Internal Alpha Particle Dosimetry of Plutonian Miners Inhaling Plutonium: A Rick and Morty Occupational Exposure Case Study

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1. INTRODUCTION

In the cartoon Rick and Morty, the premise is built on a scientist who can defy all logic with his inventions, including traveling across alternate dimensions. One episode follows the scientist's grandson's visit to the dwarf planet Pluto, which is inhabited by aliens called Plutonians. The major plot in this episode is that Pluto is no longer a planet due to corporate greed, which mines the planet for all of its plutonium (shrinking it further into a dwarf planet).

Figure 1. The Plutonian scientist "Mr. Scoopy Noopers" is holding crushed Plutonium and blowing it into the air [1].

This episode inspired this dose construction project because plutonium is a radioactive element that naturally emits alpha particles via alpha decay. Although the radioactivity of plutonium was not discussed in the episode, as it appeared only as a comedic effect revolving around Pluto being made of element plutonium; the concept of miners working with a pure radioactive element raises the question of how dangerous that would be in theory. Since alpha radiation poses a primarily internal risk, this technical note addresses the internal dosimetry of plutonium's alpha decay for these workers on Pluto. As seen in Figure 1, plutonium can be easily crushed and become airborne, making internal respiration of the particles a probable occupational hazard.

2. BACKGROUND

In order to address this occupational exposure scenario, two concepts are important to cover and expand on. The first is the mechanics of alpha decay and properties related to the occupational internal exposure by Pu-239. The second is modeling used to analyze the internal radiation, including dosimetric and biokinetic models. As a disclaimer, while discussing this topic, estimations of the scenario will be made conservatively, since the analysis would be used to make precautions to protect these theoretical miners.

2.1. Alpha Decay and Internal Exposure

Alpha decay occurs mainly in heavy, unstable nuclei that emit alpha particles in order to become more stable. These particles consist of a helium nucleus, two protons, and two neutrons. These particles contain high amounts of energy that are deposited in tissue; however, the external threat of the alpha particle is minimal. This is due to the fact that alpha particles have high linear energy transfer (LET), meaning they deposit a large amount of energy over a very short range, easily blocked by paper or skin [2]. In the case of people, the outer layer of dead skin on their bodies can serve as a shield against these particles. Because of this, alpha particles acting by themselves only pose a threat internally. The main internal pathways alpha particles can enter the body are through respiration, ingestion, wounds, and injection. In the scenario of miners mining plutonium, we can assume they have rigorous hygiene standards preventing ingestion and making inhalation the only main concern.

The plutonium isotope being used for this case study is plutonium-239. This is because Pu-239 has a long half-life of 2.41e+4 yr, ensuring decay during the mining is minimal [3]. Therefore, decay products can be ignored for this analysis. The specific activity of 0.063 Ci/g also provides a significant internal radiation source while being primarily alpha emission (negligible beta and gamma decay)[4].

Making assumptions based on real occupational mining conditions, the mass of inhaled Pu-239 can be calculated using the average amount of particles in the air for underground workers at 0.26mg/m^3, the average male volume inhalation during light exercise of 1.5 m^3/hr, and the specific activity of the isotope [5, 6]. Below is a table of the mass, number of particles, and activity of Pu-239 that would be inhaled over an 8-hour mining shift.

Table 1. The average inhalation values of a Pu-239 miner during an 8-hour shift.

Mass Inhaled	$3.12\ mg$
Number of Particles	$7.86e18\ atoms$
Activity of Particles	$7.29e6\ Bq$

Additionally, when considering inhalation of radioactive material in occupational scenarios, two important factors outlined by the ICRP are activity median aerodynamic diameter (AMAD) and solubility type. AMAD describes the size of particles, and the ICRP 66 publication suggests a 5µm assumption during occupational exposure if AMAS is otherwise unknown [6]. Solubility type describes the solubility of the inhaled particles and can be used to model how particles travel through the body. They are categorized as slow (S), medium (M), or fast (F). In the case of pure plutonium, it would not be very soluble and therefore be type S.

2.1.1. Dosimetric and Biokinetic Models

In order to measure and analyse internal exposure, two models are primarily used: the dosimetric (physical) model as well as the biokinetics model. The dosimetric model primarily relies on known decay data, while the biokinetics model describes how the inhaled Pu-239 actually moves through different organs over time and how much activity each compartment retains. Each model can then be used to calculate organ dose, and from there, equivalent dose and the effective dose. Below is a diagram showing the flow of the models, with the left as the biokinetic model and the right as the dosimetric model.

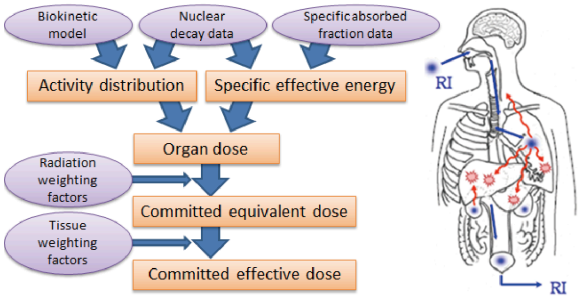

Figure 2. Biokinetic and Dosimetric Model Processes (reproduced from [7]).

Activity distribution in biokinetic models consists of a system of differential equations accounting for activity entering from radioactive particles and leaving through decay or natural body processes, such as the digestion of materials. Dosimetric models are defined by their use of Specific Effective Energy (SEE), which is the mean energy deposited per nuclear transformation. SEE is calculated by multiplying the radiation energy (5.2357 MeV for Pu-239 [3]), the number of decays (e.g, Table 1 for an 8-hour shift), and the specific absorbed fraction (SAF) from ICRP 133 [8]. SAF is the fraction of energy emitted by a source organ that is absorbed by a target organ per unit mass. In some cases, especially alpha emitters, the SAF values primarily have the target organs the same as the source.

Once the activity distribution in the body has been determined using either model, the absorbed dose to each organ can be calculated. Absorbed dose represents the energy deposited

per unit mass of tissue and is computed by dividing the energy deposited in an organ by the mass of that organ.

Using the absorbed dose, the equivalent dose, H_T, is then obtained by multiplying by the radiation weighting factor, which accounts for the type of radiation (for alpha particles, w_R=20.)

Finally, the effective dose, E, can be calculated, and its role is to estimate the overall radiation risk to a reference person. It is calculated by summing the equivalent doses of all major tissue categories, each multiplied by its tissue weighting factor w_T, which reflects radiosensitivity. The effective dose is averaged over both genders, as it represents a standard reference person rather than a specific individual.

In the case of plutonium inhalation, literature supports the conclusion that lung, liver, and skeleton are the primarily affected categories of tissue that are of interest [9, 10, 11, 12]. This conclusion is supported by both human and animal exposure data. For example, postmortem analysis of an acutely exposed plutonium worker, it was reported that most of the inhaled activity remained in the lungs, skeleton, and liver [9]. Data from urine bioassay studies in exposed workers also confirms that the skeleton and liver receive the highest systemic doses following inhalation of Pu-239 [10].

In the case of pure Pu-239 exposure, there are no reports since it would require such stringent circumstances. However, in the case of the Manhattan project workers exposed to plutonium compounds, ICRP biokinetic models for exposure appeared to be accurate in the case of the urine bioassay compared to post-mortem analysis. This supports the effectiveness of these models [10]. However, when it comes to creating biokinetic models, it is important to keep in mind, based on the literature, that certain amounts of radionuclides are retained in certain organs and do not leave via normal body clearances. For example, in one study, it was found that about 8% of the plutonium initially deposited in the respiratory tract was not biologically cleared and was instead bound, and only decreased to 2% after 38 years [9]. Additionally, in the case of the skeletal system, .7% of the plutonium in rats appeared to be bound and not leave due to normal clearances [12].

3. METHODOLOGY

To evaluate this exposure scenario, the effective dose will be calculated since it reflects the overall health risk associated with the exposure. For this study, a simplified four-compartment biokinetic model will be used. The compartments include the lungs, liver, and skeleton, which the literature identifies as the primary contributors to internal dose following inhalation of plutonium [9, 10, 11, 12]. The fourth compartment is the blood, since it interacts with all three of these major compartments and plays a key role in systemic distribution of the radionuclide. The effective dose will not need sex averaging since these four compartments will have the same tissue weighting factors for males and females.

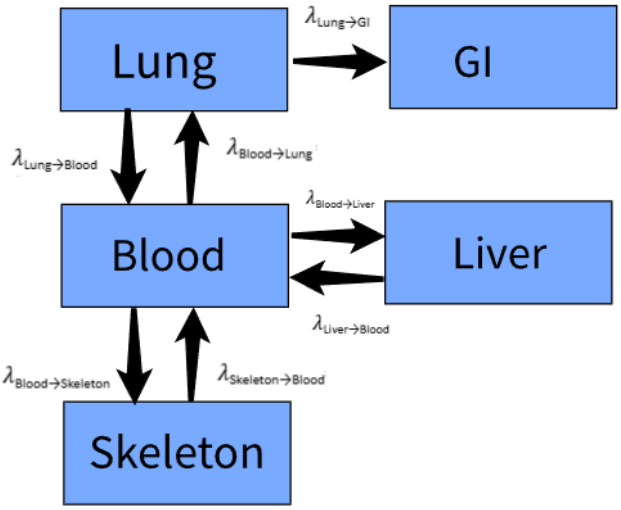

Figure 3. Four Compartment Biokinetic Model.

To find the effective dose, two methods will be used:

1) A dosimetric model that is hand calculated using tabulated SAF values.
2) A biokinetic model that is programmed in Python using tabulated transfer coefficients.

Hand calculation will involve using the process outlined in the background section and Figure 2 for an 8-hour shift. The biokinetic program will then be created using simple differential equations and clearance constants found via ICRP publications. Additionally, it will account for 3 scenarios of exposure: a one-day occupational exposure, a one-year occupational exposure, and a thirty-year occupational exposure. One represents a scenario where perhaps air circulation systems were not working properly, and the latter represents no guidelines throughout a career in plutonium mining.

To account for bound radionuclides outlined by literature, 2% of activity in the lung will be left from the clearance, as well as 0.7% of the activity in the skeletal system.

Table 2 displays the important constants that are to be used for finding activity distribution for the biokinetic model and the SAF constants for the SEE of the dosimetric model.

Table 2. Compartment SAF values from ICRP 133 with a placeholder value for blood [8].

Compartment	***SAF (1/kg)***
Lung	Bronch-sec<-Lung-Tis = 2.003E+00 Bchiol-sec<-Lung-Tis = 2.003E+00 AI<-Lung-Tis = 8.648E-01
Liver	Liver<-Blood = 4.235E-02 Liver<-Liver = 4.238E-01
Skeleton	Endost-BS <-C-bone-S = 1.286E-01 R-marrow <-T-bone-S = 1.163E-01 Endost-BS <-T-bone-S = 8.621E-01 R-marrow <-T-bone-V = 1.040E-02 Endost-BS <-T-bone-V = 7.257E-02
Blood	Blood<-Blood = 1.000E-03*

Table 3. Compartment transfer coefficients using ICRP 130 and ICRP 67 [13, 14].

Compartment	$\lambda_{T\rightarrow}$ ***(d^{-1})***
Lung	$\lambda_{\text{Lung}\rightarrow\text{Blood}} = 0.1001$ $\lambda_{\text{Lung}\rightarrow\text{Bronch}} = 0.2$
Liver	$\lambda_{\text{Liver}\rightarrow\text{Blood}} = 0.03$
Skeleton	$\lambda_{\text{Skeleton}\rightarrow\text{Blood}} = 0.0076$
Blood	$\lambda_{\text{Blood}\rightarrow\text{Skeleton}} = 0.3235$ $\lambda_{\text{Blood}\rightarrow\text{Liver}} = 0.1941$ $\lambda\text{B}_{\text{lood}\rightarrow\text{Lung}} = 0$ (negligible)

It is noteworthy that some coefficients were not explicitly stated in publications, and estimates/calculations were used. For the SAF values of blood, there was no data, presumably because blood is not an organ. Therefore, a value of 0.001 was used as a placeholder for calculations. Second, the transfer coefficients were not outlined for lung to blood, so the equation below was used, using coefficients from Table A.4 in ICRP 130 for type S particle respiration [13].

$$\lambda_{Lung\rightarrow Blood} = f_r \times S_r + (1 - f_r) * S_s \qquad (Eq.\ 1)$$

Additionally, the transfer of radionuclides from the lungs to the GI tract involves two regions: the distal bronchioles (bb) and the bronchi (BB). Because of their small size, the particles are most likely to deposit in the distal bronchioles,

which have a transfer coefficient of 0.2, while the bronchi have a coefficient of 10. Since material from the distal bronchioles first moves to the bronchi before being excreted, the overall effective transfer was estimated to be 0.2, because the bronchi clearance is so fast.

The differential equations to model the change in activity of each compartment are as follows, where I(t) is the radiation being inhaled during shifts (b=blood, l=lung, li=liver, br=bronchi, sk=skeleton, and R=decay constant).

$$\frac{dq_{lung}}{dt} = I(t) - \lambda_R q_l - (\lambda_{l\to b} + \lambda_{l\to br}) q_l \quad (Eq.\ 2)$$

$$\frac{dq_{skeleton}}{dt} = \lambda_{b\to sk} q_b - \lambda_R q_{sk} - \lambda_{sk\to b} \quad (Eq.\ 3)$$

$$\frac{dq_{liver}}{dt} = \lambda_{b\to li} q_b - \lambda_R q_{li} - \lambda_{li\to b} q_{li} \quad (Eq.\ 4)$$

$$\frac{dq_{blood}}{dt} = \lambda_{l\to b} q_l + \lambda_{sk\to b} q_{sk} + \lambda_{li\to b} q_{li} - \lambda_R q_b - (\lambda_{b\to sk} + \lambda_{b\to li}) q_b \quad (Eq.\ 5)$$

Each compartment is solved for in the code by calculating activity in increments of dt (one hour) over a for-loop, accounting for time where the miner is not at work and, therefore, away from the exposure (I = 0) or at work. The solutions for these differential equations using the for-loop are as follows. The solution utilizes the law of radiative decay equation.

$$q_l(t + \Delta t) = q_l(t)\ e^{-(\lambda_R + \lambda_{l\to b} + \lambda_{l\to br})\Delta t} + \text{I(t)}\Delta t \quad (Eq.\ 6)$$

$$q_{sk}(t + \Delta t) = q_{sk}(t)\ e^{-(\lambda_R + \lambda_{sk\to b})\Delta t} + \lambda_{b\to sk} q_b(\text{t})\ \Delta t \quad (Eq.\ 7)$$

$$q_{li}(t + \Delta t) = q_{li}(t)\ e^{-(\lambda_R + \lambda_{li\to b})\Delta t} + \lambda_{b\to li} q_b(\text{t})\ \Delta t \quad (Eq.\ 8)$$

$$q_b(t + \Delta t) = q_b(t)\ e^{-(\lambda_R + \lambda_{b\to sk} + \lambda_{b\to li})\Delta t} + [\lambda_{l\to b} q_l(t) + \lambda_{sk\to b} q_{sk}(t) + \lambda_{li\to b} q_{li}(t)]\Delta t \quad (Eq.\ 9)$$

4. RESULTS AND DISCUSSION

The results are separated into hand calculations and biokinetic model program output. Both are compared in section 4.1.3.

4.1.1. Hand Calculation

Hand calculations involved using SAF factors tabulated in the methodology section, as well as the assumptions and resulting values tabulated in Table 1. During hand calculations, the SEE was calculated first using the equation below, where Y represents the activity per second, and E is the energy deposited per alpha particle.

$$SEE = Y \times E_{alpha} = 6.115\text{e-}6\ \text{J/s} \quad (Eq.\ 10)$$

After that, the absorbed dose was found by multiplying SEE by the total SAF for the compartment that is being analyzed and then multiplying by the time of exposure, in this case, eight hours.

$$D = SEE \times SAF_{total} \times \text{time} \quad (Eq.\ 11)$$

Finally, an equivalent dose was found by multiplying by the alpha radiation weighting factor 20, and from there using the ICRP 103 tissue weighting factors for all four compartments previously calculated.

$$E = \sum_i (D_i \times 20) * w_{T,i} \quad (Eq.\ 12)$$

Table 3. Compartment transfer coefficients using ICRP 130 and ICRP 67 [13, 14].

Compartment	Absorbed Dose (Gy)	Equivalent Dose (Sv)
Lung	0.8578	17.156
Liver	0.0821	1.642
Blood	0.0002	0.004
Skeleton	0.2096	4.192

Effective Dose (Sv) = 2.63

4.1.2. Biokinetic Program Output

To solve the differential equation, a for-loop time increment method was utilized in Python (Appendix B.) Additionally, the time outside of the work exposure per day was accounted for, and weekends off from work. Below are the results of this method.

Table 5. Biokinetic script outputs for activity, absorbed dose, equivalent dose, and effective dose for compartments of interest following a 8-hour shift.

Compart-ment	Activity (Bq)	Absorbed Dose (Gy)	Equivalent Dose (Sv)
Lung	5746440	0.676	13.525
Liver	43418	0.0005	0.0098
Blood	509197	1.23e-05	0.0002
Skeleton	72808	0.002	0.0419

Effective Dose (Sv) = 1.63

It can be seen that the amount of radiation a plutonian miner would receive is beyond the annual occupational limit exposure in the U.S. of 50mSv per day. Instead, the worker would be exposed to over thirty times the amount of the safe limit per year in the time frame of eight hours.

Table 6. Approximated effective dose for miners working 1 day, 1 year, and 30 years.

Time	1 day	1 year	30 years
Effective Dose (Sv)	1.63	10470	8.5e+85

Additionally, the effective dose by varying timelines of exposure demonstrates an absurd amount of exposure in the span of years. Assuming the miner works thirty years before retiring, he would have an effective dose of 8.5e+85 Sv, meaning there is no chance he would survive.

4.1.3. Comparison

Comparing the hand calculations to the biokinetics model, it can be seen that the biokinetic model demonstrated a smaller absorbed dose and therefore, effective dose, in this 4-compartment system. This is most likely due to the difference in the simplifying assumptions and coefficients used.

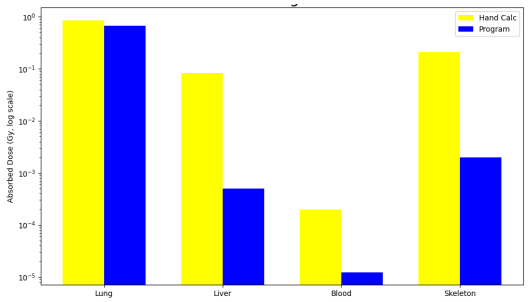

Figure 4. Difference in absorbed dose between hand calculations and biokinetic program output.

The literature related to this scenario varies greatly from these results due to no such acute scenario of Pu-239 occurring. However, it does match that the skeleton and liver have about the same absorbed dose [10].

5. CONCLUSIONS

Overall, this project analysed a theoretical occupational exposure scenario where a miner mines pure Pu-239, resulting in internal alpha exposure. Two techniques were used to find the amount of radiation the miner was exposed to. The first involved a hand calculation using specific absorbed fractions, and the second involved using a set of differential equations and solving them using a time increment method in a Python program. The body in this case study was reduced to a 4-compartment system of major areas of the body, including the lungs, skeleton, blood, and liver.

The results indicate that exposure to any theoretical miner mining Pu-239 would be extremely dangerous. Even one day of mining would result in over 30 times the amount of dose that is considered occupationally safe for a whole year, according to the Nuclear Regulatory Commission U.S. annual limit of 50mSv. One year of working as a miner resulted in over two hundred thousand times the safe limit. In the span of thirty years, the miner would experience astronomical amounts of radiation, which highlights the absurdity of this scenario.

The results indicate that in order for miners to safely work in these conditions, major safety precautions would need to be taken, including proper respiratory precautions. Whole body suits free from the air would most likely be reasonable standards considering the extreme internal threat of alpha decay. While there are no studies outlining similar situations, less extreme literature demonstrates that the lung, liver, and skeleton would experience large amounts of dose, as seen in the results.

It is important to note that the case study results do not accurately reflect this exposure scenario. After all, the model used a simple 4-compartment model of the body, ignoring many components to simplify the problem and focus on major compartments. Additionally, many assumptions were made that could change based on the scenario. For example, the amount of particles in the air was estimated using average mining data from Tanzania miners; however, this scenario could have very few particles.

For future work, it would be beneficial to not model the exposure scenario off of Pu-239, which has significantly less data than other isotopes, and instead model it off of a more well-known and documented element with similar properties, such as Uranium.

Overall, however, it is important to note that, regardless of conditions, this scenario highlights the extreme danger of alpha emitters when they are introduced internally into the body. While it may be harmless outside of the body, the moment it is introduced internally, it can wreak havoc throughout the biological system. In any scenario remotely similar to this one, proper precautions would need to be taken to ensure the safety of the workers and prevent exceeding the annual occupational exposure of 50mSv per year.

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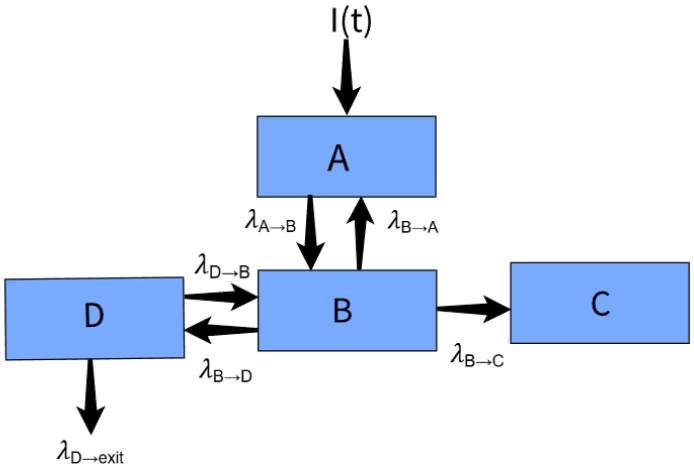
APPENDIX A – SYNTHESIS

1. **[Q]: What is the difference between the dosimetric (physical) vs. biokinetic approaches? Why do they both end with the effective dose calculation?**
   [A]: The dosimetric approach uses pre-determined values that contain the physical qualities of different organs. The biokinetics model, however, uses a series of time-dependent evaluations amongst a system of organs, evaluating the overall activity based on where the particles are in that system.

   Both approaches ultimately end at the effective dose because that is the quantity used to estimate overall health risk, which is one of the most important factors when evaluating an exposure scenario.
2. **[Q]: Write a set of differential equations for the 4-compartment biokinetics model below (where λ_R = radiation decay constant.)**



   [A]:

$$\frac{dq_A}{dt} = I(t) - \lambda_R q_A - \lambda_{A\to B} q_A$$

$$\frac{dq_B}{dt} = \lambda_{A\to B} q_A + \lambda_{D\to B} q_D - (\lambda_{B\to A} + \lambda_{B\to C} + \lambda_{B\to D} + \lambda_R) q_B$$

$$\frac{dq_C}{dt} = \lambda_{B\to C} q_B - \lambda_R q_C$$

$$\frac{dq_D}{dt} = \lambda_{B\to D} q_B - (\lambda_{D\to B} + \lambda_{D\to Exit} + \lambda_R) q_D$$

3. **[Q]: The paper references the conditions of an average underground miner in a workspace with 0.26mg of particles per m^3 of air. However, when Mr. Scroopy Noopers introduces the viewers to the Plutonium caves, the ceilings are high, and there is no visible dust. Assuming the amount of Pu-239 in the air is less than we thought, calculate the activity of those particles**

in Bq but with one tenth the amount of Pu-239 in the air (assuming the same specific activity of 0.0.063 Ci/g and volume breath rate of 1.5 m^3/hr.) What is the equivalent dose for the lung in this scenario following an eight-hour shift? What is the effective dose in this scenario, assuming all other organs other than the lung have an equivalent dose of zero? Is this occupationally safe for a one-day exposure?

[A]

Step 1 ⟶ Find the mass inhaled in an 8-hour shift:

- M = 0.26 (1/10) particles/m^3* 1.5 m^3/hr * 8hr = 0.312 mg

Step 2 ⟶ Find the corresponding activity of mass inhaled (in Bq:)

- Y = 0.312e-3 g * 0.063 Ci/g * 3.7e10 Bq/Ci = 7.29e5 Bq

Step 3 ⟶ Find specific effective energy (Eq. 10:)

- $SEE = Y \times E_{alpha}$ = 7.29e5 Bq * 5.24 MeV * 1.60218e-13 J/MeV = 6.12e-7 J

Step 4 ⟶ Find the absorbed dose of the lung (Eq. 11:)

- $D = SEE \times SAF_{total} \times$ time = 6.12e-7 J *(2.003 +2.003 + .8648)kg^-1 *(8*60*60)s = 0.8585 Gy

Step 5 ⟶ Find the equivalent dose by multiplying by the radiation weighting factor of 20 for alpha radiation:

- D_eq = 0.8585 * 20 = 17.17 Gy

Step 6 ⟶ Find the equivalent dose (Eq. 12:)

- $E = \sum_i D_i * w_{T,i}$ = 17.17 Gy * 0.12 = 2.0604 Sv

This is not occupationally safe for a one-day exposure since it is 41.21 times (2.0604Sv/50mSv) the safe annual occupational limit in the U.S.

APPENDIX B – Code

```
##############################################ACTIVITY DISTRIBUTION COMPUTATION
import math
t=24 #amount of time since first exposure in hours

A_perday = 7.29 * 10**6 #activity of Pu239 inhaled (Bq) per mining shift
shift = 8 #shift length in hours
offshift = 16 #time not at work in hours
weekhours = 168 #hours in week
weekend = 48 #hours in weekend
lambda_pu = 0.693 / (24110 * 365) #radioactive decay constant of Pu-239  in d^-1

#Decay constants:
lambda_LtB = 0.1000989 #clearance from lung to blood in d^-1
lambda_LtGI = 0.2   # clearance from distal bronchioles -> main bornchi (-> GI) d^-1
lambda_lung_total = lambda_pu + lambda_LtB + lambda_LtGI

lambda_LitB = 0.03 #clearance from liver to blood in d^-1
lambda_liver_total = lambda_LitB + lambda_pu

lambda_StB = 0.0076 #clearance from skeleton to blood in d^-1
lambda_skeleton_total = lambda_StB + lambda_pu

lambda_BtS = 0.3235 #clearance from blood to skeleton in d^-1
lambda_BtoLi = 0.1941 #clearance from blood to liver in d^-1
lambda_blood_total = lambda_StB + lambda_BtoLi + lambda_pu

stuck_fraction = 0.02  #the 2 percent of lung Pu that doesn't get cleared evidenced by literature
A_lung_stuck = 0
A_lung_clearing = 0
A_liver = 0
stuck_skeleton_fraction = 0.007  #the .7 percent of skeletal Pu that doesn't get cleared evidenced by literature
A_skeleton_stuck = 0
```

```
A_skeleton_clearing = 0
A_blood = 0

#For-loop to calculate activity from differential equations:
dt = 1  #in hours
for hour in range(t):
    hour_of_the_week = hour % weekhours #take remainder to find what hour in the week it is at
    if hour_of_the_week >= (weekhours - weekend): #scenario of weekend (no work -> I(t) = 0)
        I_t = 0
    else:
        hour_of_the_day = hour_of_the_week% 24 #take remainder to find what hour it is at

        if hour_of_the_day < shift: #scenario where its either the hour in day of a shift or not
            I_t = A_perday / shift #average activity over the shift length
        else:
            I_t = 0

    A_lung_clearing = A_lung_clearing * math.exp(-lambda_lung_total * (dt / 24)) + I_t * (1 - stuck_fraction)
    A_lung_stuck = A_lung_stuck * math.exp(-lambda_pu * (dt / 24)) + I_t * stuck_fraction
    A_lung = A_lung_clearing + A_lung_stuck

    A_liver = A_liver * math.exp(-lambda_liver_total * (dt / 24)) + lambda_BtoLi * A_blood * (dt / 24)

    A_skeleton_clearing = A_skeleton_clearing * math.exp(-lambda_skeleton_total * (dt / 24)) + lambda_BtS * A_blood * (dt / 24) * (1 - stuck_skeleton_fraction)
    A_skeleton_stuck = A_skeleton_stuck * math.exp(-lambda_StB * (dt / 24)) + lambda_BtS * A_blood * (dt / 24) * stuck_skeleton_fraction
    A_skeleton = A_skeleton_clearing + A_skeleton_stuck

    A_blood = A_blood * math.exp(-lambda_blood_total * (dt / 24)) + lambda_LtB * A_lung * (dt / 24) + lambda_LitB * A_liver * (dt / 24) + lambda_StB * A_skeleton * (dt / 24)

print("Activity in lung, liver, skeleton, and blood in Bq:", A_lung, A_liver, A_skeleton, A_blood)
```

```
##############################################ABSORBED DOSE COMPUTATION
time_passed = 28800 # seconds
alpha_E = 8.3897 * 10**(-13) #J/one alpha decay

lung_SAF = 4.8706
liver_SAF = 0.46615
skeleton_SAF = 1.19
blood_SAF = 0.001

D_lung = (A_lung * time_passed) * lung_SAF * alpha_E
D_liver = (A_liver * time_passed) * liver_SAF * alpha_E
D_skeleton = (A_skeleton * time_passed) * skeleton_SAF * alpha_E
D_blood = (A_blood * time_passed) * blood_SAF * alpha_E

print("Absorbed dose in lung, liver, skeleton, and blood in Gy:", D_lung, D_liver, D_skeleton, D_blood)

##############################################EQUIVALENT DOSE COMPUTATION
eD_lung = D_lung * 20
eD_liver = D_liver *20
eD_skeleton = D_skeleton *20
eD_blood = D_blood*20
print("Equivlanet dose of lung, liver, skeleton, and blood in Sv:", eD_lung, eD_liver, eD_skeleton, eD_blood)

##############################################EFFECTIVE DOSE COMPUTATION
E = (0.12)*eD_lung + (0.04)*eD_liver + (0)*eD_blood + (0.12)*eD_skeleton
print("The approximated effective dose in Sv:", E, "in time", t, "hours")
```