Radiation doses: large, small, and unavoidable

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November 2023: Revisions to dose rate *notes*

Contents

Now that the terminology of radiation exposure and dose have been discussed in A crash course in radiation biology and health physics we return to an overview of the relation between radiation exposure and cancer risk.

Exposure and dose

The 'radioactivity' of a particular source is measured in nuclear disintegrations per second (becquerel = Bq = 'activity') or curies (Ci: 1 Ci = 3.7×10^{10} Bq, or 1 Bq = 27 picocuries = 27 pCi).[1] The Bq is the official international unit, but curies are still used in older references. The activity is not very useful by itself; however, if you know the energy of the particles emitted in each nuclear disintegration and how far you are away from the sources, your radiation dose is fairly simple geometrical calculation. Two examples are given in the document Rocky Flats, radiation, and risk.

[1] Ugh: before 1946 radioactivity was measured in curies, thereafter in Bq.

Geiger counters are frequently calibrated with ^{137}Cs, a radioactive isotope of cesium which is a common fission product in nuclear reactors. It has a half life of 30.17 years and emits almost entirely 0.6617 MeV γ rays and β particles. The long half life means that a given source for calibration can be used for a long time; the γ ray-only spectrum means that even a cheap Geiger-Müller counter can detect them, albeit it at low efficiency since γ rays 'interact' only weakly with the atoms of a gas.

In environmental contexts it it usually more useful to know *concentrations* of various radioactive species. For example, the limit for remediation of radon in a house in the U.S. is 4 picocuries (pCi) per liter of air. Surface contamination, such as occurs on and around the Rocky

Flats site, would be measured in $\mathrm{Bq\,m^{-2}}$ (or, if the distribution of contaminant by volume is well characterized, as $\mathrm{pCi/cm^3}$ or pCi/g if measured by weight). As you know from a previous document, *radiation dose* is measured in a different set of units, related to the energy absorbed per unit mass of a given type of body tissue. Common units in the US are the *rad* (for 'radiation absorbed dose'); there are 100 rad per Gy (the gray is the standard international unit for radiation dose). The dose *rate* to a human being from common radiation sources such as 'background' (see below) might be measured in millirad per hour or (if we know the biological impact) in μSv (microSieverts) per hour.

Not surprisingly, if you know your way around MKS units, this is measured in joules per kilogram, defined to be 1 Gray (Gy).

Large and small dose rates

On the surface of the Earth a variety of sources give rise to a "background" level of radiation (radioactive minerals in the soil, the bombardment of the Earth by cosmic rays) which depends on altitude (the atmosphere partially absorbs cosmic rays) and the local geology. The working definitions of "large" and "small" dose rates[2]

$$\textit{large}\quad \frac{\text{dose rate}}{\text{background dose rate}} \gg \text{(much greater than) } 1$$

$$\textit{small}\quad \frac{\text{dose rate}}{\text{background dose rate}} \lesssim \text{(less than or about) } 1$$

[2] As I constantly told my students, in physics there are no "large" quantities—only the ratio of one physical quantity to another with the same units can be large or small.

I have chosen to use dose rates (for example, in $\mathrm{\mu Sv\,h^{-1}}$) rather than doses; the same distinction of course also holds for the doses themselves. This classification will turn out to be very important because cellular repair mechanisms appear capable of coping with dose rates comparable to background.

Additions, November 2023: A great deal is now known about the time scales for biochemical changes in response to ionizing radiation. (These range from seconds to weeks, depending on dose.) Some of this is due to the search for biomarker for radiation exposure. In this context 'low doses' are around 1 Gray–in the ballpark of one million times annual estimated doses per year from inhaling or swallowing plutonium in dust. A recent *Nature* article [1] surveys this work. Nonetheless [2], a clear framework for including dose rates is so far lacking.

Fig. 1 shows that relevant ranges of radiation dose (in Sievert) span a factor of 100,000 or so; the U.S. Nuclear Regulatory Commission 2010 diagram on which it is based [3] is the most useful chart I have encountered for comparing doses. It is very important to note that the life

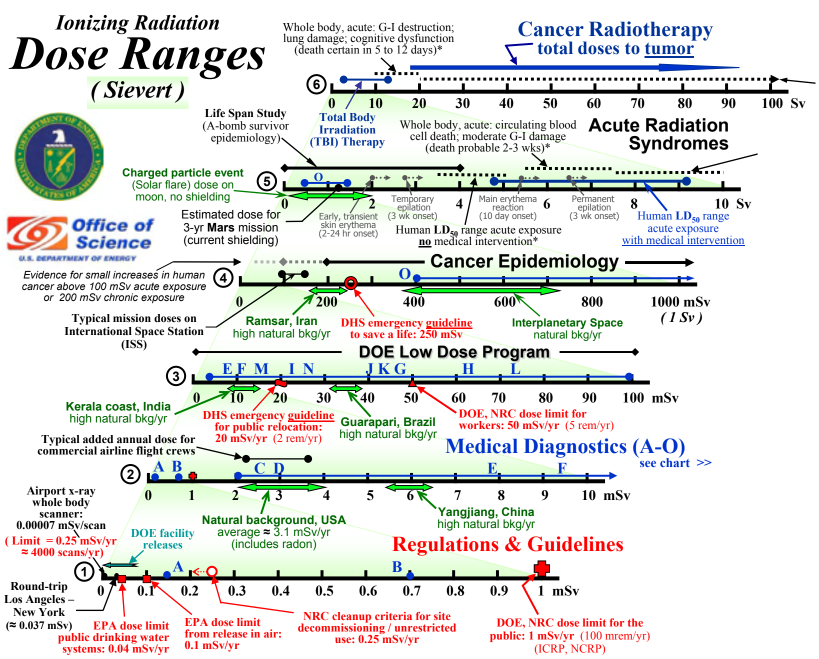

Figure 1: Classification of dose ranges, as of June 2010, according to the Office of Science of the DOE. (This graphic has edited by DMW for compactness.) Note that each row involves a dose range 10× higher than the one below it.

span studies of atomic bomb survivors examined people whose dose range was up to 4 Sv and that medical *diagnostics* (but not cancer radiation *therapy*) cover a dose range 1000 times smaller. Also important: cancer epidemiology (which requires the study of large numbers of people since the cancer risks are small) spans a range 100 times *higher* than the background rates in the U.S. The Department of Energy's Low Dose Program (canceled in 2016) studied dose ranges 100 times larger than U.S. background levels. In the very lowest row (10,000 smaller doses than for A-bomb survivors) are EPA limits in mSv per year for water, for air releases, and for the Nuclear

Regulatory Commission's site decommissioning limit, required to release land without radiological use restrictions (0.25 mSv per year).

These observations are meant to put ordinary background radiation into perspective.

As stated in the document *Off-Site Lands* no longer available in 2023 in the archives of the Rocky Flats Stewardship Council,

> Most of the soil samples taken by CDPHE and others were either at background or slightly higher. However, a few samples were greater. The highest concentration, which was found 1,800 feet east of Indiana Street near the site's east entrance, was 6.5 pCi/g. This level of radioactivity corresponds to [a dose rate of–Ed] approximately 0.12 millirem/year, another measure of radioactive dose.

Remembering that 100 rem ('roentgen equivalent man') = 1 Sv, this amounts to a dose of about 1.2 μSv per year. Compare this with what is on the chart!

Typical radiation exposures to Americans

As mentioned earlier, background radiation is partially due to radioactive minerals in soil (whose concentration varies strongly from place to place) and partially to cosmic rays (mostly high-energy protons). There is a very strong dependence of cosmic ray dose on altitude since the atmosphere absorbs cosmic rays strongly (because it is so thick) and its density depends roughly exponentially on altitude. Fig. 2 shows background radiation doses around North America due to radioactive soil minerals and cosmic rays. Fig. 3 shows EPA data on typical non-background (generally, medical) sources of radiation and radon levels around the US.

There is also some dependence on latitude (because of the role of the Earth's magnetic field in deflecting charged particles.

Colorado experiences a 'triple whammy' of background radiation: much of the state is at high altitudes, the minerals that make up the Rocky Mountains include uranium and a variety of other radionuclides that emit γ rays, and (mostly as a consequence of minerals) we are in the belt of high radon (an α emitter) concentrations. As you have already seen in the site document Cancer epidemiology, despite this Colorado has among the very lowest cancer rates in the US (Summit County has *the* lowest); we will revisit this in the document 'Recent' developments in low-dose radiation response.

Why *internal* radiation in the pie chart? A human body is radioactive simply because some of the isotopes of elements common in the body are themselves radioactive. Different isotopes generally behave identically in terms of their biochemistry. Bananas, rich in potassium, gave rise to the tongue-in-cheek radiation dose unit called the 'banana equivalent dose' of ^{40}K. Why *consumer* dosage? 'Ionization'-type smoke detectors use the synthetic α-emitter ^{241}Am (americium 241) to establish a tiny current whose interruption by smoke particle is used to trigger an alarm. Because it is an α emitter, it is easily shielded by a thin aluminum cage around the source. The source itself is covered by an encapsulant which assures that none of the ^{241}Am itself escapes the source.

The full EPA pie chart [5] indicates an additional 2.28 mSv per year due to radon exposure (mostly α particles) for an *average* citizen; *A quick check:* I read values of 88 nGy/hr and 83 nGy/hr as dose rates from cosmic rays and from γ rays due to soil minerals for Colorado, for an annual dose of 1.5 mGy/year—or 1.5 mSv/year since this radiation is assumed to be mostly γ rays. Adding the 2.28

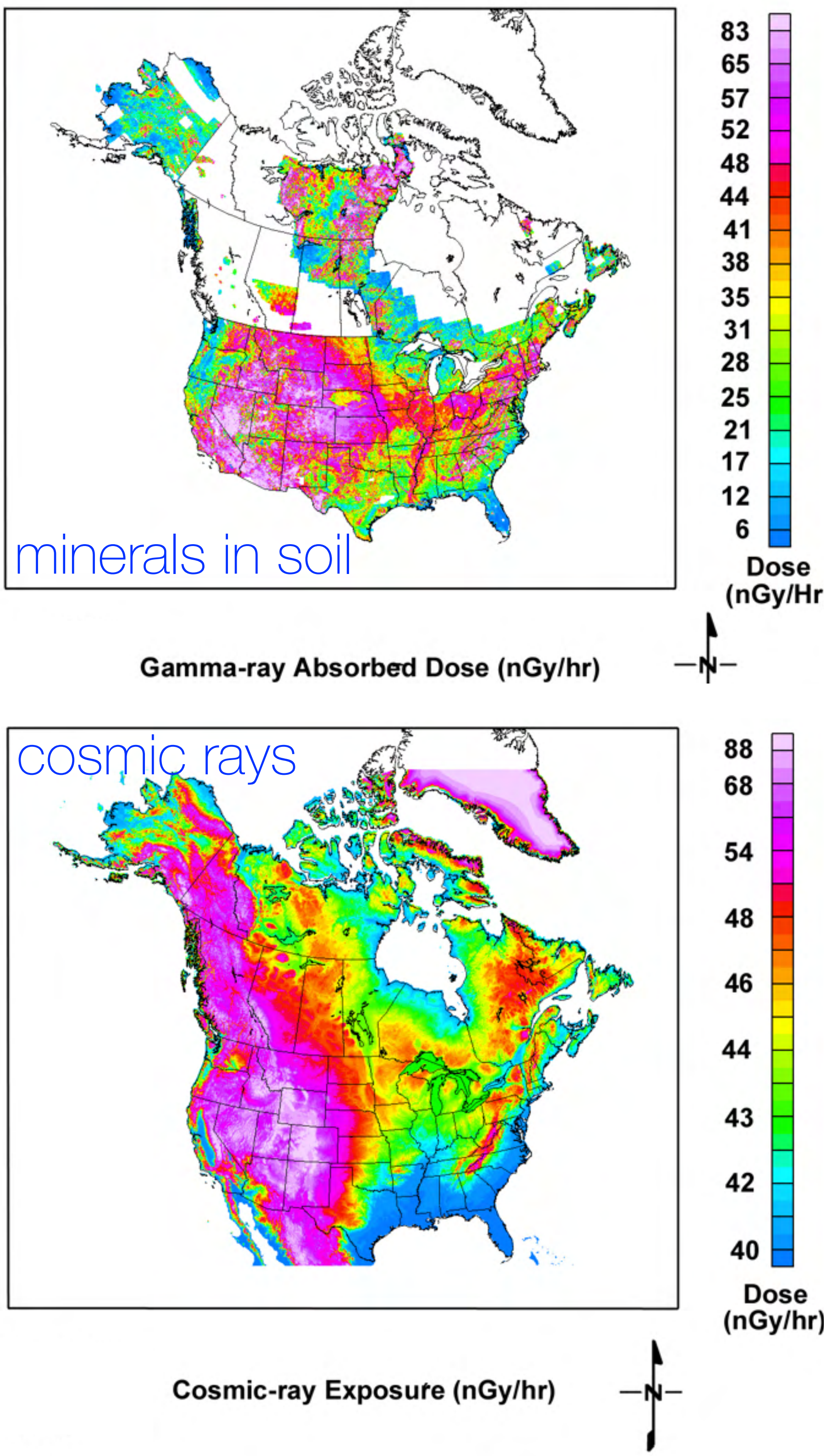

Figure 2: Radiation doses from soil minerals (upper panel) and from cosmic rays (lower panel). The cosmic ray exposure map is virtually indistinguishable from the elevation map. From USGS. [4]

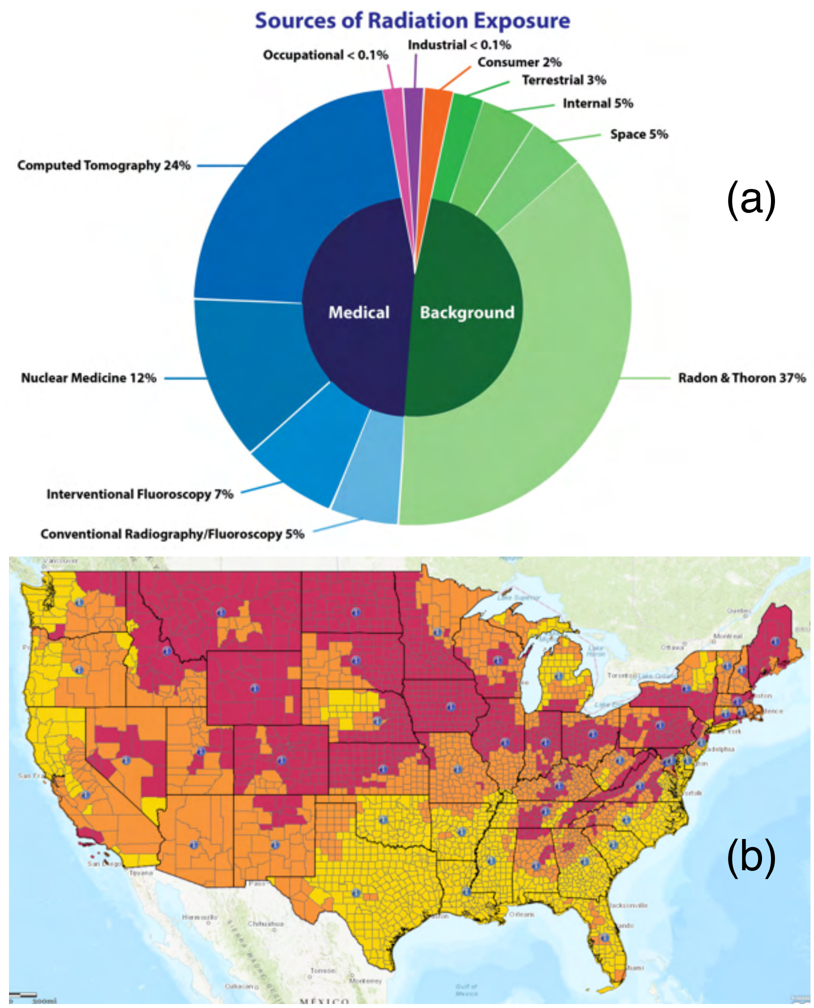

Figure 3: Sources of radiation exposure for average American, panel (a). Screen grab, panel (b) of radon levels by region from the EPA. Red is high.

mV for radon exposure, we find about 3.8 mSv per year for the average population of Colorado, at the high end of the green arrow indicating natural background in the U.S. in the DOE dose chart. We will revisit the importance to cancer epidemiology of the much (10-50 times) higher background rates at other locations around the world.

Perspective on medical uses of radiation

You cannot necessarily assume that X-ray or nuclear medicate diagnostics are ‘safe’. The Cancer Prevention and Treatment Fund [6] has excellent information comparing the radiation exposure of common diagnostic procedures here. I have redrawn the table prepared by Julie Bromberg and Laura Covarrubias (vetted by Dr. Diana Zuckerman) [6] Fig. 4 but have added in the chart an entry for the exposure associated with living in Colorado for one year. [I added an entry for 'one year in Colorado' assuming the same lifetime risk as the next higher dose category. At most two significant figures are relevant for the doses, despite the chart formatting.]

The bottomm panel shows the approximate dose in mSv while the upper panel shows approximate ranges (high in red, low in blue) for the lifetime additional risk in the form of "1 in" chances. As we will see later, this data will put into stark perspective how low the doses from plutonium around and inside the Wildlife Refuge really are.

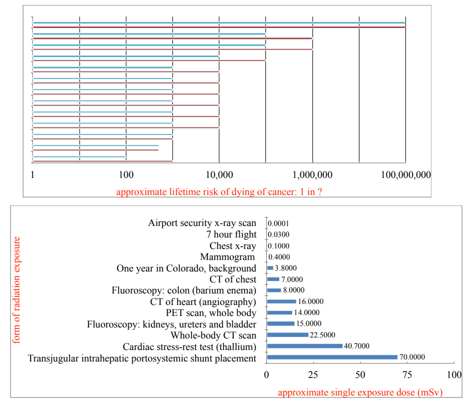

Figure 4: Radiation dose and additional approximate lifetime risk of dying of cancer associated with common medical procedures. Mostly from [6].

A quick look at the Front Range

A bar chart of background counts I measured is in the document Seeking clarity in Fall 2013 elsewhere on this site. Since that time I placed my Geiger-Müller counter online as part of one of several international radiation monitoring networks. Count rates for Colorado are visible in the lower right corner of the Pacific Northwest detail map. In Fig. 5 I show comparisons between count rates for four Geiger-Müller counters of the *same model*, spread from Colorado Springs in the south through Centennial, Lakewood, and the south boundary of Rocky Flats, where I live. Please note that although my count rates (taken on the ground floor of a two-storey house) tend to be the lowest, I attribute no significance to this because background rates are a matter of local geology. There are significant weather-induced variations of all count rates. What *is* noteworthy is that despite our proximity to Rocky Flats there is no discernible impact on the count rate. (This is scarcely surprising since my counter is inside a house, but so are the other three counters.)

Radiation network lore suggests that rates go up when the *edge* of the jet stream moves overhead. Apparently wind shear causes particulate matter suspended in the jet stream to precipitate out.

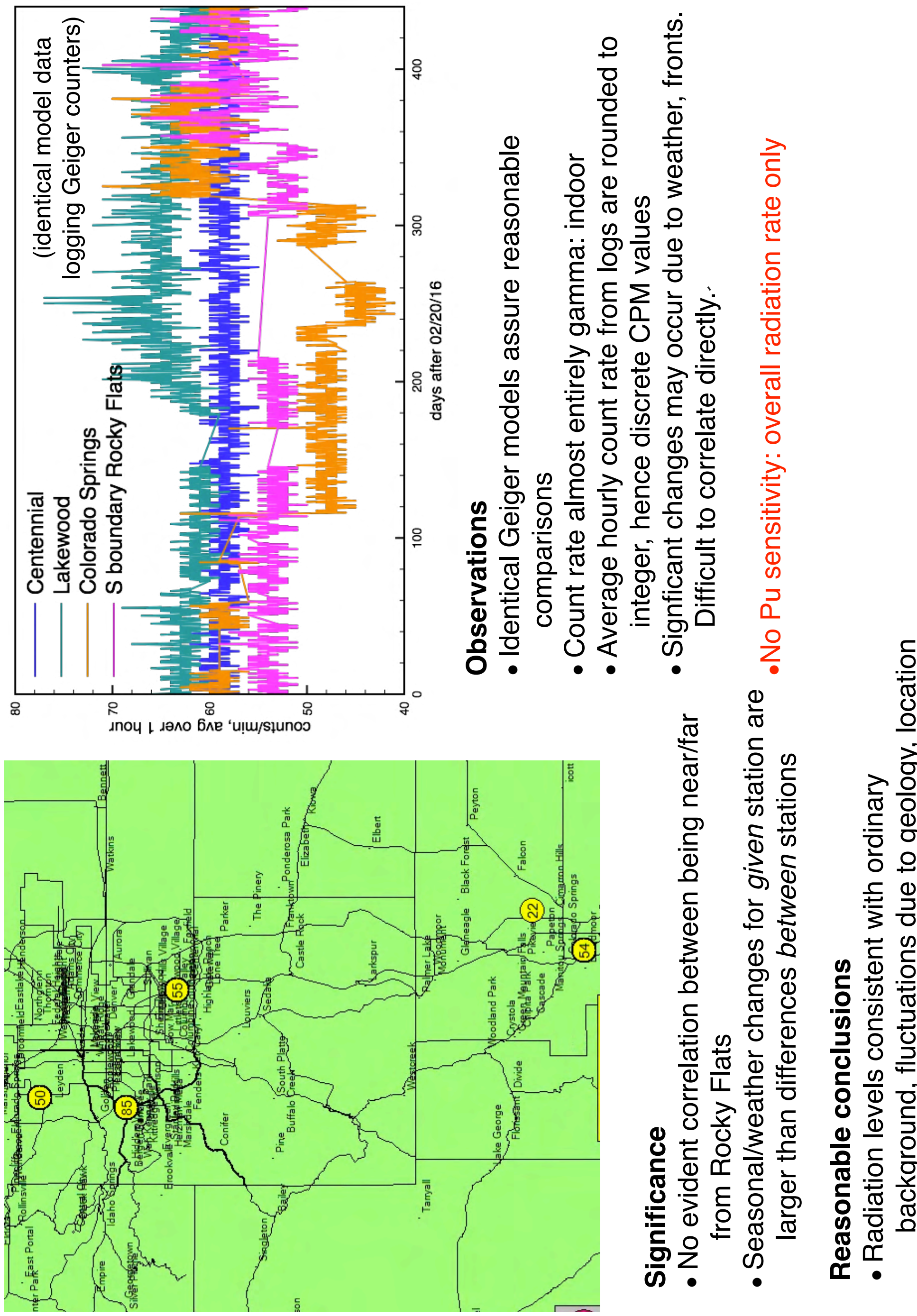

Figure 5: Records over more than a year for four identical-model Geiger-Müller counters along the Front Range.

More citizen science

A zoomable Google map may be used to examine background radiation wherever there are (usually) roads or (sometimes) paths. These levels are directly measured using a standardized kit-built Geiger-Müller counter (using the same high-sensitivity Geiger-Müller tube as mine) with built-in GPS support developed by the wonderful, non-political, and comprehensive citizen-science environmental safety cooperative SAFECAST [7] set up shortly after the Fukushima Daiichi disaster. The August 2017 SAFECAST report [8] indicates that more than 70 million measurements around the world are available;

An example comparing downtown Boulder with part of Candelas is shown in Fig. 6. It is amusing to note that

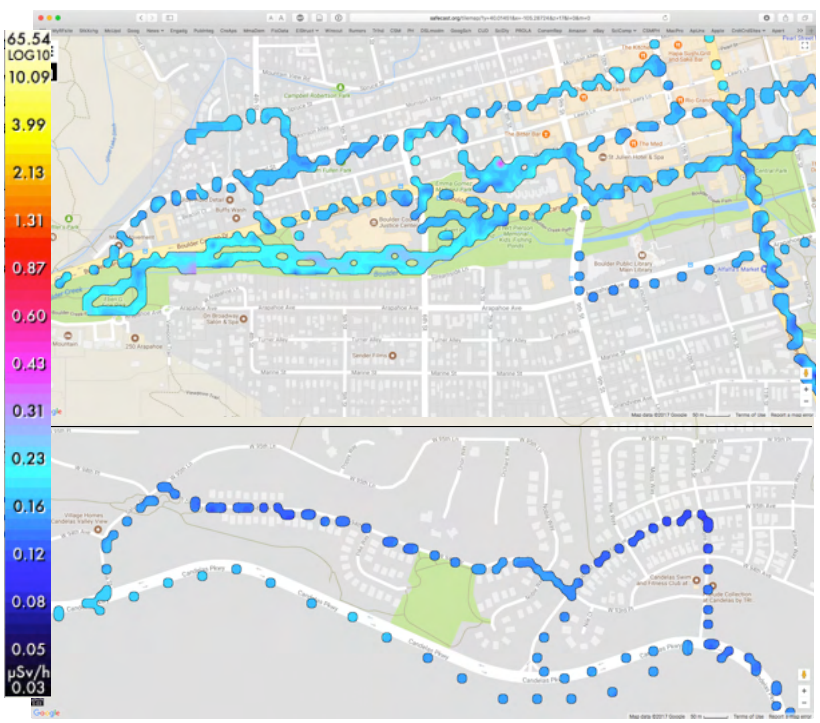

Figure 6: SAFECAST radiation background levels in Boulder (upper panel) compared with those in Candelas (lower panel).

values along Boulder Creek (about 0.12-0.31 μSv/hour) exceed those measured in the Candelas development (about 0.08-0.23 μSv/hour). I would guess this is from mineral-laden water in Boulder Creek leaving deposits on its banks.

Takeaway messages

- Radiation doses and dose rates are very usefully classified as large or small based on how they compare with unavoidable *background* radiation rates.
- Background radiation is considerably higher in Colorado than in any other U.S. state, due both to minerals in the soil (and hence radon) and its average altitude.
- Pu- and Am-contaminated soils around Rocky Flats give rise to radiation doses generally well below 1 µSv per year.

References

[1] Kiran Maan et al. "Metabolomics and transcriptomics based multi-omics integration reveals radiation-induced altered pathway networking and underlying mechanism". In: (), pp. 1–13. DOI: 10.1038/s41540-023-00305-5. URL: https://www.nature.com/articles/s41540-023-00305-5.

[2] Donna Lowe et al. *Radiation dose rate effects: what is new and what is needed?* Vol. 61. 4. Springer Berlin Heidelberg, 2022, pp. 507–543. ISBN: 0123456789. DOI: 10.1007/s00411-022-00996-0. URL: https://doi.org/10.1007/s00411-022-00996-0.

[3] N F Metting. *Ionizing Radiation Dose Ranges*. Tech. rep. Department of Energy, 2010. URL: https://www.nrc.gov/docs/ML1209/ML120970113.pdf.

[4] United States Geological Survey. *USGS Open-File Report 2005-1413: Terrestrial Radioactivity and Gamma-ray Exposure in the United States and Canada*. 2005. URL: https://pubs.usgs.gov/of/2005/1413/maps.htm (visited on 01/10/2018).

[5] U.S. Environmental Protection Agency. *Sources of radiation exposure*. URL: https://www.epa.gov/sites/production/files/2017-04/donut-pie-chart.png (visited on 03/04/2018).

[6] Julie Bromberg and Laura Covarrubias. *Cancer Prevention and Treatment Fund*. URL: http://stopcancerfund.org/pz-environmental-exposures/everything-you-ever-wanted-to-know-about-radiation-and-cancer-but-were-afraid-to-ask-2/ (visited on 03/06/2018).

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[8] Azby Brown et al. *THE SAFECAST REPORT*. Tech. rep. SAFECAST, 2017. URL: https://blog.safecast.org/wp-content/uploads/2017/10/safecastreport2017-part1safecastproject-final-171004011228.pdf.

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