.04098	0.4880	10.5	1.00	0.4880	22920	3.57E-25	0
80	0.02407	0.5193	3	1.00	0.5193	24389	5.76E-22	0
100	0.02305	0.4338	1.67	1.00	0.4338	20375	2.46E-18	0
200	0.02672	0.1871	0.328	1.00	0.1871	8788	5.41E-09	0
300	0.02872	0.1161	0.166	1.00	0.1159	5443	8.11E-07	0
400	0.02949	0.0848	0.117	0.99	0.0839	3941	1.60E-05	0
500	0.02966	0.0674	0.095	0.98	0.0658	3090	3.70E-06	0
600	0.02953	0.0564	0.0822	0.96	0.0542	2545	3.44E-04	6
662	0.02931	0.0515	0.0766	0.95	0.0490	2300	0.00E+00	
800	0.02882	0.0434	0.0675	0.93	0.0403	1892	3.95E-04	5
1000	0.02789	0.0359	0.0588	0.90	0.0323	1516	4.70E-03	49
1500	0.02547	0.0262	0.047	0.84	0.0220	1034	2.33E-02	165
2000	0.02345	0.0213	0.0415	0.80	0.0171	804	1.18E-01	646
					Total		**1.46E-01**	**871**

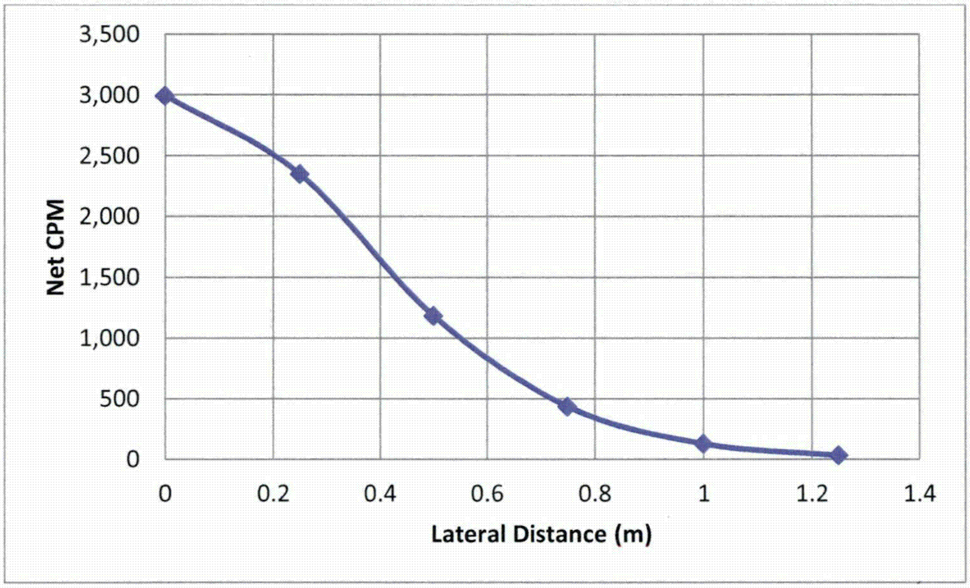
Table 9. Computed Values for a 1.25 m Lateral Distance

Energy (keV)	Mass Attenuation Coefficient - Air (cm²/g)	FRER	Mass Attenuation Coefficient - NaI (cm²/g)	P	RDR	CPM per microR/hr	R_i (μR/h)	WS_i (cpm per μR/h)
15	1.334	0.0500	47.4	1.00	0.0500	2384	5.69E-25	0
50	0.04098	0.4880	10.5	1.00	0.4880	23278	2.80E-25	0
80	0.02407	0.5193	3	1.00	0.5193	24769	2.20E-23	0
100	0.02305	0.4338	1.67	1.00	0.4338	20692	8.17E-21	0
200	0.02672	0.1871	0.328	1.00	0.1871	8925	1.66E-10	0
300	0.02872	0.1161	0.166	1.00	0.1158	5521	4.39E-08	0
400	0.02949	0.0848	0.117	0.98	0.0835	3982	1.19E-06	0
500	0.02966	0.0674	0.095	0.97	0.0652	3109	3.41E-07	0
600	0.02953	0.0564	0.0822	0.95	0.0535	2550	3.75E-05	3
662	0.02931	0.0515	0.0766	0.94	0.0482	2300		
800	0.02882	0.0434	0.0675	0.91	0.0395	1884	5.51E-05	3
1000	0.02789	0.0359	0.0588	0.88	0.0315	1502	7.85E-04	32
1500	0.02547	0.0262	0.047	0.81	0.0213	1017	5.21E-03	142
2000	0.02345	0.0213	0.0415	0.77	0.0165	787	3.13E-02	659
					Total		**3.74E-02**	**837**

6. CONCLUSIONS

The MDCR is presented in Table 1 for an average 7 µR/hour background as 1356 cpm. The field of view is determined by graphing the cpm obtained at each lateral distance and selecting the distance corresponding to the MDCR. This graph is provided as Figure 3.

Figure 3. 1 mCi Net cpm for Various Lateral Distances



For a 1 mCi source buried at a depth of 3 feet, the lateral distance for the MDCR is very close to 0.5 m which is a radius of the field of view and the total field of view is 1 m wide as an *a priori* effort.

As the cpm values are linear with respect to the source activity, Figure 4 presents the net cpm for various lateral distances for a 10 mCi source buried at a depth of 3 feet. For a 10 mCi source, the total field of view is approximately 2 m wide.

Figure 4. 10 mCi Net cpm for Various Lateral Distances