Hot particles: Nevermore

D. M. Wood, [substantially revised] July 2019

Contents

Version 1.2 revisions: Recent work discussed, dose estimates and comparison with DOE values.

Among all plausible safety concerns, the question of 'hot particles' was the most rapidly dealt with by the scientific community (around 1976). The concern has been kept alive (mostly by LeRoy Moore) for more than 40 years despite its rapid dismissal as a special risk by the scientific community.

It is *not* that hot particles do not exist (they will be defined below and are present around many nuclear sites); it is that (i) they are quite unlikely to be inhaled, and if they were, (ii) they are in fact probably *less* dangerous than other 'whole body' exposures to Pu or other α-emitting radionuclides, such as swallowing. These other pathways to ingestion are already included, for example, in the RESRAD software used by the Office of Legacy Management of the Department of Energy to model (via various scenarios, discussed elsewhere) radiation exposure around and within the Rocky Flats National Wildlife Refuge.

RESRAD is discussed at more length in the document From radiation dose to cancer risk.

What are 'hot particles'?

On the EPA web site [1] is a clear report (in parts technical) entitled *Health effects of alpha-emitting particles in the respiratory tract: Report of Ad Hoc Committee on "Hot particles" of the Advisory Committee on the biological effects of ionizing radiation*, prepared [2] by the National Academy of Sciences and the National Research Council for the EPA in 1976.

You will need to search for this by name: 'alpha-emitting particles in the respiratory tract' should do it

> Since the early 1950's, various groups with responsibility for determining the effects of radiation sources on human health have recognized the possibility that radioactive material deposited in tissues of the body as high specific activity [very radioactive–Ed] particles might be a greater health hazard than the same source distributed more homogeneously. This has been referred to as the "hot particle" problem. In 1974 Cochran and Tamplin hypothesized that the intense and highly localized dose from inhaled insoluble plutonium particles larger than a specified size causes greater tissue damage, and is therefore more carcinogenic, than more uniformly-delivered irradiation. On this basis Cochran and Tamplin advocated a 115,000-fold reduction in the current radiation standards governing exposure to insoluble alpha-emitting ("hot") particles.

Large particles never make it into the lungs; tiny particles are breathed in and out again (and are too small to statistically contain much Pu anyway). So the issue could arise for particles only in a 'window' of particle size.

Radiation dose rate from hot particles

We will *set up* a calculation to appreciate why the hot particle issue was plausible in 1974. Our simplified description of a hot particle will consist of a spherical microcrystal of PuO_2 of diameter of 3μ (microns, 1μ=10^{-6} m). We assume all Pu atoms are ^{239}Pu, since this is by far the most common at Rocky Flats. PuO_2 occurs in the cubic fluorite crystal structure, with four formula units per conventional cubic unit cell of lattice constant a=5.398Å. Thus the number density of Pu atoms is

$$n = \frac{4}{a^3}$$

In a spherical particle of diameter $d = 3\mu$ there are therefore

$$N = \frac{4\pi}{3}(d/2)^3 \times n = \frac{4\pi}{3}\frac{1}{2}(d/a)^3 = 3.5952 \times 10^{11} \qquad (1)$$

Pu atoms. If we multiply the number of atoms from Eq. 1 by the activity per atom s^* (in Bq/atom) for a particular Pu isotope we have the number of decays per second within the particle. We assume the radioisotope of interest emits strictly α particles of energy E_α. If we measure this kinetic energy in MeV, as is common, and multiply by the emission rate we have the energy per second (joule/s) emitted by the particle:

$$q = Ns^*[\text{decays/atoms per s}]E_\alpha[\text{MeV}]1.602 \times 10^{-13}\text{J/sec} \tag{2}$$

where we have been careful to convert MeV per second into joules per second. (There are 1.602×10^{-13} joules per MeV.)

As specified above, we will take ^{239}Pu as the isotope of interest. Then the particle has an activity of 0.328 Bq (8.86 pCi) and the energy escaping the hot particle per second is

$$q = 2.704 \times 10^{-13}\text{J/s}. \tag{3}$$

If we divide by the mass of whatever the α particles are irradiating we have the *dose rate* in grays per second.

At this point we must decide how to treat this energy production rate *biologically*. If we use the finite range of α particles in tissue, estimate the number of cells within this range, then the average dose per cell from the energy production rate in Eq. 3 and the cell mass, we find a prodigious dose rate, enough to kill all cells within range. The Appendix shows a detailed calculation and a few remarks about the impact of radiation on cells. This was where things stood in about 1974.

isotope	spec activ s^*	E_α
^{238}Pu	2.51 10^{-10}	5.486
^{239}Pu	9.12 10^{-13}	5.148
^{240}Pu	3.35 10^{-12}	5.155
^{241}Am	5.08 10^{-11}	5.480 FIX

Table 1: Ingredients for hot particle energy deposition rate. Specific activities (Bq per atom) are taken from and α energies are averaged over all α emissions weighted by probability per decay.

A long history of negative findings about dangers of hot particles

The 1976 EPA report discussed above concluded that

> . . . The evidence does not support the NRDC petition for a special, lower radiation protection standard for inhaled alpha-emitting particles. The current state of knowledge about the 'hot particle' problem can be summarized as follows:
>
> 1. In animals, all experimental data so far obtained indicate that when insoluble plutonium particles are inhaled, the major radiation dose

in the lungs occurs in the pulmonary (i.e., alveolar) region. The principal delayed effect in the lung of breathing these particles is induction of alveolar cancers. An analysis of mortality from these cancers in beagle dogs indicates that if there is a hot-particle effect, Cochran and Tamplin have overestimated the cancer risk per particle by at least two orders of magnitude. However, analyses indicate that the observed lung cancer mortality in these dogs can be adequately accounted for by the conventional method of averaging the absorbed alpha radiation dose over the entire lung. Therefore, it is concluded that if there is a "hot particle" risk, it is small by comparison with the lung cancer risk attributable to the generalized alpha radiation.

One 'order of magnitude' = 10^1 =factor of 10; two orders of magnitude = 10^2 factor of 100, etc.

2. In human beings, epidemiological evidence gained from experience with inhalation of alpha-emitting radon daughters and with external X or gamma irradiation of the thorax strongly suggests that the radiocarcinogenic sensitivity of the tracheobronchial region is greater than that of the alveolar regions where inhaled plutonium is retained. Therefore, we would not expect the human cancer risk from alpha irradiation of the deep lung tissues to be underestimated by applying risk factors obtained from human experience with cancer induced by irradiation of the lining of the bronchial tree.
3. Current evidence indicates that the cancer hazard from insoluble particulate plutonium deposited in the lungs is not markedly greater than would be caused by the same quantity of radioactivity distributed more uniformly. The experimental evidence suggests that the carcinogenic response is more a function of the amount of radioactivity in the lung than of its distribution.

There are useful and clear (if technical) appendices in the report.

A 1987 German article [3] came to somewhat surprising conclusions:

> The biological relevance of local megadoses from particulate α-emitters was discussed and studied in the seventies. . . . Experimental findings from animal studies and theoretical considerations lead to the hypothesis that a strongly inhomogeneous irradiation induces less health detriment than a homogeneous irradiation. The main argument being that in the case of α-particles, a clearly defined tissue area is irradiated at dose rates leading to acute cell death or total loss of proliferative capability. Outside this area, the dose is practically zero. Hence, almost all ionizations and excitations occur in dead tissue . . . The wasting of a large fraction of the radiation dose on dead cells is thought to cause the relative innocuousness of α-hot particles. . .
>
> In several facilities involved in the US military bomb program, groups of workers were exposed to measurable amounts of airborne, particulate plutonium activity. A population of 25 workers involved in the Manhattan Project showed initial lung depositions of plutonium in the range of 15 kBq. This would correspond to about 100,000 hot particles with a diameter of 1μm. [In] 1972, more than 25 years after the

> contaminations, the average body burden still amounted to about 3.7 kBq ^{239}plutonium with about 5 to 10% residing in the lung. No health detriments traceable to these extremely hot particle exposures have been found so far.
>
> Another group was exposed during a fire in Rocky Flats on October 15th, 1965. The initial lung burden corresponded to about 10,000 to 100,000 plutonium particles of the size generated in the fire. . . . Although a longer follow-up of this population has to be awaited to draw final conclusion, the lack of lung diseases in the first 15 years allows to refute some of the hypotheses on the extreme radiotoxicity of hot particles.

They conclude, "Contrary to the impression at first glance, radiation from hot particles was never shown to be more radiotoxic than the same activity uniformly distributed in the organ. Both from theoretical considerations, from animal studies and from human epidemiology, it seems that wasting of dose on dead cells introduces a safety factor. Therefore, the general conclusion stressed also in review papers by Bair et al. and Feinendegen et al. is that, with increasing inhomogeneity, the detrimental effects of ionizing radiation to the lung tend to decrease."

Harrison's 2003 article [4] in the Journal of Radiological Protection entitled *Carcinogenic risk from hot particle exposures—has ICRP got it right* remarks

> The argument has become very familiar—that radionuclides introduced into the environment from nuclear installations, fall-out from weapons testing, or whatever source, are responsible for substantial increases in cancer rates, and, because current risk estimates do not support this conclusion, they must be very wrong. It is argued that there must be some way in which low levels of artificial radionuclides, levels that result in tissue doses lower than from naturally-occurring radionuclides, pose a risk that is yet to be appreciated. One obvious problem with current risk estimates, it is suggested, is the simplistic averaging of doses from hot particles–see, for example, the home page of the Low Level Radiation Campaign website (www.llrc.org) . . .
>
> It can be concluded that, on current evidence, hot particle effects do not provide a mechanism for doses from environmental levels of artificial radionuclides to be more effective in causing cancer than larger doses from naturally-occurring radionuclides. The ICRP approach of averaging dose to target cells and tissues appears to give reasonably reliable estimates of risk.

Charles, Mill, and Darley [5] in 2003 report in a 23-page careful review with 86 references remark: "These conjectural arguments [of extra carcinogenicity for hot particles–

Ed] were reviewed by a number of workers. Their conclusions supported the continued use of mean organ dose as a predictor of cancer risk. Albert, whose work on skin cancer induction in rat skin was the basis for this conjecture, has also criticised the rationale and conclusions of Tamplin and Cochran."

"In summary, in very broad terms (within a factor of $\sim \pm 3$) the results of a large number of animal studies and a growing number of in vitro studies are in agreement regarding the lack of evidence to support a large hot-particle enhancement factor. Human evidence is limited but does not support any significant hot-particle enhancement. All of this is in stark contrast to the claims made more than 30 years ago, which fuelled so much concern, that this could be as much as five orders of magnitude."

Section 3.6 (Carcinogenic risks of particulates) of the 2004 English CERRIE report [6] concluded

> 16 The Committee examined the suggestion that spatially non-uniform radiation exposures, from radioactive particulates, may be much more carcinogenic than uniform exposures throughout tissue volumes. It therefore commissioned a literature review of the possible carcinogenic effects of particulate radioactive materials, which has since been published... The review concluded that, on current evidence, the conventional assumption of average dose to a tissue or relevant component should provide a reasonable estimate of carcinogenic risk within a factor of three up or down of the central estimate ...
>
> 18 Data on lung cancer mortality following occupational inhalation of plutonium aerosols, and on the incidence of liver cancer and leukaemia due to Thorotrast administration for clinical diagnoses, did not support a significant risk enhancement factor for particles. Very few animal studies, including mainly lung and skin exposures, provided any indication of a particle enhancement. Some recent in vitro malignant transformation experiments provided evidence for an enhanced cell transformation for 'hot' particle exposures but the effect was modest. However, most doses were very high: few studies concerned doses below 100 mGy—the area of interest to the Committee.
>
> 19 It appeared from the literature review that there was no convincing evidence from worker, animal or in vitro studies that 'hot' particles that delivered high doses to a small surrounding volume of tissue were more hazardous than more uniform irradiation. However, the situation for 'warm' particles that delivered lower doses was less clear due to the paucity of direct observations.
>
> 20 Most [10 of 12–Ed.] of the Committee agreed that little information

> existed which supported enhanced risks from exposures to 'hot' particles, although most studies used relatively high doses. Two members considered that the possibility that 'warm' particles presented a high risk could not be ruled out. The remainder of the Committee remained unconvinced or uncertain of this hypothesis mainly because of the paucity of evidence presented...

The last definitive discussion of the health impacts of 'hot particles' I could find occurs in a 2007 journal article (*i.e.*, 21 years after the Chernobyl incident (which itself rekindled concern and re-examination of hot particle issues) entitled *Hot particle dosimetry and radiobiology—past and present* [7]

> The claim of increased carcinogenicity was referred to as the 'hot particle hypothesis'. After a decade of intensive experimental and theoretical investigation an ICRP review of the biological effects of inhaled radionuclides in 1980 refuted this claim in the context of inhaled hot particles. The 'hot particle hypothesis' in the context of skin exposure has been refuted by a series of skin cancer induction experiments in mice and in cell studies of induced malignant transformation. The ICRP has maintained its advice that the use of mean organ or tissue dose is appropriate for the evaluation of carcinogenic risk for radiological protection purposes.
>
> ...Our understanding of the radiobiological effects of hot particles, and our ability to measure relevant doses from them, has increased dramatically over the past 25 years.
>
> The likelihood of a casual encounter with a hot particle in the environment, even in the environs of Dounreay is very low. ...It is possible to predict significant health effects but only by making assumptions which have a low probability, such as exceptionally long residence/transit times. This low probability must be compounded with the already very low probability of encountering a particle. The challenge for regulators remains, as in other situations of environmental contamination, to determine the extent to which remediation is required in the light of potential health effects with a low probability of occurrence.

Dounreay is a now-decommissioned Scottish nuclear installation with 5 reactors. Chunks of old fuel rod washed ashore on public beaches in 2007, provoking intense investigation of 'hot particles' in the United Kingdom.

Current status

As noted in 2017 by Caffrey *et al.* [8], although there remains plenty of uncertainty about how to treat such localized doses, "...the literature suggests that non-uniform exposure from an inhaled hot particle is likely less carcinogenic than that from a spatially uniform exposure for the same average dose (Charles and Harrison 2007;

Charles et al. 2003; Richmond et al. 1970; Sanders et al. 1977; Sanders 1975)." They reiterate, "Previous laboratory studies have demonstrated a reduction in carcinogenesis in animals exposed to particulate radiation vs. soluble forms (e.g., Charles and Harrison, 2007; Harrison and Stather 1996; Sanders et al. 1977)." Caffrey *et al.* used a Monte Carlo radiation transport code and examined doses from a wide range of PuO_2 particle sizes and for several different nominal Pu compositions. They clearly demonstrate that at a particle diameter of about 3μ only about 50% of the energy carried by α particles actually escapes the particle itself because of 'self shielding' by the dense plutonium. (This is still likely to kill all cells within range, as discussed in the Appendix.) Beyond about 10μ less than 10% of the radiated energy is available to irradiate tissue.

Although hot particles are no longer regarded as a special threat, attention remains focussed on integrating their contribution into a general framework of radiation exposure. National Commission on Radiological Protection (NCRP) and the International Commission on Radiological Protection (ICRP). 'Task Group 64' of the ICRP is currently addressing [9] the issue of of α-particle emitters and "tissue that is not subect to mechanical transport or absorption into blood". This includes lung tissue.

Three estimates of lifetime cancer risk due to 'hot particles'

In keeping with the multiple findings above, hot particles are generally neglected in radiation doses. Nonetheless, we can readily estimate their impact by treating their dose as administered to the entire body. This will *overestimate* their health impact, as discussed above.

Direct whole body dose from hot particles

We will assume that the hot particle is inhaled at a particular time, is somehow trapped in place, and remains there for a nominal human lifetime (generally taken as

50 years in epidemiology). Because α particles are doubly charged, their 'relative biological effectiveness' (RBE) in doing cellular damage will enter in the calculation of the *effective* dose (measured in sieverts, Sv) from the radiation dose in gray (Gy), given in Eq. 3 For α particles the RBE is the dimensionless number 20.

It might be helpful to review the distinction between radiation dose and the effective dose, which reflects the type of radiation and the tissue affected. Our review is here.

We assume an average body mass M of 75 kg (165 lbs) for concreteness. Per second, if we treat the radiation as delivered to the *entire body*, then the dose rate in Sv (1 joule of energy per kilogram, effective dose) is

$$\text{RBE} \times q/M = 7.21 \times 10^{-14}\text{Sv/s} = 2.27\mu\text{Sv/year}, \qquad (4)$$

for a lifetime dose of 0.114 mSv. Given that the *annual* average U.S. background radiation dose is 3.10 mSv, it is clear that the added impact of a single hot particle is negligible (0.07%) on a whole-body basis.

On the other hand, the 2007 ICRP Publication 103 [10] recommends the value of 5.5 % per Sv [delivered to the entire body] as the 'risk coefficient' for stochastic effects (see A crash course in radiation, biology, and health physics), including cancer, at low dose rates, for the entire population. (It is not easy to say whether this is for fatal cancers or development of cancers.) Using this figure the additional (lifetime??? CHECK) cancer risk os about

$$\frac{5.5\%}{\text{Sv}} \times 0.114 \times 10^{-3}\ \text{Sv} \simeq 6.27 \times 10^{-4}\ \% \qquad (5)$$

Thus for a 1% increase in lifetime cancer risk, we would need about 1,600 of the 'hot particles' modeled above. The *Environmental Health Fact Sheet* published by Argonne National Laboratory in August 2005, currently available via the Wayback Machine here, states

I thank John Yoder for bringing the Argonne Environmental Fact Sheet to my attention. It is what motivated me to do the calculation above.

> . . . for inhalation (the exposure of highest risk), breathing in 5,000 respirable plutonium particles of about 3 microns each is estimated to increase an individual's risk of incurring a fatal cancer about 1% above the U.S. average.

Using tabulated U.S. 'radiological risk coefficients'

In the same Argonne document mentioned above are tabulated the radiological risk coefficients for the lifetime

cancer mortality per unit radioisotope intake in pCi, averaged over all ages and both genders. For ^{239}Pu these are 2.9×10^{-8} for an inhalation route and 1.3×10^{-10} for ingestion. In Eq. 1 we found the number of Pu atoms in a 3μ hot particle; multiplying by the specific activity per atom and converting from Bq to pCi (1 Bq = 27.027027 pCi) we find an activity of 8.86 pCi per particle. In order to have a lifetime excess cancer mortality risk of 1% due to hot particles, 39,000 such particles would need to be inhaled, or 8,700,000 particles ingested.

ICRP risk coefficients

The International Commission on Radiation Protection has its own tables [11] that relate the effective radiation dose in Sv to the radioactivity in Bq, and separate tables [10] to relate these to lifetime cancer risk. As above, we can estimate the number of 3μ ^{239}Pu hot particles required to raise your excess cancer mortality risk to 1%. For slowly absorbed inhaled PuO_2 particles, for adults the effective dose is 1.6×10^{-5} Sv/Bq. For ingested particles the figure is 2.5×10^{-7} . We use the 0.328 Bq activity for our particles estimated above and the 5.5% per sievert cancer mortality coefficient to find that we would need to inhale about 35,000 particles or ingest about 2,220,000 particles

The ICRP and U.S. estimates are remarkably close to one another. This is probably due to U.S. authorities using ICRP recommended values

Summary of estimates

Thus different ways of estimating lifetime cancer risks due to hot particle exposure give somewhat different values for the number required for a 1% excess risk, but the conclusion remains the same. Results from our direct estimate above are consistent with my experience comparing them with DOE estimates. They never agree extremely well, but as ballpark estimates they *always* agree. A factor

of three disagreement in such estimates (in which someone could have chosen different a different plutonium compound as typical, a different typical radioisotope or some sort of average, slightly different α particle energies, different sources of epidemiological data, different average body weight, etc.) is very reasonable. It is also a reminder that you do not need access to elaborate DOE facilities or data to make reasonable estimates. This is very reassuring to me.

Takeaway messages

- Hot particles (small, highly radioactive α-particle emitting specks of dirt or other material) definitely exist around radiation-contaminated sites. They were thought in the early 1970s to be especially dangerous via inhalation.
- The current literature (through 2017) concurs that 'hot particles' are in fact *less* carcinogenic than equivalent doses of ordinary (uniform) radiation.
- Inhaled Pu is *already included* in the RESRAD software used to describe Pu exposure and cancer risk within and around Rocky Flats, which have been assessed as posing excess cancer risks of between 1 in 100,000 and 1 in 1 in 1,000,000.

Appendix: dose per cell within range of α particle

We found in the text that a 3μ ^{239}Pu 'hot particle' produced energy at a rate of

$$q = 2.704 \times 10^{-13}\text{J/s}.$$

The whole point of the 'hot particle' question was to treat this entirely as a 'committed' dose deposited at one location (generally assumed to be somewhere in the lungs). To be concrete, we will assume that the hot particle is inhaled at a particular time, is somehow trapped in place,

and remains there for a nominal human lifetime (generally taken as 50 years in epidemiology). Because α particles are doubly charged, their 'relative biological effectiveness' (RBE) in doing cellular damage will enter in the calculation of the *effective* dose (measured in sieverts, Sv) from the radiation dose in gray (Gy). For α particles the RBE is the dimensionless number 20.

It might be helpful to review the distinction between radiation dose and the effective dose, which reflects the type of radiation and the tissue affected. Our review is here.

A reasonable analysis (i) acknowledges that α particles have a relatively short range in tissue, (ii) estimates the number of cells within that range, and (iii) examines the dose per cell. It is important to include the average lifetime of such a cell since it is *far* less than the lifetime of a human being. Previous careful examinations of the 'hot particle' problem suggest that that such particles are most likely to lodge among bronchial or alveolar cells.

So almost all ionziations occur in dead tissue? An alveolar cell has a diameter [12] of about 200μ; bronchial epithelial cells have a diameter of about 10.4μ [13]. By contrast, the range of a 5.5 MeV α particle in *water* (a very reasonable approximation to human tissue) is about 43.4μ [WolframAlpha]. The volume associated with the range of particles really is a sphere whose radius is the range; cells are only roughly spherical, with a radius of half their diameter. Thus the number of cells within range of α particles from ^{239}Pu is approximately

$$N_{cell} = \frac{\text{volume in range}}{\text{volume per cell}} \simeq \begin{cases} \left(\frac{43.4}{10.4/2}\right)^3 \simeq 582, & \text{bronchial} \\ \left(\frac{43.4}{200./2}\right)^3 \simeq 0.082, & \text{alveolar} \end{cases} \tag{6}$$

(I will end the analysis of the alveolar cell because these cells may be mostly filled with air in living animals.) The *mass* of a bronchial cell (needed to compute the dose in Gy) is just its volumes times its mass density, assumed to be 1 gram per cubic centimeter (the mass density of water). This is about 5.89×10^{-13} kg for a bronchial cell. We can now compute the average *dose rate* to the bronchial cells in the range of the α particles emitted by ^{239}Pu: this

is

$$\text{dose/cell} \simeq \frac{q}{M_{cell} N_{cell}} \text{Gy/s} \simeq 2.84 \text{Gy/hr} \qquad (7)$$

This is an *extremely* high dose rate! Many cells are killed outright by doses of 1 Gy.

The 'survival curve' shows the fraction of an initial cell population which survives after cumulative doses of ionizing radiation. It is the *log* of this fraction which is linearly related to the dose.

At this point we can understand why radiation doses from 'hot particles' was a serious concern when the issue was first raised in the early 1970s. What has been learned since then has been an illustration of a phrase commonly used in the radiation protection field, that '. . . radiation is a very good cell killer (this is why we use it in radiation therapy), but that it is a poor carcinogen' [14].

Double-strand DNA breaks are believed to be the most significant impact of ionizing radiation in terms of (i) causing outright cell death, and (ii) the eventual induction of cancers. They are produced at a rate of about 35-40 per Gy of radiation dose. "Among these lesions, DNA double-strand breaks correlate best with cell killing, because they can lead to certain chromosomal aberrations (dicentrics, rings, anaphase bridges) that are lethal to the cell. Lethality, from the perspective of radiation biology, means the loss of reproductive integrity of tumor clonogens; that is, the tumor cells may still be physically present or intact and may still be able to undergo a few cell divisions, but they are no longer able to form a colony of cells." [15].

So a very tentative picture emerges about the actual cellular-scale effect of a fixed 'hot particle': essentially all cells within range of the α particles are killed (generally by 'apoptosis', a programmed cell death stimulated by double strand DNA breaks). Because of this controlled death, scavenger cells are signaled and engulf dead cells before cell contents spill into their surroundings. This means that the 'hot particle' simply kills each new generation of surrounding cells, which in their turn absorb most of the ionizations from the particle, making its net impact *less* than an equivalent uniform dose of radiation.

A very readable account on this process for real (not cultured) tissue exists [16], which notes "Besides macrophages,

some tumor cells and some normal epithelial cells can also engulf suicidal cells, such as some alveolar epithelial cells in the mammary gland and some bronchial epithelial cells in the lung." It is remarkable that these examples are drawn from tissue that are the likely resting places for inhaled 'hot particles'.j

References

[1] United States Environmental Protection Agency. *Simple Search | NSCEP | US EPA*. URL: https://nepis.epa.gov/Exe/ZyNET.EXE?ZyActionL=Register{\&}User=anonymous{\&}Password=anonymous{\&}Client=EPA{\&}Init=1 (visited on 03/05/2018).

[2] Ad Hoc Committee on "Hot Particles" of the Advisory Committee on the Biological Effects of Ionizing Radiation. *Health Effects of Alpha-Emitting Particles in the Respiratory Tract*. Tech. rep. Office of Radiation Programs, U.S. Environmental Protection Agency, 1976, p. 127. URL: https://nepis.epa.gov.

[3] Werner Burkart and Hanspeter Linder. "Hot Particles in the Environment: Assessment of Dose and Health Detriment". In: *Medicine sociale et preventive* 32 (1987), pp. 310–315. URL: https://link.springer.com/content/pdf/10.1007/BF02078168.pdf.

[4] John Harrison. "Carcinogenic risk from hot particle exposures -has ICRP got it right?" In: *Journal of radiological protection* 23 (2003), p. 1. URL: https://pdfs.semanticscholar.org/cf0f/d006ccfd4fb5f9af6bb04cbcee797aa85a05.pdf.

[5] M. W. Charles, A. J. Mill, and P. J. Darley. "Carcinogenic risk of hot-particle exposures." In: *Journal of radiological protection* 23.1 (2003), pp. 5–28. ISSN: 0952-4746. DOI: Piis0952-4746(03)58850-410.1088/0952-4746/23/1/301. URL: http://iopscience.iop.org/article/10.1088/0952-4746/23/1/301/meta.

[6] Dudley Goodhead OBE. *Committee Examining Radiation Risks of Internal Emitters (CERRIE)*. Vol. 22. 2. 2002, pp. 195–195. ISBN: 0859515451. DOI: 10.1088/0952-4746/22/2/604. URL: http://stacks.iop.org/0952-4746/22/i=2/a=604?key=crossref.ba548f32bb39fc474ca6ef91423064d8.

[7] M W Charles and J D Harrison. "Hot particle dosimetry and radiobiology—past and present". In: *Journal of Radiological Protection* 27.3A (2007), A97. URL: http://stacks.iop.org/0952-4746/27/i=3A/a=S11.

[8] Emily Caffrey et al. "Comparison of Homogeneous and Particulate Lung Dose Rates For Small Mammals". In: *Health Physics* 112.6 (2017), pp. 526–532. ISSN: 0017-9078. DOI: 10.1097/HP.0000000000000668. URL: http://insights.ovid.com/crossref?an=00004032-201706000-00003.

[9] W. F. Morgan. "Overview of ICRP Committee 1: radiation effects". In: *Annals of the ICRP* 45.November 2015 (2015), pp. 9–16. ISSN: 1872969X. DOI: 10.1177/0146645315614497.

[10] International Commission on Radiological Protection. *The 2007 Recommendations of the International Commission on Radiological Protection: Publication 103*. Elsevier, 2007. ISBN: 9780702030482. URL: https://journals.sagepub.com/doi/pdf/10.1177/ANIB{_}37{_}2-4.

[11] K. Eckerman et al. "ICRP Publication 119: Compendium of Dose Coefficients based on ICRP Publication 60". In: *Annals of the ICRP* 41.SUPPL1 (2012), pp. 1–130. ISSN: 01466453. DOI: 10.1016/j.icrp.2012.06.038. URL: http://dx.doi.org/10.1016/j.icrp.2013.05.003.

[12] Matthias Ochs et al. "The Number of Alveoli in the Human Lung". In: *American Journal of Respiratory and Critical Care Medicine* 169.1 (2003), pp. 120–124. ISSN: 1073-449X. DOI: 10.1164/rccm.200308-1107oc.

[13] J. L. Devalia et al. "Culture and comparison of human bronchial and nasal epithelial cells in vitro". In: *Respiratory Medicine* 84.4 (1990), pp. 303–312. ISSN: 09546111. DOI: 10.1016/S0954-6111(08)80058-3.

[14] Antone L. Brooks, T. Edmond Hui, and Lezlie A. Couch. "Very Large Amounts of Radiation are Required to Produce Cancer". In: *Dose-Response* 5.4 (2007), dose–response.0. ISSN: 1559-3258. DOI: 10.2203/dose-response.07-013.brooks.

[15] Jose G. Bazan, Quynh-Thu Le, and Daniel Zips. *Radiobiology of Lung Cancer*. Second Edi. Elsevier Inc., 2018, 330–336.e2. ISBN: 9780323523578. DOI: 10.1016/B978-0-323-52357-8.00035-4. URL: https://www.sciencedirect.com/science/article/pii/B9780323523578000354.

[16] Bingya Liu et al. "Apoptosis in living animals is assisted by scavenger cells and thus may not mainly go through the cytochrome c-caspase pathway". In: *Journal of Cancer* 4.9 (2014), pp. 716–723. ISSN: 18379664. DOI: 10.7150/jca.7577.

Reminders: (i) Just click on a reference in the text to reposition the cursor in the bibliography; (ii) generally

by simply clicking on the URL field or the DOI field in a bibliographic entry will fire up our Web browser and take you to where the original file is available.