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SPECIFIC BLOOD ABSORPTION PARAMETERS FOR $^{239}PUO_2$ AND $^{238}PUO_2$ NANOPARTICLES AND IMPACTS ON BIOASSAY INTERPRETATION

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Abstract

Specific absorption parameters for $^{239}PuO_2$ and $^{238}PuO_2$ have been determined based on available biokinetic data from studies in rodents, and the impacts of these parameters on bioassay interpretation and dosimetry after inhalation of nanoPuO_2 materials have been evaluated. Calculations of activities after an acute intake of nanoparticles of $^{239}PuO_2$ and $^{238}PuO_2$ are compared with the corresponding calculations using standard default absorption parameters using the International Commission on Radiological Protection (ICRP) 66 respiratory tract model. Committed effective doses are also evaluated and compared. In this case, it was found that interpretation of bioassay measurements with the assumption that the biokinetic behaviour of PuO_2 nanoparticles is the same as that of micrometre-sized particles can result in an overprediction of the committed effective dose by two orders of magnitude. Although in this case the use of the default assumptions (5 μm AMAD, Type S) for assessing dose following inhalation exposure to airborne PuO_2 nanoparticles appears to be conservative, the evaluation of situations involving PuO_2 nanoparticles that may have different particle size and solubility properties should prudently follow the ICRP recommendation to obtain and use additional, material-specific information whenever possible.

INTRODUCTION

Default blood absorption parameters for radionuclides in the lungs are described and discussed in International Commission on Radiological Protection (ICRP) Publication 66 on the Human Respiratory Tract Model (HRTM)[(1)]. However, as pointed out in ICRP

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Publication 30, if the behaviour of any specific material is expected to differ significantly from that of the biokinetic model employed, then the model parameters should be modified to take account of the available data[2]. In the case of plutonium (Pu), a considerable number of studies involving Pu particles in the micrometre size range have demonstrated that in general plutonium dioxides (PuO_2) behave as a Type S material[3]. It is of interest to determine how the use of material-specific particle size and bioassay parameters for PuO_2 materials in the nanosize range might influence decision-making for health protection.

Traditional risk management of the biological effects and related health consequences of inhalation exposure to radionuclides such as PuO_2 has relied on data and default assumptions from studies involving particles in the micrometre size range. Nonetheless, as work with nanometre-sized materials expands, it is reasonable to ask whether the biological behaviour of plutonium dioxide in the nanometre size range might differ significantly from its behaviour in the micrometre size range. While the current default values for biokinetic models are representative of the experience base for materials in the micrometre size range, there has been no assessment to date as to whether or not the use of the defaults would be protective for someone exposed to $^{239}PuO_2$ and $^{238}PuO_2$ in the nanosize range. Correct assessment of the biokinetic behaviour of Pu following an inhalation exposure requires determination of when default assumptions are adequate or when material-specific information is needed.

The impacts using specific absorption parameters for $^{239}PuO_2$ and $^{238}PuO_2$ and the impacts on bioassay interpretation and dosimetry after inhalation of nanoPuO_2 materials need to be evaluated. To address this, historical data on the biokinetic behaviour of Pu observed in rats, exposed by pulmonary intubation to plutonium dioxide (PuO_2) nanoparticles, are used to derive specific blood absorption parameters for use with the HRTM published by the ICRP, ICRP Publication 66. This work illustrates the use of material-specific particle size and bioassay parameters with corresponding bioassay tables and dose coefficients. Calculations of activities after an acute intake of nanoparticles of $^{239}PuO_2$ and $^{238}PuO_2$ are compared with the corresponding calculations using standard default absorption parameters using the ICRP 66 respiratory tract model. Committed effective doses are also evaluated and compared.

MATERIALS AND METHODS

Available data

There are no human data available to assess absorption of PuO_2 from nanometre-sized particles in the respiratory tract. Therefore, biokinetic information must be derived from experiments with laboratory animals, notably the studies conducted by Smith *et al.* with $^{239}PuO_2$ nanoparticles and Stradling *et al.* with $^{238}PuO_2$ nanoparticles[4, 5].

According to Smith *et al.*, size-fractionated ^{239}Pu particles that were produced by arc vaporisation of a Pu metal wire were obtained by membrane filtration into sizes <25 nm, 25–220 nm and 220 nm to 1.2 μm physical diameters. Separation of particles in the <25 nm suspension via membrane filtration with nominal pore diameters of 12, 9, 6 and 4 nm were attempted but were not successful[4]. However, ultrafiltration through a membrane with a

nominal pore size of 1 nm was successful, indicating that the particle size in the <25 nm suspension was primarily uniform with a diameter of 1 nm[4]. Particles in the largest size range (220 nm to 1.2 μm) were not used in the Smith *et al.* pulmonary intubation study. Stradling *et al.*, using the same filtration method used in Smith *et al.*, prepared size-fractionated ^{238}Pu particles of fresh and aged (32 weeks) particles into four particle size ranges <25 nm, 25–220 nm and 220 nm to 1.2 μm, and 1.2–5 μm diameters. Stradling *et al.* attempted to fractionate the particle sizes in the <25 nm suspension and found through electron microscopy and ultrafiltration that the <25 nm suspension of $^{238}PuO_2$, like the $^{239}PuO_2$ <25 nm suspension analysed by Smith *et al.*, consisted primarily of 1 nm particles. Stradling *et al.* only used the <25 nm particles for their pulmonary intubation study.

Rats in both studies were administered the suspensions of PuO_2 nanoparticles by pulmonary intubation through a cannula temporarily inserted into the trachea. Following exposure, animals were immediately put into metabolism cages to allow for the separate collection of urine and faeces and were given access to food and water at all times. After exposure, the groups of animals exposed to $^{239}PuO_2$ were sacrificed at 18 h, 6 d and 17 d, while the groups of animals exposed to $^{238}PuO_2$ fresh and aged suspensions were sacrificed at 1, 6 and 21 d[4, 5]. For both studies, there were four animals in each group except for a group of eight animals that were sacrificed on Day 17 of the $^{239}PuO_2$ study. To analyse the plutonium distribution in various tissues, Smith *et al.* collected urine and faeces over the course of their study and separated out the animal's lungs, liver, spleen, blood, carcase and other tissues (kidneys, testes, adrenals, thymus and gastrointestinal tract) at the time of sacrifice. Stradling *et al.* collected urine and faeces over the course of their study and separated out the lungs, liver, blood, carcase and other tissues (spleen, kidneys, ovaries and gastrointestinal tract) at the time of sacrifice.

Equivalent aerodynamic diameter

Plutonium dioxide nanoparticle sizes in Smith *et al.* and Stradling *et al.* were reported as physical diameter based on size separation of the particles by filtration and examination of the separated particles by electron microscopy[4, 5]. Smith *et al.* reported a uniform physical size of 1 nm for particles <25 nm and a mass median diameter of 48 nm for material in the 25–220 nm size range. Stradling *et al.* also reported a uniform 1 nm particle diameter for particles <25 nm. Conversion of physical diameters to an equivalent aerodynamic diameter was done using the equations in Section D.4.1 in Annexe D of ICRP Publication 66[1]. For the calculation, the density of plutonium was assumed to be 9 g cm^{-3} and the shape factor was assumed to be 1. The aerodynamic diameters of plutonium nanoparticles were calculated to be 9 and 258 nm for 1 and 48 nm diameter particles, respectively. Thus, for the purposes of calculating daily urinary excretion and dose, nominal particle sizes were taken to be 1 and 48 nm when expressed in terms of activity median thermodynamic diameter (AMTD) and 10 and 250 nm when expressed in terms of activity median aerodynamic diameter (AMAD). For the purposes of presenting data in this paper in a uniform way across the wide particle size range from 5 um AMAD (the default work-place diameter) to 1 nm physical diameter, the authors have chosen to present graphical and tabular results in terms of AMAD. Many workplace studies involving cascade impaction provide particle size

distributions in terms of aerodynamic diameter. It is appropriate to express particle sizes for nanoparticles in terms of AMTD, and some data based on diffusion analysers are available for some workplace situations. However, AMAD correspondences will be used throughout this paper for purposes of comparison of calculation results.

Determination of material-specific blood absorption parameters

Lung and systemic biokinetic models for the rat, shown in Figure 1, were developed to fit the available experimental data. The systemic portion of the model was based on the current ICRP plutonium systemic model for humans[6]. Recycling of plutonium in organs to and from blood has also been taken into account. The model contains blood, liver1 (which describes biliary excretion), liver2 (which describes recycling back to blood and biliary excretion), carcase and other (other soft tissues). The main difference from the ICRP plutonium systemic model and the rat model developed here is that only prompt urinary excretion to the urinary bladder was considered without considering retention in the kidney compartment because the amount of available data was insufficient to support the inclusion of this pathway. To distinguish it from data in other soft tissues, a separate ‘carcase’ compartment was generated, which encompasses skeletal Pu content as well as that in attached undissected muscle tissue.

Transfer rates for the systemic portion of the model were derived from the intravenous injection experiments conducted by Smith *et al.*[4]. Transfer rates derived for ^{239}Pu can be seen in Table 1, and ^{238}Pu results are shown in Table 2. In this work, two lung compartments, named Lung1 and Lung2, were added to the systemic model to represent the transfer processes from particles in initial state to blood (sp) and to particles in transformed state (spt) and from particles in transformed state to blood (st). Regarding the transfer rates presented in Table 1, at first glance one would expect a greater transfer of materials from smaller particles due to their higher surface area when compared with larger particles that have a smaller surface-to-mass ratio. However, there are several pathways involved in this recycling model, so the fitting process involves the overall examination of transfer as a whole and not by individual transfer rates. In addition, it is recognised that the same metabolism can be described by different combinations of transfer rates.

RATDOSE software was used to determine the material-specific blood absorption parameters[7]. It is a software application that was developed to provide the ability to empirically model the biokinetics of radionuclides administered in animal experiments. The software allows the user to produce a computational framework in which complex compartmental models together with tissue and excreta activity data can be fitted with fidelity thus minimising the uncertainties in the predictions. It has a robust statistical treatment of the data and good presentation of the results. Goodness of fit for how well the model describes the available data is assessed through the determination of χ^2.

Activities and dose calculations

Activities predicted in organs and excreta for standard workers following acute inhalation of PuO_2 for both isotopes ^{239}Pu and ^{238}Pu for AMADs 5 μm Types M and S, particles of physical diameter 1 nm (10 nm AMAD) of each isotope, and particles in the 25–220 nm

diameter range (250 nm AMAD) for ^{239}Pu were evaluated using a software package (AIDE) that calculates activities in compartments and committed doses due to intakes of radionuclides[8]. In this work, inhalation intakes of plutonium were calculated using the ICRP HRTM[1] together with the ICRP Publication 67 plutonium systemic model[6]. Output of the AIDE model is in terms of daily urinary excretion activities and corresponding committed dose coefficients for ^{239}Pu and ^{238}Pu. Committed effective dose coefficients (e50) per unit measured activity in daily urinary excretion (Sv Bq^{-1}), also known as dose per unit content, were calculated using AIDE for acute intakes of ^{239}Pu and ^{238}Pu for several particle sizes and solubilities.

RESULTS AND DISCUSSION

Data extracted from the studies for ^{239}Pu and ^{238}Pu oxides of 1 nm diameter size (10 nm AMAD) and for ^{239}Pu oxide in the particle size range of 25–220 nm (250 nm AMAD) were entered into RATDOSE software. Initial fittings of transfer rates s_p, s_{pt} and s_t were done using ^{239}Pu data with a corresponding χ^2 per degree of freedom of 3.0 for 10 nm AMAD particles. Fitting of s_p, s_{pt} and s_t for ^{238}Pu are also shown in Table 3, with corresponding χ^2 per degree of freedom of 6.3 for fresh and 8.4 for aged materials, which are not as good as the one obtained for 10 nm AMAD particles of ^{239}Pu. For larger particles of 250 nm AMAD, the corresponding χ^2 per degree of freedom was 29.7 as also shown in Table 3. While unsatisfactory in terms of the χ^2 result, it is probably enough to show that larger particles present much longer lung retention as can be seen by the s_t value of 1.2×10^{-5} d^{-1}, which corresponds to a biological half-life of roughly 158 y. It must be noted though that this number was derived using data points for times only up to 17 d. The results for the larger particle sizes should therefore be interpreted with caution.

The derived blood absorption parameters for ^{239}Pu shown in Table 3 for particles of 10 nm AMAD are similar to those presented by Davesne *et al.*[9] who followed the recommendations of the ICRP Supporting Guidance 3[10] for using the systemic model for plutonium in the rat when obtaining material-specific blood absorption parameters. In Supporting Guidance 3, a much simpler model is proposed in which activity leaves the blood at a rate of 280 d^{-1} (half-time ~4 min). Of this, ~70 % is deposited in body tissues that correspond to the 'carcase', from which it clears at a rate of 0.003 d^{-1} (half-time ~230 d)[10]. The blood absorption parameters were calculated using the same data, but the results from Davesne *et al.*[9] were presented using the alternate representation for the blood absorption process through f_r, s_r and s_s parameters. Comparison of the s_p, s_{pt} and s_t results calculated in this work with those converted from Davesne *et al.* values[9], using the relationship conversion $s_r = s_p \pm s_{pt}$, $f_r = (s_p - s_t) / (s_p \pm s_{pt} - s_t)$ and $s_s = s_t$ and are shown in the last column of Table 3. The results for $^{239}PuO_2$ are remarkably similar, despite the use of completely different methods. The results for $^{238}PuO_2$ appear different, mainly with an order of magnitude slower removal rate (s_p) from the initial state to blood and higher retention shown for particles being absorbed from the transformed state to blood (s_t).

Using AIDE software[8] for comparison, Figure 2 shows the calculated daily urine excretion as a fraction of inhaled activity for ^{239}Pu for AMADs 5 μm Types M and S and AMADs of 250 and 10 nm using the calculated specific blood absorption parameters. The figure shows

that fraction of activity excreted in urine for the specific materials is larger than that for the default Type S material. As expected, the urinary excretion associated with a larger particle size AMAD 250 nm appears closer to the behaviour of a more soluble Type M material. The corresponding daily urine excretion as a fraction of inhaled activity was also calculated for ^{238}Pu with the same magnitude difference as found for ^{239}Pu.

Committed effective dose coefficients (e50) (Sv.Bq^{-1}) and committed equivalent dose coefficients for body organs were calculated for acute intakes of plutonium dioxide for several particle sizes and solubilities. The committed effective dose coefficients and the committed equivalent dose coefficients for bone surface and for extrathoracic region (ET) are shown in Table 4. In most cases, the highest committed equivalent dose occurs for bone surface. The committed effective dose for inhalation intakes of ^{239}Pu compounds associated with nanoparticles of AMAD 10 nm is ~34 times higher than that for Type S compounds with AMAD 5 μm, as seen in Table 4.

At first glance, the significant difference in the committed effective dose coefficient could impact the setting of operational radiation exposure limits in the field since the same activity measured in a filter will be associated with a higher dose when treated as a nanoparticle material. However, when a dose assessment is performed through urine bioassay measurements, a smaller committed effective dose per unit of ^{239}Pu activity measured in a daily urinary excretion sample will be calculated for nanoparticles when compared with Type S materials, as shown in Figure 3. It can be seen that the dose per unit content curves as a function of time after intake for 5 μm Types M and for nanoparticles of AMAD 10 and 250 nm using specific absorption parameters are similar and show smaller values than those for Type S compounds. The reason is because even having committed effective dose coefficients for inhalation of nanoparticles higher than that for Type S material, when it is divided by the much higher daily urinary excreted activity values for nanoparticles it results in smaller values for the ratios. It must be pointed out that the concept of dose per unit urinary excretion content is very useful for explaining the differences in committed effective dose coefficients for the several types of material when the intake estimates are made through urinalysis. However, committed dose estimates due to intakes of radionuclides using *in vivo* or *in vitro* techniques are mostly done in practice by initially performing the intake amount estimate and then using committed effective dose coefficients per unit intake to calculate the committed doses.

Figure 4 shows the comparison among the committed effective dose coefficients (e50) per unit measured activity in daily urinary excretion (Sv Bq^{-1}) for acute intakes of ^{239}Pu for the environmentally relevant AMADs 1 μm Types F, M and S with the AMADs 250 and 10 nm using specific blood absorption parameters derived from rat pulmonary intubation studies. The 1 μm Type F and AMAD 10 nm specific curves overlap. For the material evaluated in this study, it was concluded that in the absence of bioassay data tables, which were derived using material-specific absorption parameters, practitioners could use AMAD 1 μm Type F tables to reasonably interpret results for PuO_2 particles in the AMAD 10 nm diameter size range. Based on data for the larger nanoparticles evaluated in this study, a more reasonable interpretation of bioassay measurements can be achieved by using intake retention fraction

tables derived for materials with a greater degree of solubility than the default Type S materials and a smaller particle size.

Nevertheless, studies with other materials are needed to determine if these observations are generally applicable.

CONCLUSIONS

Material-specific blood absorption parameters have been derived for PuO_2 in the nanometre size range from pulmonary intubation experiments in rats[11]. Using ICRP HRTM default parameters in the micrometre size range for PuO_2 to predict biokinetic behaviour of PuO_2 following inhalation of Pu nanoparticles of AMAD 10 and 250 nm would underpredict the urinary excretion of plutonium. For ^{239}Pu and ^{238}Pu material of AMAD 10 nm and ^{239}Pu of AMAD 250 nm, a higher urinary excretion of plutonium is likely to occur compared with excretion associated with Type S material of the default occupationally relevant particle size of 5 μm. The daily urinary excretion activity values for nanoparticles with an AMAD of 10 nm are about two orders of magnitude higher than those for a typical 5 μm Type S material. These conclusions assume that the biokinetic behaviours noted in the previously described rat studies are predictive of biokinetics in humans exposed to similarly produced Pu aerosols and having similar particle size distributions.

Interpretation of bioassay measurements from individuals exposed to PuO_2 nanoparticles with the assumption that the biokinetic behaviour of PuO_2 nanoparticles is the same as that of micrometre-sized Pu particle parameters can result in an overprediction of the committed effective dose by two orders of magnitude. Consequently, intakes and committed effective doses could be overestimated from bioassay measurements if the materials contained in the exposure were known to be in the nanoparticle size range and Type S absorption parameters were assumed.

The committed effective dose for inhalation intakes of ^{239}Pu materials associated with nanoparticles is higher than that for Type S materials with AMAD 5 μm if air measurements are used for interpretation. However, a smaller committed effective dose will be calculated when the dose assessment is performed based on urinary excretion measurements. Although in this case the use of the default assumptions (5 μm AMAD, Type S) for assessing dose following inhalation exposure to airborne PuO2 nanoparticles appears to be conservative, the evaluation of situations involving PuO_2 nanoparticles that may have different particle size and solubility properties should prudently follow the ICRP recommendation to obtain and use additional, material-specific information whenever possible.

Additional biokinetic studies of AMADs between 10 and 250 nm would be helpful to determine the size at which the transition from Type S to a more soluble behaviour occurs. Such information would provide a stronger basis for determining when the HRTM default assumptions are adequate and when material-specific information is needed to correctly assess biokinetic behaviour associated with an inhalation exposure.

Analyses in the current work show that use of those default parameters to predict biokinetic behaviour of Pu following inhalation of PuO_2 nanoparticles can result in an underprediction

of the urinary excretion of plutonium. Thus, continuing the current practice of using the traditional default assumptions for assessing dose following inhalation exposure to airborne PuO_2 nanoparticles appears to be conservative, and therefore can be justified as prudent in the absence of additional, material-specific information.

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References

1. Smith H. ICRP. International Commission on Radiological Protection Publication 66: Human Respiratory Tract Model for Radiological Protection. Annals of the ICRP. 1994; 24:1–3.
2. Sowby FD. ICRP. International Commission on Radiological Protection Publication 30: Limits for Intakes of Radionuclides by Workers. Annals of the ICRP. 1979; 2:3–4.
3. ICRP. International Commission on Radiological Protection Publication 71: Age-dependent Doses to Members of the Public from Intake of Radionuclides—Part 4 Inhalation Dose Coefficients. Annals of the ICRP. 1995; 25:3–4.
4. Smith H, Stradling GN, Loveless BW, Ham GJ. The in vivo solubility of plutonium-239 dioxide in the rat lung. Health Phys. 1977; 33(6):539–551. [PubMed: 604297]
5. Stradling GN, Ham GJ, Smith H, Cooper J, Breadmore SE. Factors affecting the mobility of plutonium-238 dioxide in the rat. Int J Radiat Biol Relat Stud Phys Chem Med. 1978; 34(1):37–47. [PubMed: 309441]
6. ICRP. International Commission on Radiological Protection Publication 67: Age-Dependent Doses to Members of the Public from Intake of Radionuclides—Part 2 Ingestion Dose Coefficients. Annals of the ICRP. 1993; 23:3–4.
7. Miller G, Bertelli L, Klare K, Weber W, Doyle-Eisele M, Guilmette R. Software for empirical building of biokinetic models for normal and decorporation-affected data. Health Phys. 2012; 103(4):484–494. [PubMed: 22929474]
8. Bertelli L, Melo DR, Lipsztein J, Cruz-Suarez R. AIDE: internal dosimetry software. Radiat Prot Dosim. 2008; 130(3):358–367.
9. Davesne E, Paquet F, Ansoborlo E, Blanchardon E. Absorption of plutonium compounds in the respiratory tract. J Radiol Prot. 2010; 30(1):5–21. [PubMed: 20220216]
10. ICRP. International Commission on Radiological Protection Supporting Guidance 3: Guide for the Practical Application of the ICRP Human Respiratory Tract Model in Annals of the ICRP 32 (1–2). 2000
11. Cash, LJ. Doctoral dissertation. 2014. Risk-informed decision-making for potential inhalation of plutonium-239 and -238 dioxide nanoparticles: Use of default assumptions and material-specific data for assessing dose.

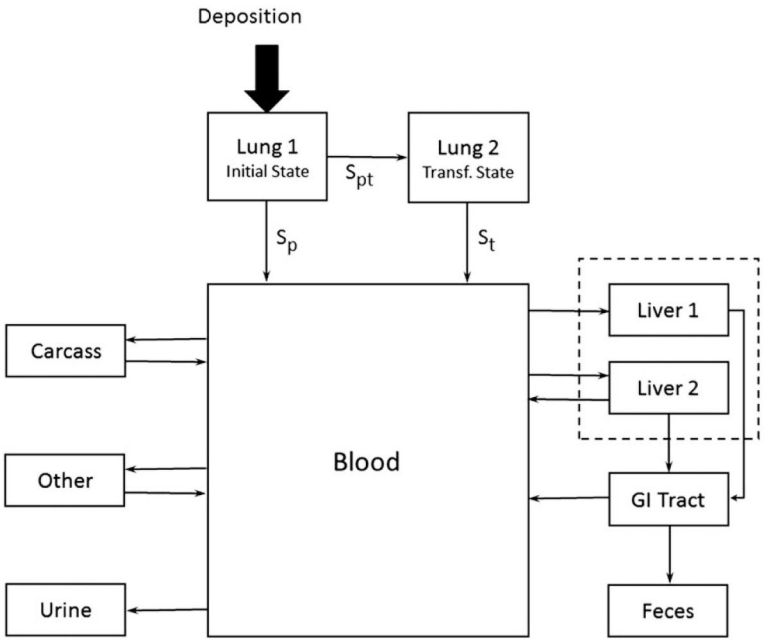

Figure 1.
A lung and a systemic Pu biokinetic model for the rat.

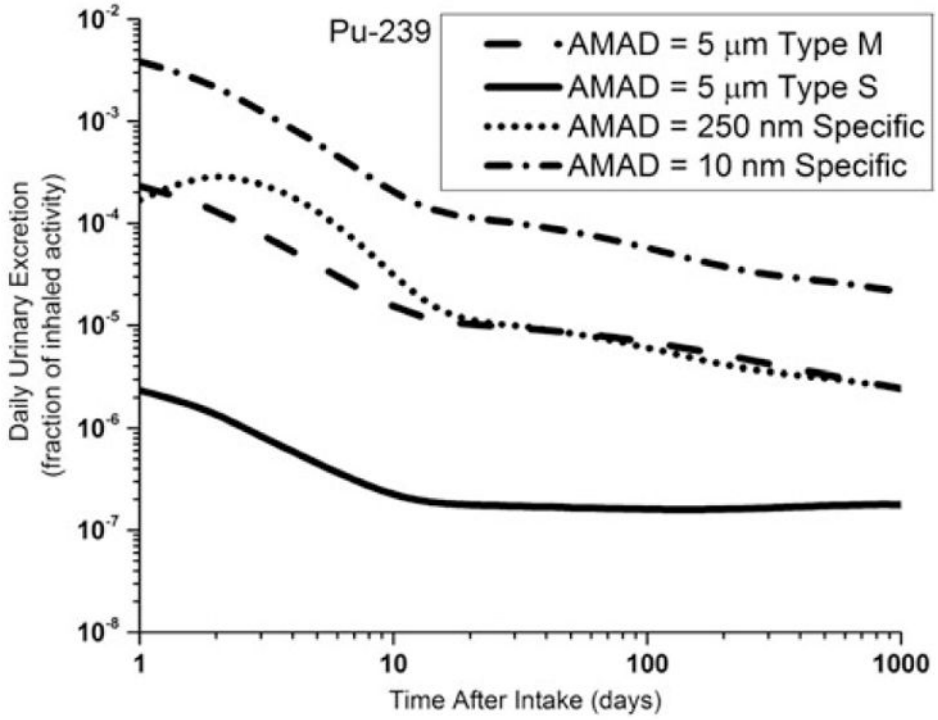

Figure 2.

Comparison of calculated daily urine excretion as a fraction of inhaled activity for ^{239}Pu using the default 5 μm AMAD with Type M and S blood absorption parameters and using the AMAD 250 nm and AMAD 10 nm with corresponding material-specific blood absorption parameters.

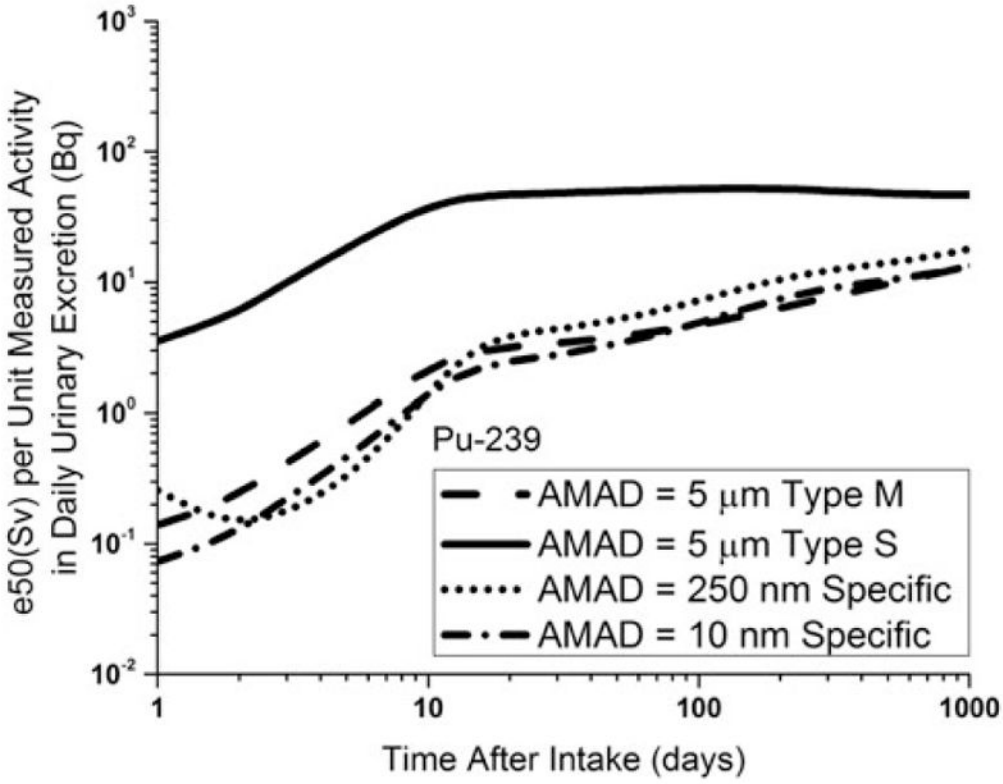

Figure 3.

Comparison of the calculated dose coefficient (e50 in Sv) per unit measured activity in daily urinary excretion (Bq) for inhaled ^{239}Pu using the default 5 μm AMAD Type M and S and blood absorption parameters and using the AMAD 250 nm and AMAD 10 nm material-specific blood absorption parameters.

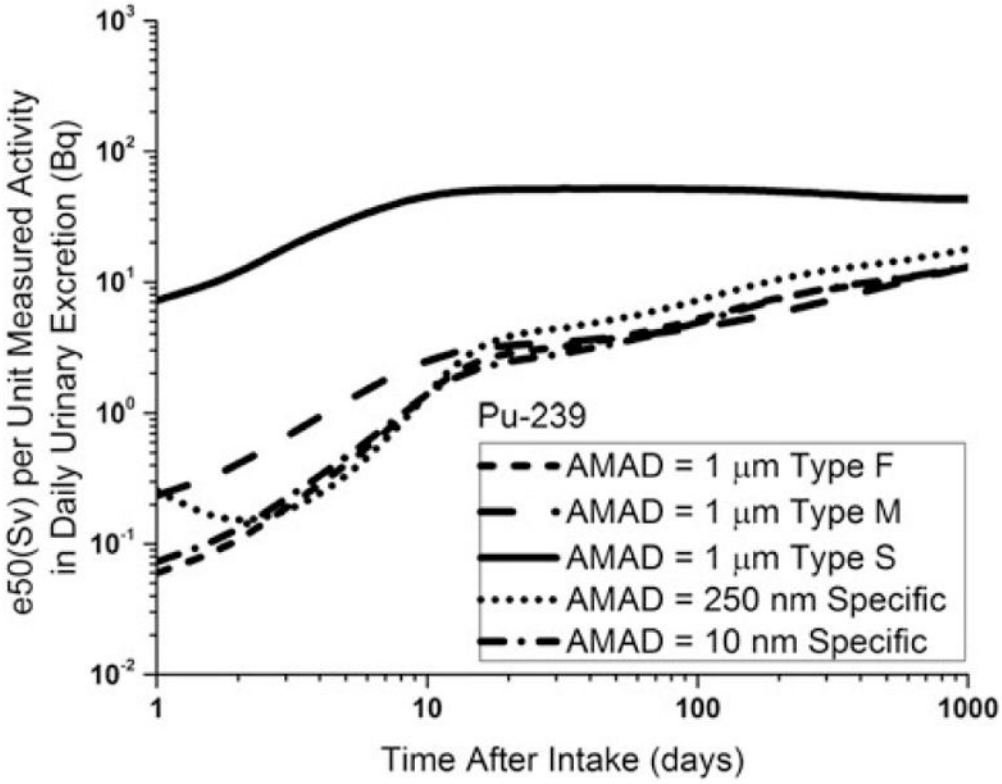

Figure 4.

Calculated influence of assumed absorption type on the dose coefficient (e50 in Sv) per unit measured activity in daily urinary excretion (Bq) for inhaled ^{239}Pu of 1 μm AMAD Type F, M, and S, and for inhaled ^{239}Pu of 250 nm AMAD and 10 nm AMAD with the corresponding material-specific parameters.

Table 1

Transfer rates for the rat Pu systemic model used in the fitting of ^{239}Pu blood absorption parameters using RATDOSE software.

Source	Target	Transfer rate (d^{-1}) for AMAD 250 nm	Transfer rate (d^{-1}) for AMAD 10 nm
Blood	Urine	6.22×10^{-2}	4.80×10^{-1}
Blood	Liver1	9.34	4.46×10^{-1}
Blood	Liver2	1.34×10^{-3}	3.09×10^{-1}
Liver1	GIT	2.58×10^{-2}	3.90×10^{-2}
Liver2	GIT	10.0	10.0
GIT	Blood	2.86×10^{-1}	6.29×10^{-5}
GIT	Faeces	4.00×10^{-1}	1.15×10^{-1}
Liver2	Blood	1.79×10^{-6}	9.57×10^{-1}
Blood	Carcase	8.16×10^{-1}	3.38
Carcase	Blood	2.85×10^{-2}	2.67×10^{-5}
Blood	Other	10.6	3.66×10^{-4}
Other	Blood	20.6	4.52×10^{16}

Table 2

Transfer rates for the rat Pu systemic model used in the fitting of ^{238}Pu blood absorption parameters using RATDOSE software.

Source	Target	Transfer rate (d^{-1}) for AMAD 10 nm	Transfer rate (d^{-1}) for AMAD 10 nm (aged)
Blood	Urine	4.40×10^{-1}	3.32×10^{-1}
Blood	Liver1	4.78×10^{-1}	5.80×10^{-1}
Blood	Liver2	1.48	2.92×10^{-1}
Liver1	GIT	3.95×10^{-2}	3.63×10^{-2}
Liver2	GIT	10.0	10.0
GIT	Blood	8.54×10^{-5}	7.66×10^{-5}
GIT	Faeces	2.01×10^{-1}	2.15×10^{-1}
Liver2	Blood	47.3	3.35
Blood	Carcase	1.87	2.07
Carcase	Blood	6.88×10^{-12}	6.88×10^{-12}
Blood	Other	4.39×10^{-4}	4.39×10^{-4}
Other	Blood	5.43×10^{16}	5.42×10^{16}

Table 3

Specific blood absorption parameters calculated for inhaled plutonium materials.

Material	AMAD (nm)	Specific blood absorption parameters (d^{-1})	χ^2/n Data	Specific blood absorption parameters (d^{-1}) Davesne *et al.*
$^{239}PuO_2$	250	$s_p = 0.25$ $s_{pt} = 0.51$ $s_t = 1.2 \times 10^{-5}$	29.71	Not available
	10	$s_p = 75.7$ $s_{pt} = 33.8$ $s_t = 1.7 \times 10^{-2}$	2.99	$s_p = 64$ $s_{pt} = 36$ $s_t = 1.6 \times 10^{-2}$
$^{238}PuO_2$	10	$s_p = 12.8$ $s_{pt} = 7.0$ $s_t = 2.1 \times 10^{-2}$	6.27	$s_p = 1.5$ $s_{pt} = 1.0$ $s_t = 3.3 \times 10^{-3}$
	10 (aged)	$s_p = 22.7$ $s_{pt} = 16.0$ $s_t = 2.3 \times 10^{-2}$	8.42	$s_p = 2.0$ $s_{pt} = 1.1$ $s_t = 9.2 \times 10^{-3}$

Table 4

Committed effective dose coefficients for inhaled PuO_2 particles for standard workers.

Material	AMAD (nm)	Absorption type	e(50) (Sv Bq^{-1})	$h_{BoneSurf}$(50) (Sv Bq^{-1})	h_{ET}(50) (Sv Bq^{-1})
$^{239}PuO_2$	5000	M	3.23×10^{-5}	1.01×10^{-3}	1.48×10^{-5}
	5000	S	8.28×10^{-6}	9.10×10^{-5}	7.93×10^{-5}
	250	Specific	4.35×10^{-5}	1.06×10^{-3}	8.91×10^{-6}
	10	Specific	2.80×10^{-4}	9.17×10^{-3}	1.65×10^{-5}
$^{238}PuO_2$	5000	M	2.98×10^{-5}	9.07×10^{-4}	1.51×10^{-5}
	5000	S	1.05×10^{-5}	7.97×10^{-5}	8.11×10^{-5}
	10	Specific	2.29×10^{-4}	7.36×10^{-3}	1.33×10^{-5}
	10	Specific (aged)	2.30×10^{-4}	7.35×10^{-3}	1.33×10^{-5}

Calculated using AIDE software.