

U.S. EPA Superfund Counts Per Minute (CPM) Electronic Calculator – 17305

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) Superfund program is developing a new Counts Per Minute (CPM) calculator to correlate real-time survey results, which are often expressed as counts per minute, to contaminant concentrations that are more typically provided in risk assessments or for cleanup levels, usually expressed in pCi/g or pCi/m². Currently there is no EPA guidance for Superfund sites on correlating count per minute field survey readings back to risk, dose, or other Applicable or Relevant and Appropriate Requirements (ARAR) based concentrations. The CPM calculator is a web-based model that estimates a gamma detector response for a given level of contamination. The intent of the CPM calculator is to facilitate more real-time measurements within a Superfund response framework.

INTRODUCTION

Field sampling has the potential to be an extremely time-consuming and expensive portion of a radiological site remediation. Collected samples must be shipped to an off-site laboratory or counted in an on-site mobile unit in order to establish areas of contamination and to ensure that acceptable residual levels of contaminants remain. The CPM calculator has two major sub calculators based on the field survey scenario: (1) ground based scanning of surface contamination, and (2) ground based scanning of volumetric contamination.

The intent of the CPM calculators is to facilitate more real-time measurements within a Superfund response framework. The EPA Superfund guidance document “Radiation Risk Assessments at CERCLA Sites: Q&A” [1] discusses the use of real-time measurements of direct radiation to supplement risk assessment. However, the Superfund guidance for risk characterization, the “Soil Screening Guidance for Radionuclides” [2, 3] only discusses sampling procedures. Other technical guidance documents such as Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) [4] and the ITRC “Real-Time Measurement of Radionuclides in Soil: Technology and Case Studies” [5] provide information on field survey approaches and techniques for using scanning equipment that may be useful for Superfund site decision-makers.

METHOD

Calculator overview

The CPM calculator is a web-based model that estimates a gamma detector response for a given level of contamination. This calculator provides a rapid, exceptionally cost-effective assessment of contamination and cleanup standards based on field instrument data, which minimizes the use of more expensive sample collection and laboratory analysis. **A correction factor for cpm analysis established between these calculator results and lab sampling analysis may be needed to account for ground truthing and other field nuances. The user should verify calculator results with lab sampling.**

The CPM calculator will be developed as a stand-alone device but in the future may be incorporated into all of EPA's Superfund models for risk and dose assessment (e.g., the six existing Preliminary Remediation Goal (PRG) and Dose Compliance Concentrations (DCC) calculators). The CPM calculator should help focus sampling efforts in the site evaluation and final status survey phases to ensure that response objectives are being met during the conduct of the site remediation, and provide better estimates of risk posed at initial site surveys. The CPM calculator includes 783 gamma emitting radionuclides that can be selected. There are some important caveats that users of the CPM calculator should be aware, including: (1) the CPM tool is intended to facilitate use of real-time measurement techniques to supplement, not replace physical sampling, (2) the CPM tool only addresses gamma emitters, (3) the CPM tool assumes uniform contamination, (4) the source surface should not be shielded by water or other material, and (5) the CPM tool does not account for backscatter or build-up in the surface.

Gamma Scintillation Detectors

Detector data is based on four sizes of gamma scintillation detectors by Ludlum Measurements Inc. The models are the 44-2, 44-10, 44-62 and the 44-22 NaI (TI) crystal gamma scintillation detectors of sizes 1.27 centimeters (cm) x 2.54 cm (0.5"x1"), 2.54 cm x 2.54 cm (1"x1"), 5.08 cm x 5.08 cm (2"x2") and 7.62 cm x 7.62 cm (3"x3") NaI crystals. The detector sensitivity (S), a constant that converts exposure to cpm, and the detector response, a coefficient dependent on the detector's cataloged response to the photon energy are fed into the Area CPM Calculator equations. The response coefficient is found in a graph of photon energy and response from the detector user manual. Datathief, a shareware program, was used to visually trace the graphs and convert the values to text for the four detector sizes. For an example of the graph for the model 44-2 detector can be seen below in Figure 1:

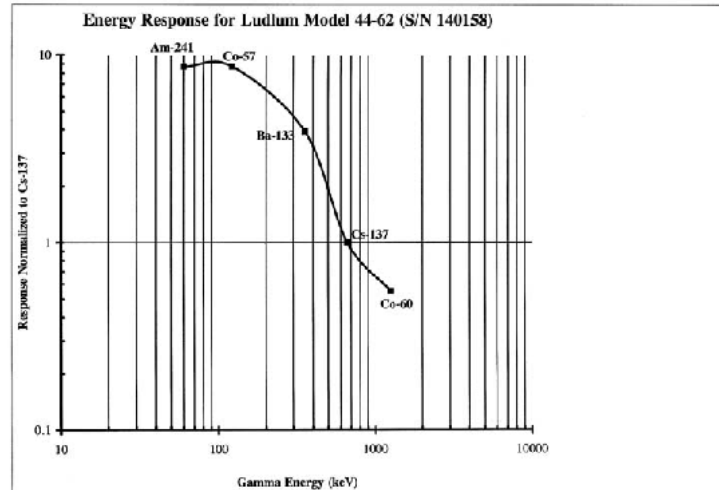


Figure 1 Photon Energy and Response from Ludlum

Daughters and Chains

By default, the Area CPM Calculator estimates the detector response for the primary radionuclide in secular equilibrium with its daughters. This is meaningful, especially in the common case of Cs-137 (the well-known 662 keV gamma of Cs-137 is actually produced by its metastable daughter, Ba-137m). However, this feature can be deactivated by deselecting the check box beneath the radionuclide selection list. The three main natural decay chain series have been truncated for use with manmade or purified radionuclides of U-238, U-235 and Th-232. For example, selecting U-238 will only include the immediate three daughters. The next sequential daughter, U-234, being so long lived, is considered a new radionuclide. To calculate for the natural state of the above three chains, as in calculating for uranium ore, select from the radionuclide list the natural instance of the parent radionuclide, denoted by the suffix, n: U-238n, U-235n, and Th-232n. Selecting one of these radionuclides will include the contribution of the entire natural chain.

Model Geometry

The geometry of the model is a disc source above which a detector is suspended. The height (h) of the detector is the user's estimate of the distance in centimeters between the detector and the source of contamination. The maximum radius of the disc (R) is calculated such that the distance from the detector to the outer circumference of the circle is seven mean free paths ($7/\mu$) of the greatest photon energy, a distance at which the photon is safely assumed to be attenuated. See Figure 2 on the exposure derivation.

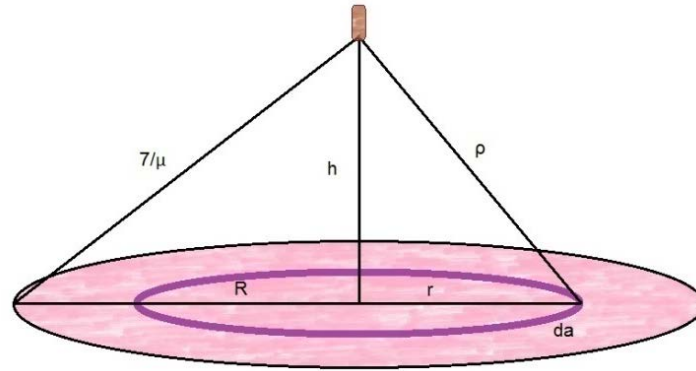


Figure 2. Exposure Geometry of a Disc Source

The exposure derivation, including calculations for deciding the outer radius, R, is shown below:

$$da = 2\pi r dr$$

$$dX = \frac{A da \Gamma}{\rho} = \frac{\Gamma A 2\pi r dr}{h^2 + r^2}$$

$$X = \Gamma A 2\pi \int_0^R \frac{r dr}{h^2 + r^2}$$

U substitution. Let,

$$u = h^2 + r^2$$

$$du = 2 r dr$$

$$X = \Gamma A 2\pi \int_{h^2}^{h^2+R^2} \frac{du}{2u}$$

$$X = \Gamma A \pi \ln \frac{h^2 + R^2}{h^2}$$

Outer "infinite" radius, R:

$$\sqrt{h^2 + R^2} = 7 mfp = \frac{7}{\mu}$$

$$h^2 + R^2 = \left(\frac{7}{\mu}\right)^2$$

$$R^2 = \left(\frac{7}{\mu}\right)^2 - h^2$$

$$R = \sqrt{\left(\frac{7}{\mu}\right)^2 - h^2}$$

(Eq. 1)

Equations

The target activity concentration (TAC) is converted to detector response in cpm using an equation for exposure, the radionuclide-specific gamma constant and detector-specific parameters. If multiple primary radionuclides are selected each TAC is converted separately and then summed with a risk-weighted equation using ratios established from the field activity concentrations, or FACs.

The FAC is the actual activity of each primary radionuclide in the contamination. FACs are used to establish field ratios for multiple radionuclides. The target detector responses, in cpm, are then figured together to obtain the Gross Detector Response (GDR). First, the theoretical exposure rate at the detector is calculated for each TAC. The exposure rate is then multiplied by the detector sensitivity to convert to detector response in cpm and then corrected for the energy-specific detector response of the radionuclide's energy spectrum. Finally, a sum-ratio equation from MARSSIM that accounts for the contamination ratios and restrictive radionuclide concentrations is applied.

Exposure

The exposure rate at the detector is calculated as follows:

$$\dot{X} = \Gamma * A * \pi * \ln\left(\frac{h^2 + R^2}{h^2}\right) \quad (\text{Eq. 2})$$

where X is the exposure rate in $\mu\text{R/hr}$,
 Γ is the gamma coefficient in $\mu\text{R hr}^{-1} \text{cm}^2 \text{pCi}^{-1}$;
A is the surface activity in pCi/cm^2 ,
h is the distance from the detector to the surface in cm, and
R is the radius of the contamination boundary.

R is designed so that the range from the detector to the boundary is 7 mean free paths and is defined:

$$R = \sqrt{\left(\frac{7}{\mu}\right)^2 - h^2} \quad (\text{Eq. 3})$$

thus,

$$\dot{X} = \Gamma * A * \pi * \ln \frac{(7/\mu)^2}{h^2} \quad (\text{Eq. 4})$$

Normalized, Weighted Response Factor

The detector response varies by the energy of the incident photon. A normalized and weighted detector response factor, RF_{norm} , is calculated to correct the response for the photon spectrum:

$$RF_{norm} = \sum \frac{Y * dfrac}{\sum Y * dfrac} RF \quad (\text{Eq. 5})$$

where Y is the yield of each photon of each radionuclide, dfrac is the emitting radionuclide's activity based on the primary parent's activity, and RF is the response factor correlating to the energy of each photon.

CPM

The detector response in cpm is found by multiplying the exposure rate at the detector by the detector's sensitivity and response factor, RF_{norm} , resulting in cpm corrected for the spectrum's energy variance:

$$RF_{norm} = \sum \frac{Y * dfrac}{\sum Y * dfrac} RF \quad (\text{Eq. 6})$$

where S is the sensitivity of the detector in cpm / ($\mu\text{R/hr}$), and RF is the energy response factor of the detector.

Relative Fraction

When the CPM is being used to assess multiple radionuclides, the relative fraction, f_i , is the fraction of the total activity contributed by each radionuclide. The field activity concentrations are used to find the relative fractions of each radionuclide which are then applied to the Gross Detector Response. MARSSIM Chapter 4 (U.S. EPA, 2000)

$$f_i = \frac{cpm_{FAC_i}}{cpm_{FAC_1} + cpm_{FAC_2} + \dots + cpm_{FAC_n}} \quad (\text{Eq. 7})$$

Where cpm_{FAC_j} is the field activity concentration of each radionuclide, j, in units of detector cpm.

Gross Detector Response

The Gross Detector Response is the total calculated response of the detector in cpm for the desired remedial activity of the particular radionuclides in the soil. MARSSIM Equation 4-4 "Gross Activity DCGL" (U.S. EPA, 2000) is applied to find the gross detector response and can be seen in an edited form below:

$$GDR = \frac{1}{\frac{f_1}{cpm_{SAC_1}} + \frac{f_2}{cpm_{SAC_2}} + \dots + \frac{f_n}{cpm_{SAC_n}}} \quad (\text{Eq. 8})$$

Where f_j is the relative fraction of each radionuclide, j , and cpm_{SAC_j} is the target activity concentration for each radionuclide, j , in units of detector cpm. **Addressing Volumetric Contamination**

When using the Volume calculator, there are six different options for source material, which are soil, concrete, plate glass, wood, steel, and drywall. The model for soil, concrete, plate glass, wood, and steel is based on a uniformly contaminated cylindrical slab source of varying thickness that correlates to the depths of external slope factors or dose conversion factors (infinite, 1 centimeters (cm), 5 cm, or 15 cm). The model for the drywall scenario assumes the drywall is 1.6 cm (5/8 inch) thick and that a 0.5 cm gap of air exists between the detector and the wall surface. The other 5 materials get three choices for detector heights (10, 30, and 100 cm). See Figures 3 and 4 on detector heights for drywall and other materials.

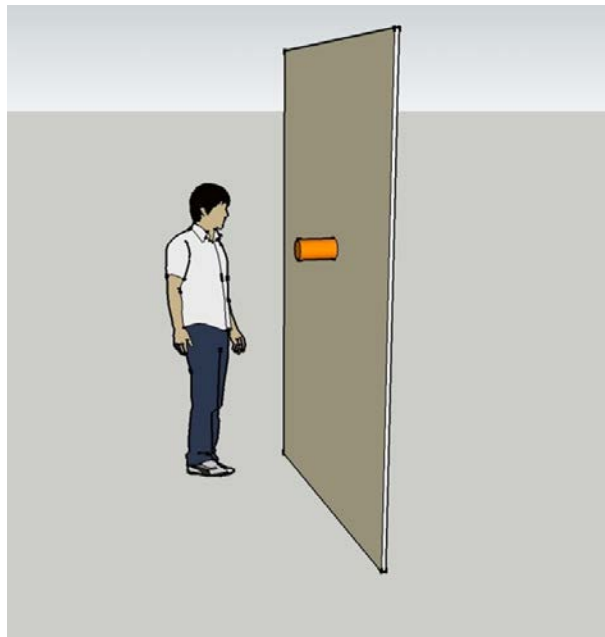


Figure 3 Detector Height for Drywall in Volume CPM Calculator

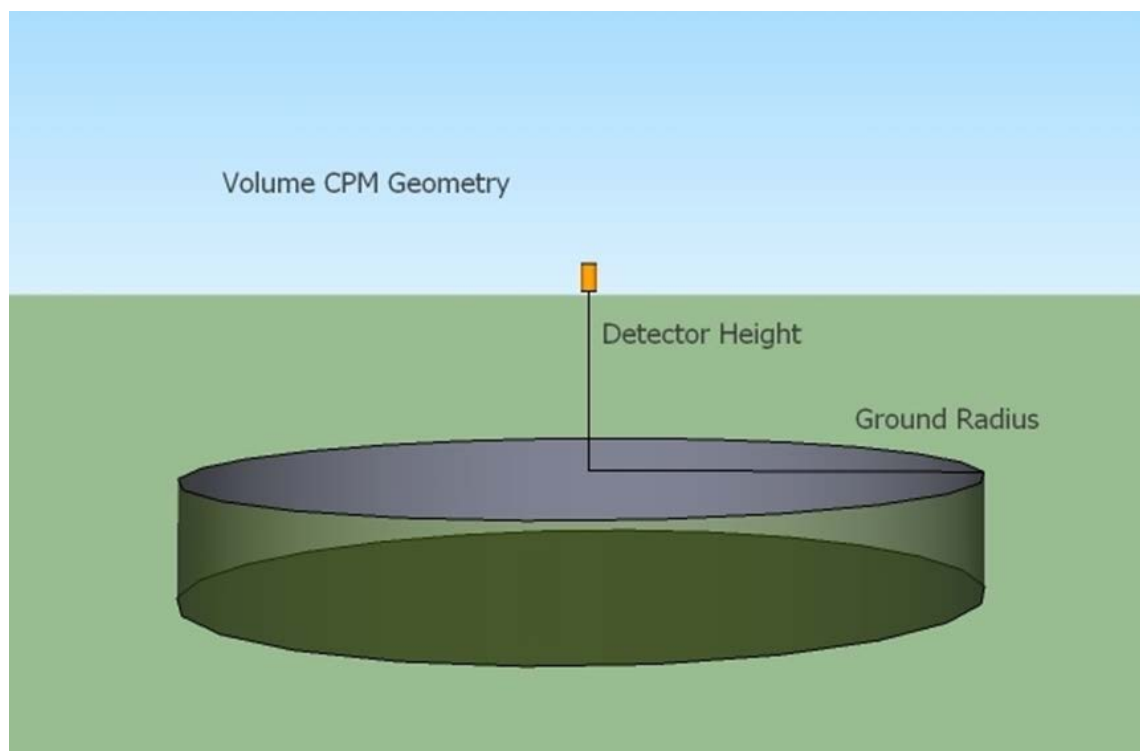


Figure 4 Detector Height for 5 Materials in Volume CPM calculator

Underpinning the Volume calculator is an analysis on the density of the six different materials and the photonic energy of radionuclides on exposure rate results. See Figures 5 and 6 below. Volume CPM will adjust for: 8 generic energies (100, 200, 350, 500, 700, 1000, 1400, 2000 keV) and use the closest for each radionuclide, or the actual energy for these radionuclides commonly found at Superfund sites (Am-241, Cs-137, I-131, Ra-226, Ra-228, Rn-220, Rn-222, Th-230, Th-232, U-234, U-235, and U-238).

Soil		Steel		Glass		Gypsum		Concrete		Wood	
Z	Frac	Z	Frac	Z	Frac	Z	Frac	Z	Frac	Z	Frac
H	0.021	C	0.001	O	0.46	H	0.023	Fe	0.014	C	0.445
C	0.016	Si	0.01	Na	0.096	O	0.558	H	0.01	H	0.062
O	0.577	P	0.001	Si	0.337	S	0.186	Al	0.034	O	0.493
Mg	0.05	Cr	0.19	Ca	0.107	Ca	0.233	Ca	0.044		
Ca	0.041	Mn	0.02					O	0.532		
Si	0.271	Fe	0.684					Si	0.337		
K	0.013	Ni	0.095					Na	0.029		
Fe	0.011										

Figure 5 on the Material Composition in the Volumetric CPM calculator

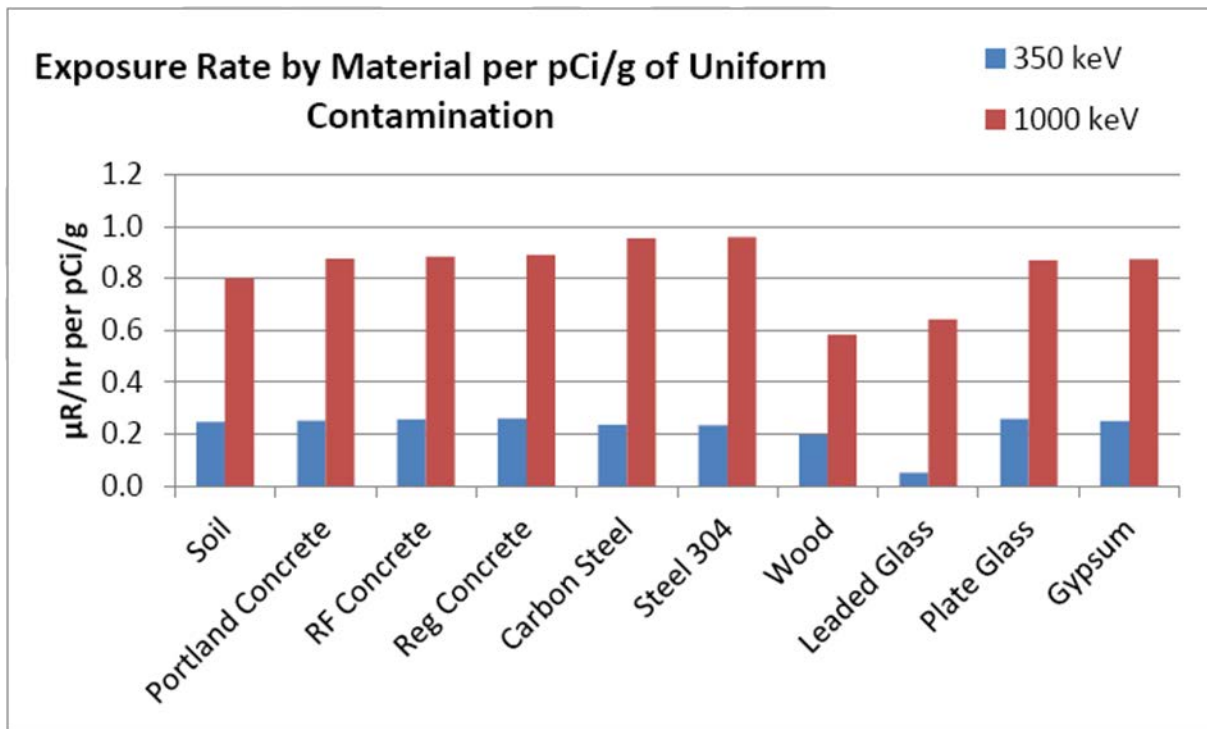


Figure 6 on Exposure Rate of Materials and Radionuclide Photonic Energy

RESULTS AND DISCUSSION

CPM Calculator Limitations

The Model

The Area CPM Calculator is designed around a model that converts surface activity in pCi/cm^2 to detector response in cpm. The model is basic, involving a contaminated surface and a detector suspended a specified distance above. Differences between the model and field characteristics may introduce error into calculator estimates. The Area CPM Calculator does not replace the need for lab-based sampling or MARSSIM final status survey requirements; however, it may provide a reasonable starting point from which to work.

Uniformity

The model source surface assumes uniform contamination, such that the radionuclides of interest are in constant ratio to each other, and that the source surface is essentially infinite in lateral extent. Incongruity of the radionuclide ratios, such as separate spills or cross-contaminated sites, will diminish the effectiveness of the calculator.

Gamma Emitters

Nuclides that emit alpha and beta radiation are difficult to measure with any accuracy in the field and are omitted from this model unless the radionuclide also emits a qualifying gamma particle.

Shielding and Attenuation

The model calculator assumes the source surface is free from all shielding from materials or substances coating or between the detector and source, such as and including paper, oil or moisture.

Background Radiation

The model calculator does not account for background radiation. The user is responsible for adding or subtracting any background counts to the GDR.

Omitted Exposure Factors

This calculator does not account for backscatter or buildup in the surface material.

Correction Factors

A correction factor may be designed and applied to correlate a few lab sampling analyses to the results of this calculator.

Guidance

Guidance on circumstances where it may be appropriate to conduct real-time methods in addition to risk estimates based on slope factors is provided in *Radiation Risk Assessment At CERCLA Sites: Q&A*. Instances where it may be beneficial to also use direct measurements for assessing risk from external exposure to penetrating radiation include:

- During early site assessment efforts when the site manager is attempting to communicate the relative risk posed by areas containing elevated levels of radiation,
- As a real-time method for indicating that remedial objectives are being met during the response action. The use of exposure rate measurements during the response actions should not decrease the need for a final status survey.

Direct radiation exposure rate measurements may provide important indications of radiation risks at a site, particularly during early investigations, when these may be the first data available. However, such data may only reflect a subset of the radionuclides and exposure pathways of potential concern (e.g., only external exposure from gamma-emitting radionuclides in near-surface soil), and may present an incomplete picture of site risks (e.g., risk from internal exposures, or potential increased future risk from radionuclides in subsurface soils). In most cases, more accurate estimation of radiation

risks will require additional site characterization data, including concentrations of all radionuclides of concern in all pertinent environmental media.

The principal benefits of utilizing direct exposure rate measurements is the speed and convenience of analysis, and the elimination of potential modeling uncertainties. However, these data should be used in conjunction with, rather than instead of, characterization data of radionuclide concentrations in environmental media to obtain a complete picture of potential site-related risks. Exposure rate measurements should be correlated with actual scanned data by co-locating them to ensure that modeled assumptions about the correlation between exposure rate and sample concentrations is accurate.

CONCLUSION

The draft of the CPM calculator has undergone external peer review. It will go through an electronic verification study, and a field test verification study. It is expected to be finalized in 2017. The CPM calculator should facilitate greater use of real-time measurement at Superfund sites. The CPM calculator may also standardize the process of converting lab data to real time measurements. It will thus lessen the amount of lab sampling that is needed for site characterization and confirmation surveys, but it will not remove the need for sampling.

REFERENCES

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