Four simple radiation dose estimates

D. M. Wood, February 2018

Contents

This document displays four straightforward estimates—given the Pu contamination levels on new housing developments like Candelas—of radiation dose. Most importantly, it compares them to the results from RESRAD, the tool used by the Department of Energy to estimate offsite (or, for that matter, onsite) cancer risks due to radioactive contamination. It may be regarded as a slightly technical appendix to the document Rocky Flats, radiation, and risk, where a table summarizing the results given here is discussed.

Quick dose calculations

1. *Using the nominal calibration of the Geiger-Müller counter* In Fall 2013 (see the document Seeking clarity in Fall 2013) I found a count rate of approximately 79 CPM about 2 cm above the soil at the back of the lot we eventually purchased. Of this, about 50 CPM was attributable to background radiation in this area. With a measured 'excess' (above background) count rate of 29 CPM, we have an annual dose of

$$\begin{aligned} \text{Sv/year} &= 29\ \text{CPM} \times \left(\frac{1}{350\ \text{CPM}} = 1\,\mu\text{Sv}\,\text{h}^{-1} \right) \\ &\quad \times 24\ \text{hrs/day} \times 365\ \text{days/yr} \\ &= 0.73\ \text{mSv/yr} \end{aligned} \tag{1}$$

or about 36 mSv over a nominal 50-year lifetime. This estimate is not very reliable mostly because the Geiger-Müller tube is calibrated for the isotope ^{137}Cs (which

I am aware of how difficult it is to translate a Geiger-Müller counts per minute figure into a dose. A clear book chapter by Joseph Alvarez [1] of Alpha Beta Gamut discusses this issue. The excellent article by Steinmeyer [2] discusses the characteristics of 'pancake'-type Geiger-Müller counters. For my Geiger-Müller counter 350 counts per minute = 1 μSv h^{-1}. Many Geiger-Müller counters (including mine) are calibrated so as to read what I think is a whole-body dose rate (in μSv/hr) based on the CPM, assuming the source is ^{137}Cs. About 95% of decays from this isotope are β particles (high-energy electrons) with an energy of 0.512 MeV. The main feature of the ^{137}Cs γ spectrum is a 662 keV peak. The Geiger-Müller tube in my counter has an approximately uniform sensitivity sensitivity to γ rays over the range from 150-1000 keV, making its use to *detect* γs for both ^{137}Cs and ^{239}Pu reasonable. It is also reasonably sensitive to β particles.

emits mostly β particles rather mostly α particles) rather than ^{239}Pu, the isotope relevant for Rocky Flats.

2. *Direct calculation of absorbed dose*
   This is an example of a 'model calculation' in which we assume that the concentration of Pu on the ground where we are living is constant, for simplicity.

   You can examine the calculation in Fig. 1 and below in the margin if you are not happy with the statement that (i) from an infinite plane the net flow of radiation is up (where we are) or down (into the ground), and (ii) half goes up, half goes down. (A physicist would say: there is no direction singled out for an infinite plane except perpendicular to the plane, and—if the contamination is just on the surface—half of the particles go up and half down, by symmetry.)

   Given the range of α, β, and γ in water (see the document A crash course in radiation, biology, and health physics), I will assume that every radiation particle that reaches my body (mostly my torso, whose shape is easy to calculate) is absorbed; the geometry is shown in Fig. 2. My waist is roughly elliptical with $a \simeq 17.5$ cm, $b \simeq 12.5$ cm and thus an area πab of about 690 cm^2, or about 0.069 m^2. I estimate my torso mass as 50 kg (about 110 lbs).

   I assume (based on the Krey/Hardy map) a radiation level of about 370 Bq m^{-2}. Assumptions about the particles making up the radiation we detect will affect our estimates of the doses to human bodies we make below. It would be plausible to expect radiation from ^{239}Pu to consist of *both* α particles and γ rays. However, we choose to attribute *all* of the radiation to one particle type or the other, to illustrate the very large dose differences. The Appendix discusses why we expect the γ-only estimate to be physically relevant: it is essentially because radiation levels around Rocky Flats were mostly *measured* by looking for γ-rays.

   (a) Only γ rays

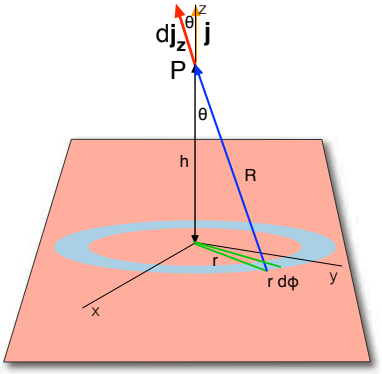

Figure 1: How to calculate radiation current upwards from a uniformly contaminated infinite plane

A patch of uniformly contaminated soil (contamination per unit area σ) contributes to the radiation flux at a point P (see the diagram) an amount $\frac{\sigma\, d(\text{area})}{r^2}$. Because of the azimuthal symmetry only the z component of the 'radiation current' contributes at P. Thus (with $R\cos\theta = h$)

$$\begin{aligned} dj_z &= \sigma \frac{r\, dr\, d\phi}{R^2}\cos\theta \\ \Rightarrow j_z &= \sigma\, 2\pi h \int_{r=0}^{\infty} dr \frac{r}{(r^2+h^2)^{\frac{3}{2}}} \\ &= 2\pi\sigma \end{aligned}$$

Had we allowed h to be negative as well we would have found $4\pi\sigma$, so that, as advertised, half of the radiation goes up.

In reality, some ^{241}Am and other radioisotopes produced by the decay of Pu and Am are present, but the concentrations of ^{241}Am were measured separately by the DOE and not considered here.

Since my torso begins vertically well above the range of α particles in air, here I will ignore them for the radiation dose to my torso. The intensity of γ rays drops to one half of its initial value due to absorption in air over [3] a distance of of 33.6, 43.6, and 62.9 meters for γ rays of energy 100, 200, and 500 keV, so they will be 'full strength' when my body absorbs them. The γ spectrum for ^{239}Pu [4] has several peaks. About 4.2 times [5] more 129.3 keV gamma rays than 413 keV gammas emerge from ^{239}Pu per unit time, so it is reasonable to use 129 keV as the energy per γ. In one hour, then, my torso receives a total energy in Joules per kilogram (kg) (noting that 1 J/kg $\equiv$ 1 Gy)

$$\begin{aligned} &\simeq \frac{1}{2}\, 370\,\mathrm{Bq\,m^{-2}} \times \frac{1\mathrm{disint/sec}}{\mathrm{Bq}} \times 129.3\,\frac{\mathrm{keV}}{\mathrm{disint}} \\ &\quad \times 1000\ \mathrm{eV/keV} \times 1.60 \times 10^{-19}\mathrm{J/eV} \times \\ &\quad \times \frac{0.069\,\mathrm{m^2}}{\mathrm{torso}} \times \frac{1\mathrm{torso}}{50\,\mathrm{kg}} \times 3600\frac{\mathrm{sec}}{\mathrm{hr}} \\ &\quad \simeq 1.9 \times 10^{-11}\ \mathrm{Sv\,h^{-1}} \end{aligned} \tag{2}$$

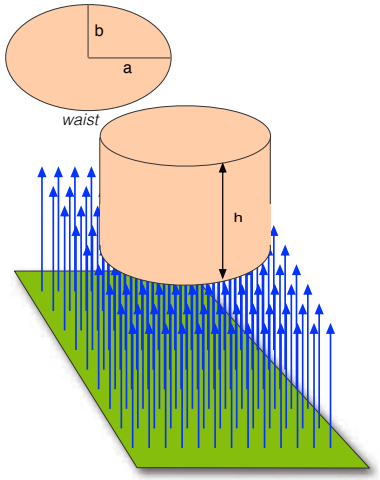

Figure 2: Schematic torso irradiated from below by uniform radiation.

where the leading factor of $\frac{1}{2}$ comes from the fact that only half of the radiation heads vertically up toward me (rather than *into* the ground). Because the radiation is γ rays, this translates directly into a (whole-body, to the extent my torso is most of my body) dose in Sv with the same numerical value. In one year this results in a radiation dose of about

I have retained more significant figures in the calculations than are shown in my equations to avoid roundoff error.

$$\begin{aligned} &1.9 \times 10^{-11}\ \mathrm{Sv\,h^{-1}} \times 24\frac{\mathrm{hrs}}{\mathrm{day}} \times 365\frac{\mathrm{days}}{\mathrm{yr}} \\ &\quad \simeq 0.17\,\mu\mathrm{Sv\ per\ year} \end{aligned} \tag{3}$$

This is roughly 4000 times smaller than the Geiger-Müller estimate.

(b) *Only α radiation*

We now make a different estimate, assuming that the whole-body dose of radiation from Pu is entirely due to α particles, which account for almost all of the particles emitted by ^{239}Pu. This is given to 'set

the scale' for doses from α particles (which have a range of 3-5 cm at most in air); in reality a standing person would receive *no* dose from Pu in the soil. The calculation is very much the same as that for γs, but now we attribute all of surface radioactivity to α particles, whose energy [6] we assume to be 5.151 MeV. Because (see the document A crash course in radiation, biology, and health physics) the 'biological weighting factor' for α particles is 20 (20 times larger than for γs), we must multiply the whole-body dose by 20 to convert the raw absorbed radiation dose (in Gray) into the equivalent effective radiation dose (in Sieverts). In one hour my torso now receives a total dose in Joules per kilogram (kg) (noting that 1 J/kg $\equiv$ 1 Gy)

$$\begin{aligned} &\simeq \frac{1}{2}\, 370\,\mathrm{Bq\,m^{-2}} \times \frac{1\mathrm{disint/sec}}{\mathrm{Bq}} \times 5.151\ \frac{\mathrm{MeV}}{\mathrm{disint}} \\ &\qquad \times 10^6\ \mathrm{eV/MeV} \times 1.60 \times 10^{-19}\mathrm{J/eV} \\ &\qquad \times \frac{0.069\,\mathrm{m^2}}{\mathrm{torso}} \times \frac{1\ \mathrm{torso}}{50\,\mathrm{kg}} \times 3600\,\mathrm{sec\,/h} \\ &\qquad \simeq 7.6\ 10^{-10}\ \mathrm{Gy\,h^{-1}} \end{aligned} \tag{4}$$

It is this number which must be multiplied by 20 to find an equivalent radiation dose. We now find an hourly dose of about 0.015 µSv, and thus an annual dose of about 0.13 mSv.

The table in the margin shows these estimates. *Remember:* the *range* of α particles is so short that, in fact, they would be absorbed before entering living human tissue, so that it is only the γ dose estimate that is physically relevant.

case	en/part	rad wgt fact	dose/yr
all γ	129.3 keV	1	0.17 µSv
all α	5.151 MeV	20	0.13 mSv

Table 1: Annual whole-body doses from nominal 370 Bq m^{-2} surface ^{239}Pu contamination with radiation type assumptions. Energy per particle ('en/part') from [6]; note inclusion of radiation weighting factors ('rad wgt fact').

3. *Using DOE dose modeling software* RESRAD-Onsite
As discussed in the previous document From radiation dose to cancer risk, the DOE uses a scenario-driven comprehensive tool named RESRAD [7] to evaluate radiation exposure and cancer risk due to radioactive contamination. The suite of computer codes (for Windows) can be downloaded and run, and has a large

number of parameters that can be tweaked to reflect a particular situation. RESRAD requires specification of contamination in radioactivity per gram of soil, so I have used the value 0.08 pCi/g from the June 1996 DOE map discussed in the document Rocky Flats, radiation, and risk.

To simplify comparison with the estimates above, I have selected a scenario in which a human being resides (100% of the time) outdoors, exposed to soil radiation from ^{239}Pu. The result—in terms of radiation dose in μSv per year—is shown in Fig. 3.

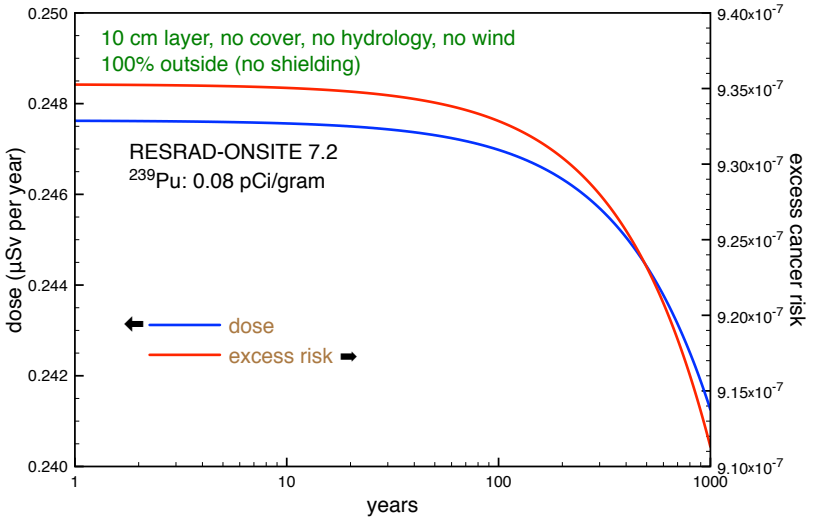

Figure 3: RESRAD dose predictions (in µSv per year) and excess cancer risk for 0.08 pCi per cm^3 of ^{239}Pu uniformly distributed over a surface layer 0.1m thick.

Because RESRAD has default values of dirt density and erosion rates, I set the erosion rate to 0. Had I not done this, the dose per year would have declined fairly quickly after a few decades as the relatively thin contaminated layer eroded away. Other default assumptions about rainfall amounts and soil porosity—while important for realism in a real scenario—nonetheless cause the radiation dose per year to slowly decline over many decades. For this reason I will use only the early-year dose rate to estimate a 50-year 'lifetime' dose for comparison with the results above.

There is a dose rate decline eventually due to computational defaults meant to retain numerical stability: this is not a half-life effect, since the half-life of ^{239}Pu is about 24,000 years. We note an annual dose of about 0.248 µSv, for a 50-year dose of $\simeq$ 0.0124 mSv. RESRAD-ONSITE also has a built-in capacity to predict the ERR (excess risk of cancer due to radiation exposure) associated with the specified levels of contamination and site parameters. This is shown in red in Fig. 3. It is less than 0.000001 (1 in a million) over a lifetime.

Appendix

I spent several hours trying to understand why my γ-only estimate should have agreed so well with RESRAD results. This is a genuinely technical issue but is included to preclude a certain class of criticisms.

The Rocky Flats isotope of interest ^{239}Pu as we have seen emits α particles. However, such 'decays' are generally accompanied by the emission of γ rays as well. In nuclear physics the intensity of these γ rays from a particular decay is usually specified by its 'branching ratio' or 'branching fraction'. What the hell is that? "The branching fraction is the equilibrium gamma-ray intensity per decay of each parent nuclide." [8]. I prefer to think of this as in fact the number of γ rays emitted per α particle (being not unhappy about fractional numbers far less than 1).

Energy (keV)	BF
129.296	8.05×10^{-5}
413.713	2.07×10^{-5}

Table 2: Two most important γ ray energies for ^{239}Pu and their branching fractions (roughly speaking, the number of γ rays per α particle). From excellent French data repository.

They are important, for example, in radiation forensics [9].

In our case the 'parent nuclide' is ^{239}Pu (the 'daughter is ^{235}U). These intensities (branching fractions) are known quite precisely for a huge number of radionuclides. The significance is that for an ideal radiation counter beyond a distance 10 cm or so from the ground (beyond the range of α particles in air) we should see *only* the γ rays, whose count rate should drop by a factor of the branching ratio with respect to the α particle count rate; this would drop the radiation *dose*. We have used the Krey-Hardy map with radiation levels in $\mathrm{Bq\,m^{-2}}$ (or, more recent DOE maps with levels in picoCuries per gram of soil), whose *net* radiation levels should drop, hugely reducing the dose, if these data included α + γ radiation.

But my γ-only estimate agreed quite well with the RESRAD benchmark results. This made me think about how the original measurements were carried out. There is no such thing as an ideal radiation detector: an α detector typically is designed to measure *only* α particles and a γ-ray spectrometer measures *only* γ rays. *If* the field measurements were carried out with a γ spectrometer, they would deduce radiation levels from the γ rays (not the

alphas) present. This, together with the fact that RESRAD apparently ignores α exposure (except via the inhalation pathway, which we have ignored above) accounts for the good agreement.

References

[1] Joseph L. Alvarez. "Measurement of Effective Dose". In: *Environmenal Instruments* June (2001), pp. 267–287. DOI: 10.13140/RG.2.1.4258.4167.

[2] Paul R Steinmeyer. "G-M Pancake Detectors: Everything You've Wanted to Know (But Were Afraid to Ask)". In: *RSO Magazine* (2005). URL: https://ehs.berkeley.edu/sites/default/files/lines-of-services/radiation-safety/G-M_pancake_detectors.pdf.

[3] National Institute of Standards and Technology. *X-Ray Mass Attenuation Coefficients - Air, Dry*. 2004. URL: https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html (visited on 02/27/2018).

[4] Radiochemistry Society Nuclear Periodic Table and Isotopic Data. *Gamma-ray spectrum catalog of isotopes*. Tech. rep. 2003. URL: http://www.radiochemistry.org/periodictable/gamma_spectra/pdf/pu239.pdf.

[5] T. E. Sampson. "Plutonium Isotopic Composition by Gamma-Ray Spectroscopy". In: *unknown*. 1986. Chap. 8. URL: http://www.lanl.gov/orgs/n/n1/panda/00326403.pdf.

[6] International Atomic Energy Commission. *Livechart - Table of Nuclides - Nuclear structure and decay data*. URL: https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html (visited on 02/24/2018).

[7] Argonne National Laboratory. *RESRAD Family of Codes*. URL: http://resrad.evs.anl.gov/ (visited on 02/27/2018).

[8] Gary W Philips, David J Nagel, and Timothy Coffey. *DTP-013: A Primer on the Detection of Nuclear and Radiological Weapons > National Defense University Press > Publications | NDU Press*. 2005. URL: http://ndupress.ndu.edu/Publications/Article/1227691/dtp-013-a-primer-on-the-detection-of-nuclear-and-radiological-weapons/.

[9] Thomas E. Sampson, Thomas A. Kelley, and Duc T. Vo. *Application Guide to Gamma-Ray Isotopic Analysis Using the FRAM Software*. Tech. rep. URL: http://www.lanl.gov/orgs/n/n1/appnotes/LA-14018-M.pdf.

Appendix: Notes on RESRAD runs

My purpose in using RESRAD-Onsite was strictly as a benchmark, to determine whether simpler, much less sophisticated approaches could be used to estimate yearly and lifetime radiation doses and hence cancer risks. They can.

1. I have assumed that the contaminated layer is about 10 cm (0.1 m) thick, has no covering dirt on top.
2. I set the geometry to be a large disk of area 1 million square meters. The linear dimension of such a disk is much larger than the range of any γ rays in air and is more computationally convenient than a rectangle.
3. I ignored all radiation exposure pathways *except* direct exposure to radiation from Pu in the soil. From the range of radiation particles, we *expect* this dose to be almost entirely due to γ rays.
4. I set erosion rates to zero simply because I had *already* set the thickness over which Pu was distributed to 10 cm and over a few decades RESRAD shows a decline in dose as the contaminated soil erodes away.
5. I left rainfall amounts (about 39 inches per year) and soil porosity at their default values. This is responsible for the gradual dose decline as the Pu soaks deeper into the ground.