General Instructions

Failure to comply with any of the following instructions may lead to disqualification.

The exam is worth a total of 20 points and will last for 3.5 hours.

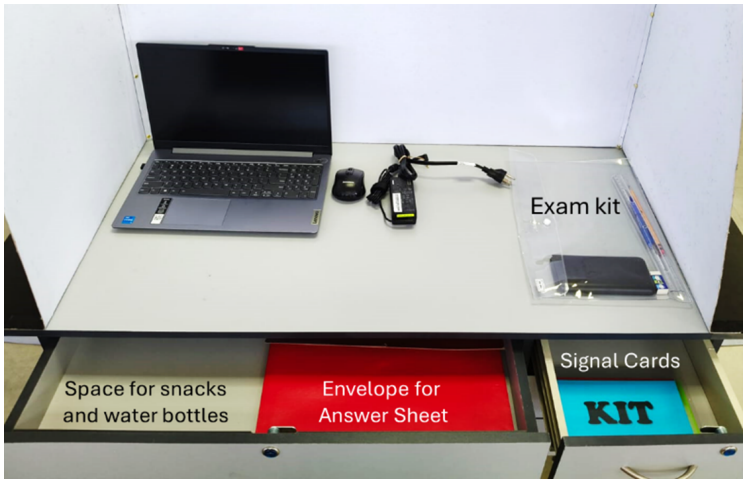
The start and end times of the examination will be announced, hourly announcements will be made, and a reminder will be provided when there are 15 minutes remaining.

Do not open the exam envelopes until instructed to do so.

The following items are provided on your table:

- Kit (1 ballpen, 1 pencil, 1 eraser, 1 ruler, 1 scientific calculator)
- 1 laptop with mouse and charger
- Snacks and water bottle
- Red envelope for answer sheets
- 5 signal cards:
  - Signal for additional water bottles, papers, or pens: "**KIT**"
  - Signal for toilet break: "**TOILET**"
  - Signal for clarification: "**?**"
  - Signal for medical aid: "**MEDIC**"
  - Signal for PC error or program error: "**ERROR**"

The location of items on your table are shown in the figure below:



During the exam:

- Use the ballpen provided. If you use the pencil to draft your notes, figures, tables, and graphs, make sure to trace the outlines of the final version with the ballpen.
- Use the software and computer applications installed in the laptops to answer the experiment questions. Raise the “Error” signal in case you need assistance related to the laptop.
- Use the Answer Sheets for your final answers. Fill in appropriate sections with your answers. Draw graphs as required. Cross out any unneeded answers.
- Blank working sheets are provided. Additional sheets are available upon request. Raise the "KIT" signal to notify the proctors.
- Keep your answers concise and legible. Use equations, operators, symbols, and sketches to convey your thoughts effectively.
- Uncertainty quantification is not required unless specified otherwise.
- Write numerical answers with 4 significant figures unless specified otherwise or when limited by the number of significant figures given in the problem. Use proper scientific notation as necessary, particularly for small (<0.01) and large numbers (>999).
- Do not leave your booth without permission. If you need a washroom break or other assistance, raise the appropriate signal(s) marked "Toilet", "Kit", "?", “Medic”, or “Error”.

At the end of the exam:

- Stop writing immediately when the end of the exam is announced.
- Place all answer sheets in the red envelope and seal. Sign across the envelope flap. Your proctor will assist you in securing the sheets in the envelope and will collect them afterwards.
- Place all other sheets (question paper, scratch paper, etc.) in their original envelope and leave on the table.
- Leave the exam kit on your table. You may take the remaining items with you, for example, the bottle of drinking water, and snacks.
- Your Proctor will let you know when you can leave.

Q1 ANALYSIS OF SEDIMENTATION PATTERNS USING LEAD-210 (10 pts)

In this experiment, alpha spectrometry data from sediment cores obtained from Sorsogon Bay, will be used to obtain the sedimentation rate in the region by calculating the concentration of Lead-210 (Pb-210) in the samples and validating the results using the Cesium-137 (Cs-137) dating technique. An Excel template is provided to aid you in performing the data analysis for the experiment. Each part of this question has a corresponding Excel sheet tab as shown below:

(1.1) Decay Constants	(1.2) Tracer Activity	(1.3) Relative Efficiency	(2.1) Total Pb-210	(2.2) Pb-210 Plot	(4.1) Cs-137 Plot	(4.2) t-tab values

Instructions for filling up the Excel file is enumerated throughout the problem in alphabetical bullets (e.g. a. In **"Tab (1.1) Decay Constants"**, calculate the decay constant). This is important as the Excel calculations will help in answering the subsequent exam questions.

Write numerical answers with only 4 decimal places (rounding up) in the answer sheet. However, use the exact value (without rounding off) in Excel when doing calculations. Refer to calculated tables and reference cells when necessary. All numerical answers should be written with appropriate SI units.

Experiment Guide

The Pb-210 dating technique is a well-established method in geochronology and environmental science. It can be used to determine the age of sedimentary deposits and the rate of sedimentation in lakes, oceans, and other bodies of water, to study sedimentation patterns, environmental changes, erosion processes, and transport of nutrition and pollution. Pb-210 (half-life = 22.3 years) is a member of the U-238 decay series which accumulates in the environment in two pathways (**Figure 1**).

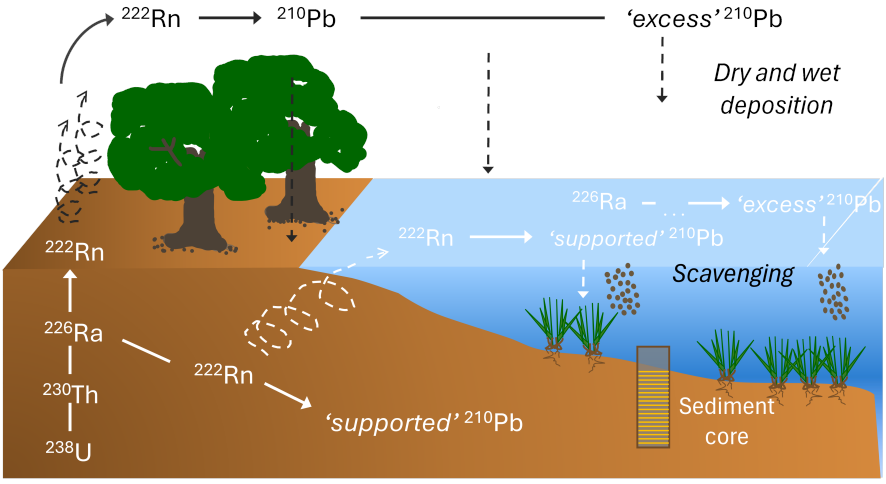


Figure 1. *The Pb-210 transport pathway*

The atmospheric origin for Pb-210 (known as *unsupported* or *'excess' Pb-210)* involves the decay of radioactive gas radon, Rn-222, which is produced in the earth and escapes to the atmosphere. Rn-222 has a half-life of 3.8 days and undergoes decay through four daughter products with short half-lives making its decay to solid Pb-210 geologically instantaneous. The Pb-210 settles out of the atmosphere or scavenged by rainwater and is then bound by organic matter and deposited in an environment such as oceans, lakes or soil. Once isolated in a sediment, Pb-210 is assumed to be immobile.

Meanwhile, the terrestrial origin of Pb-210 involves the in-situ decay of particulate Ra-226 and its daughter Rn-222 rising from sediments and rocks at depth (termed as *'supported' Pb-210).* The *'Supported' Pb-210* is in secular equilibrium with its parent radionuclide, meaning it is continuously produced by the decay of Ra-226 at a rate that balances its own decay. The Pb-210 that can be measured in sediment samples is called the total Pb-210 (*Total Pb-210 = 'supported' Pb-210 + 'excess' Pb-210*). It is essential that the total Pb-210 within a sediment sample be separated into these two components. Apart from the surface, which is a layer prone to mixing or bioturbation, i.e. restructuring of sedimentary deposits by animals or plants, it is assumed that the 'excess' Pb-210, once incorporated in the sediment, decays exponentially with time as seen in **Figure 2**. Thus, the 'excess' Pb-210 is the only component relevant to *sedimentation rate*, or the rate at which soil/sediment accumulates over time (thickness/time).

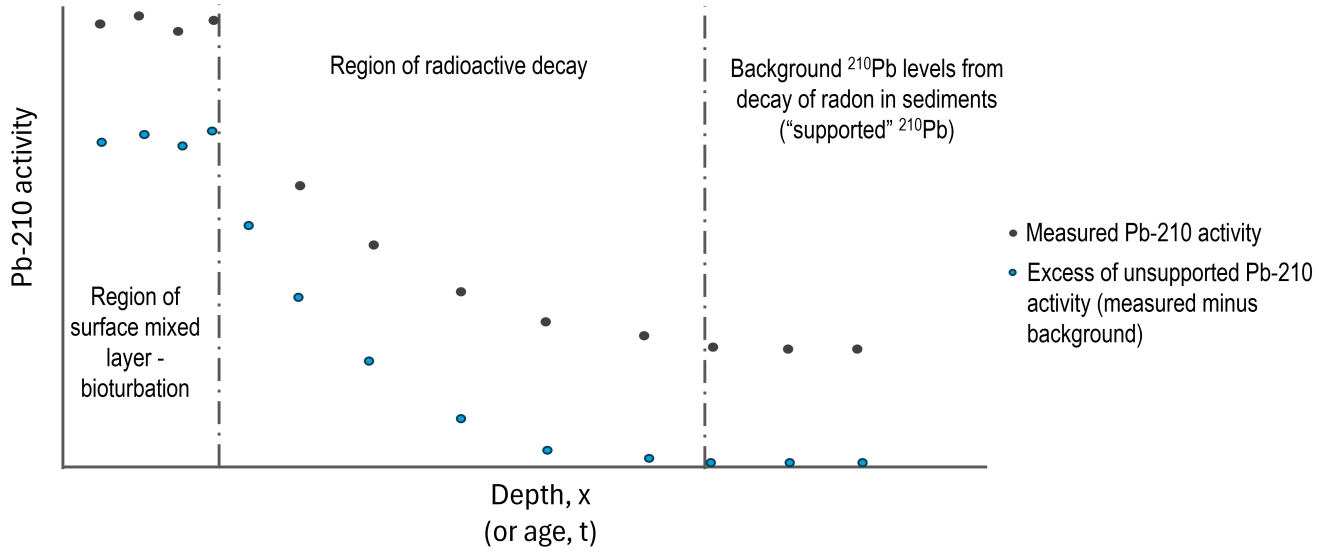


Figure 2. *Ideal profile of Pb-210 activity in sediment cores*

Experiment Scenario

In this study, sediment cores have been collected from Sorsogon Bay, to investigate and document the sedimentation patterns using Pb-210. The general steps are summarized in **Figure 3**. The Pb-210 can be determined by measurement of its daughter nuclide, Po-210 (half-life = 138.4 d), which decays 100% by alpha-particle emission. Pb-210 decays to Po-210 100% by beta-particle emission. The activity can be calculated by assuming secular equilibrium between Pb-210 and Po-210 (**Figure 4**), i.e. the decay rate of a parent radionuclide equals that of its short-lived daughter/s, maintaining constant activity levels.

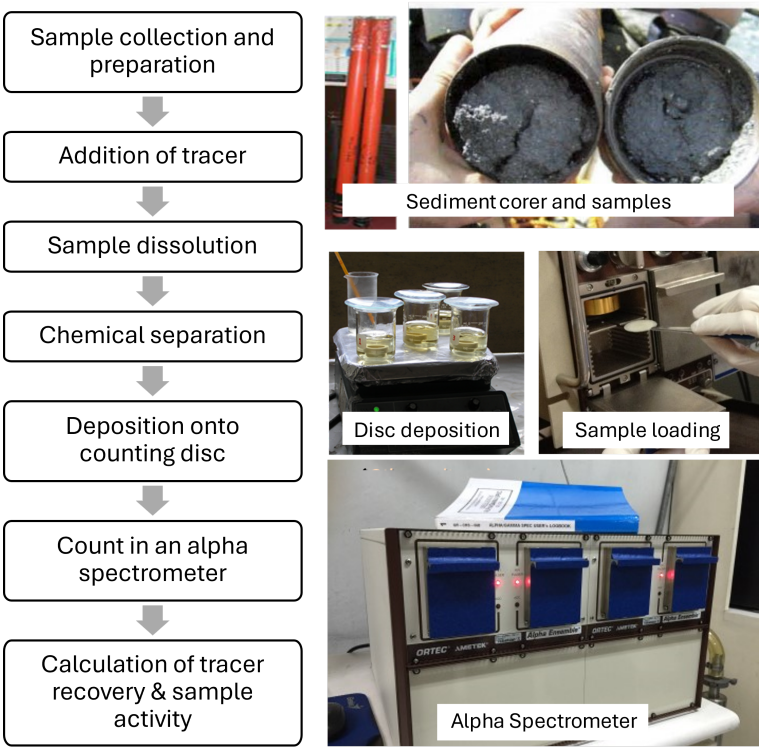


Figure 3. *Steps involved in radiochemical analysis by alpha spectrometry*

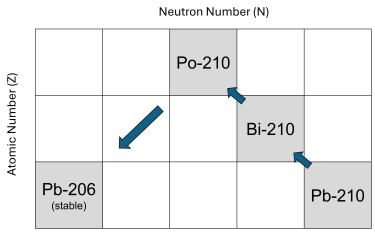


Figure 4. *Radioactive decay of Pb-210*

Sampling was conducted on April 29, 2009 (04/29/2009), where sediment core samples with approximately 150.0 cm length and 7.5 cm diameter were obtained from specific areas of Sorsogon Bay. The core was sectioned into 1 cm segments, which are then dried and homogenized. One (1) g of the sediment sample was digested by adding concentrated nitric acid and hydrofluoric acid. The extracted isotopes were plated onto silver disc from 0.5 $\mathrm{moles\ \ per\ \ liter}$ hydrochloric acid solution with ascorbic acid and hydroxylamine hydrochloride to reduce the effect of competing ions that are present in the sample. The isotope activities were then measured using an alpha spectrometry system with surface-barrier Si detector for a minimum of 24 h. The background count rates were determined. The data are collected and tabulated in the Excel file provided. The activity can be calculated by using the equation:

$$A_t = A_0 exp(-\lambda t) \quad (1)$$

where A_0 is the initial activity, A_t is the activity at time t (the time elapsed) and λ is the decay constant related to the half-life $\left(t_{1/2}\right)$, as given by:

$$\lambda = \ln(2)/t_{1/2} \quad (2)$$

Experiment Procedure

Part 1. Calculation of Tracer Activity and Relative Efficiency (2.1 pts)

Tracers are radionuclides that are added to the sample to quantify the relative efficiency of detection. They are assumed to behave in the same way as the radionuclide to be determined. The best tracers are relatively long-lived alpha-emitting isotopes that emit alpha radiation of different energy from the analyte nuclides.

During sample processing, a Po-208 tracer (half-life = 2.93 years) was added to calculate relative efficiency of the measurement. This is given by:

$$Relative\ Efficiency = A_{exp}/A_{calc} \quad (3)$$

where A_{exp} is the experimental activity calculated from the spectrometer counts, while A_{calc} is the calculated activity based on the known activity of the tracer. Starting with Core-1, 0.20 mL of Po-208 solution (activity concentration = 1.33 Bq/mL as of March 17, 2006 (03/17/2006)) was added to each segment to be extracted together with Po-210.

a. In **"Tab (1.1) Decay Constants"**, calculate the decay constant (λ) for Pb-210, Po-210 and Po-208 (Column D). These values will be used for the rest of activity/concentration calculations.

1.1	Write the **decay constant** (λ) calculated for Pb-210, Po-210, and Po-208.	**0.3 pt**

b. The data for Core-1 is shown in **"Tab (1.2) Tracer Activity"**. Calculate the tracer concentration in Bq/mL (Column C) and disintegration per minute (dpm)/mL (Column D) at the time of plating. Note: 1 year = 365.25 days

1.2	What is the average tracer concentration detected in the data set and its standard deviation?	**0.5 pt**

Shown in **Figure 5** are alpha spectra obtained from selected sections of the sediment core. The Po-208 is seen to peak at 5114.90 keV and Po-210 at 5304.38 keV. Each spectrum also indicates the total counts for both radionuclides after a specific counting time (t).

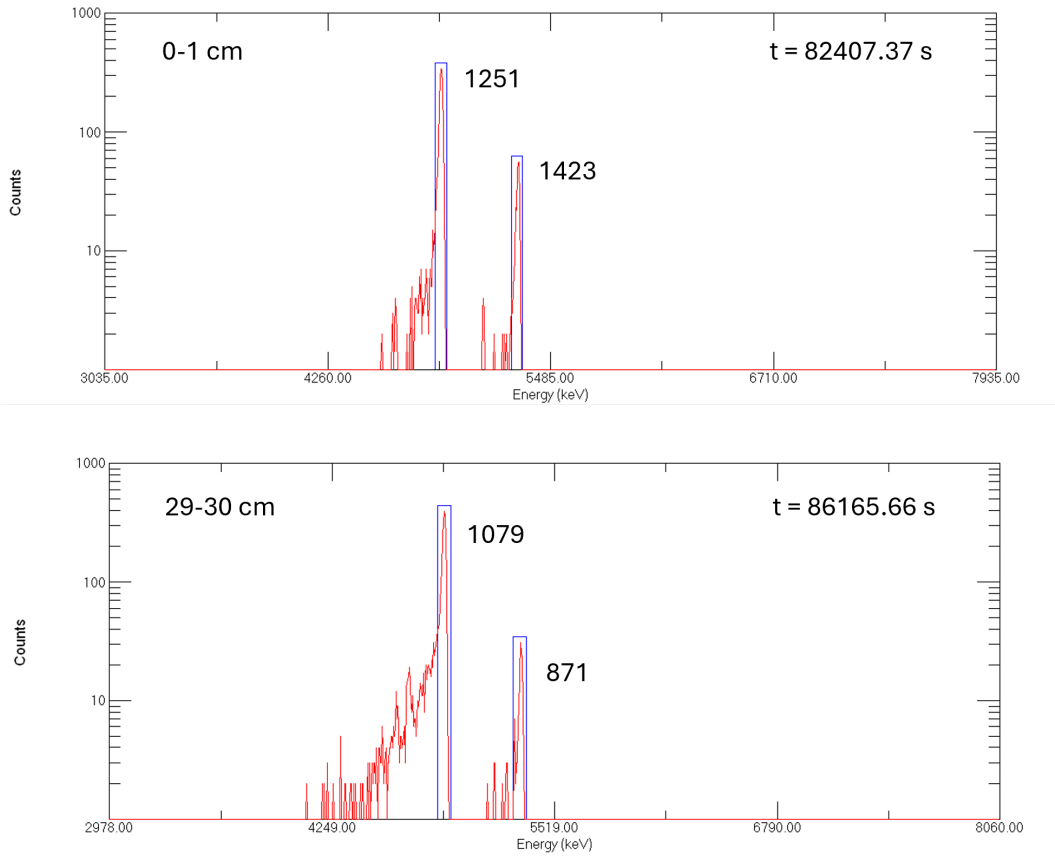


Figure 5. *Alpha spectra of two (2) segments from Core-1 showing the peak counts and total counting time (t)*

c. The total counts of Po-208, C_t, measured for each layer of Core-1 are given in **"Tab (1.3) Relative Efficiency".** Determine the actual/experimental activity (Column H) of the tracer added using the given data and correct for background activity. Note: 1 count = 1 disintegration.

d. Recalculate the tracer concentration (in dpm, Column I) to account for the time elapsed between plating and end of sample counting. This allows for their comparison with the experimental data.

e. Determine the relative efficiency of the tracer added for each layer (Column J).

1.3	**(a)** Write the experimental tracer activity concentration values for the cores with spectra provided in **Figure 5**.	**0.8 pt**
	(b) What is the average relative efficiency of the entire dataset and its standard deviation?	**0.5 pt**

Part 2. Lead-210 Determination (2.3 pts)

As mentioned previously, the total Pb-210 can be determined from the activity of Po-210, assuming it is in secular equilibrium with its daughter nuclide Po-210.

a. The total counts of Po-210, C_X measured for each layer of Core-1 is given in **"Tab (2.1) Total Pb-210"**.
b. Determine the total Po-210 activity (in dpm, Column I) and activity concentration (in Bq/kg, Column J) at the time of plating.
c. From values obtained above, determine the total Pb-210 (in dpm and Bq/kg, Columns K and L) for each segment at the time of sampling.
d. Calculate the associated relative error (Column M) of the analysis in terms of ±Bq/kg (Column N) using the equation below:

$$Relative\ Error = 2\ sqrt\left(\frac{1}{C_x} + \frac{1}{C_t}\right) \quad (4)$$

2.1	Complete the table with the calculated values for the core layers with spectra provided in **Figure 5**.	**1.2 pts**

The amount of *'supported' Pb-210* can be determined by the almost constant value of Pb-210, which is typically found in the lower region of the sediment core as shown in **Figure 1.**

e. Plot total Pb-210 versus depth along the sediment core in **"Tab (2.2) Pb-210 Plot"** to show the concentration of Pb-210 across the core. Use the average of the depth range for the depth data.
f. Use the relative error data to indicate error bars.
g. From the graph, calculate *'supported' Pb-210* using the average of the lower portion of the graph where the activity is no longer decreasing with depth. The range can be determined by using the set of consecutive values with the slope closest to 0, that is, no significant increase or decrease is observed.

2.2	Write the calculated 'supported' Pb-210 and corresponding standard deviation.	**1.1 pts**

Part 3. Lead-210 Geochronology (4.6 pts)

Pb-210 chronologies and sedimentation rate calculations can be estimated using different models, one of which is the *Constant Initial Concentration (CIC)* model. This model assumes a constant flux of the 'excess' Pb-210 such that at each stage in accumulation, the initial concentration of Pb-210 in the sediment is constant. The activity concentration, A, values of Pb-210 in undisturbed cores must decline monotonically with depth based on the radioactive decay as described below:

$$-\frac{dA}{dt} = \lambda A \tag{4}$$

Integrating this with the limits set by two points, the relationship between age and activity can be derived:

$$-\ln\left(\frac{A_2}{A_1}\right) = \lambda(t_2 - t_1) \tag{5}$$

For a constant sedimentation rate S, we can replace the depth axis x, with a time axis t, $S = x/t$. Substituting sedimentation rate in Equation 5 gives:

$$-\ln\left(\frac{A_2}{A_1}\right) = \frac{\lambda(x_2 - x_1)}{S} \tag{6}$$

Given that *sedimentation rate*, S is measured by depth $(x_2 - x_1)$ over a period of time $(t_2 - t_1)$, this can be further substituted to get an expression for sedimentation rate:

$$S = -\lambda\left[\left(x_2 - x_1\right) / \ln\left(\frac{A_2}{A_1}\right)\right] \quad (6)$$

Experimentally, the sedimentation rate can be determined by the least squares fit.

3.1	**(a)** On the grid provided, plot the logarithm of 'excess' Pb-210 values (in Bq/kg) versus sediment core depth.	**1.4 pts**
	(b) Use the least squares method to fit a straight line to the semi-logarithm plot for the top layer, from **0~20 cm.** Draw the corresponding best fit line in 3.1a. Complete the table with the calculated values from the least squares method and write down the linear equation, slope (m) and intercept (b) generated.	**0.7 pt**
	(c) Based on the slope obtained from 3.1b, what process likely explains the values obtained for this top layer?	**0.2 pt**
	(d) Use the least squares method to fit a straight line to the semi-logarithm plot for the bottom layer, from **20~60 cm**. Draw the corresponding best fit line in 3.1a. Complete the table with the calculated values from the least squares method and write down the linear equation, slope (m) and intercept (b) generated.	**0.7 pt**
	(e) Use the values obtained from 3.1d to determine the sedimentation rate of this layer.	**0.8 pt**

3.2	Determine the age (in years) of the sediment layer at **39.5 cm** at the time of sampling using the assumptions of the CIC model applied on the relevant region on the plot.	**0.8 pt**

Part 4. Cesium-137 Validation (1.0 pt)

Cesium-137 (half-life = 30.05 years) is produced by nuclear fission and has been released into the environment as a result of nuclear weapon testing during 1950–1970 (with a maximum atmospheric input in 1963) and the Chernobyl accident in 1986. It is considered an absolute dating technique that postdates these fallout events appearing as twin spikes on a profile graph. Dating using Cs-137 is usually performed to support and/or validate Pb-210 dating profiles.

a. In **"Tab 4.1 Cs-137 Plot"**, plot the measured Cs-137 activity for Core-1 versus the sediment core depth
b. Identify which depth can be dated as 1986 and 1963.

4.1	Calculate the sedimentation rate based on the two points with known dates.	**0.5 pt**

The same methods above were performed on five (5) more core samples within the same area, where we can assume comparable sedimentation conditions. The sedimentation rates are listed in **Table 1.**

Table 1. *Sedimentation rate obtained from Pb-210 and Cs-137 method*

Sample	Pb-210	Cs-137
Core-1	Value from 3.1e	Value from 4.1
Core-2	0.6213	0.5205
Core-3	0.5206	0.4309
Core-4	0.4911	0.4175
Core-5	0.5706	0.5304
Core-6	0.5516	0.5087

To check whether the Cs-137 method agrees with the data from Pb-210 method, a statistical test can be used to compare their means. The paired t-test can be used to determine whether the difference between the sample mean of two data sets performed on the same samples is significant or not. This is given by the equation:

$$t_{calc} = \left(\overline{x}_1 - \overline{x}_2\right) / \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad (8)$$

where $\overline{x}$ is the mean or average, s is the standard deviation and n is the number of samples of of the data sets 1 and 2. When $t_{calc} < t_{tab}$ at a given level of confidence, it means there is no significant difference between the two methods.

c. Calculate the mean $(\overline{x})$ and standard deviation (s) for the data obtained from each method (**Table 1**). Treat Pb-210 as data set 1 and Cs-137 as data set 2.
d. Determine the t_{calc} between the two methods.
e. Compare with the t_{tab} found in **"Tab 4.2 t-tab values"** at 95% confidence level, for the appropriate degrees of freedom (total number of samples minus one).

4.2	**(a)** Write down the t_{calc} obtained.	**0.3 pt**
	(b) Based on the calculated t_{calc}, does the Cs-137 data validate the sedimentation rate obtained from Pb-210?	**0.2 pt**

Q2 SHIELDING ACTIVATED MATERIAL (10 pts)

In this experiment, you will use computer applications that provide nuclear and radiation data on neutron activation analysis, and radiation shielding and protection scenarios. You will retrieve data from **JANIS**, a nuclear database software, to calculate the activity of a sample that is activated in a research reactor. You will also use the **EpiXS**, a photoatomic database software, to evaluate three different radiation shielding materials. Finally, you will optimize the thickness of a Lead (Pb) shielding while considering the effects of radiation buildup in a shielding material.

A. Experiment Background

A.1 Neutron Activation

Neutron irradiation plays a crucial role in advancing technology, medicine, science, and industry by enabling accurate isotopic analysis, material testing, high-grade silicone doping, and other innovative applications. To date, the strongest continuous source of neutrons for neutron irradiation applications are nuclear research reactors. During neutron irradiation, samples and instruments are placed into a research reactor core. Neutron activation may occur as the nuclides in the irradiated material absorb neutrons and become activated, producing radionuclide daughters.

The cross section (σ) of a nuclide measures the probability of its interaction with neutrons and has a unit of barns (b), with $1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$. The total cross section (σ_T) is the total probability of scattering and absorption interaction between a neutron and a target nuclide. Scattering interactions may be elastic or inelastic, while neutron absorption may result in radiative capture, neutron multiplication, charge multiplication, or nuclear fission among others. Neutron cross section is energy dependent and is unique for different parent nuclides. But a general trend is observed where interaction probability tends to be higher for low energy or thermal neutrons $(< 0.5\ \mathrm{eV})$, with resonance absorptions observed in the epithermal energy range $(0.5\ \mathrm{eV} - 10\ \mathrm{keV})$, while inelastic scattering tends to have higher probabilities for fast neutrons $(> 10\ \mathrm{keV})$. For this experiment, we will deal with radiative capture reaction where a target nucleus absorbs a neutron, becomes a radioactive nuclide, and decays at a specific half-life while emitting a gamma ray.

The saturated activity A_∞ of a neutron-activated material, defined as the maximum activity that is attained after very long irradiation times (i.e. ~5 times the half-life of the daughter nuclide), can be determined from the neutron flux (ϕ_i) in the irradiation location:

$$A_\infty = N(\phi_{th}\,\sigma_{th} + \phi_{epi}\sigma_{epi} + \phi_{fa}\sigma_{fa}) \tag{1}$$

where σ_i is the target nuclide cross-section, 'th', 'epi', and 'fa' refers to thermal, epithermal, and fast neutrons, respectively, while N is the total number of target atoms of the target nuclide calculated as follows:

$$N_i = \frac{m f_i N_A}{M} \quad (2)$$

In equation (2), m is the mass of the element, f_i is the natural abundance and M is the atomic mass of the target nuclide i, and $N_A = 6.02214 \times 10^{23}\,\mathrm{mol}^{-1}$ is the Avogadro's number. For samples retrieved before the A_∞ is reached, a decay correction is applied to equation (1) to obtain the prompt activity $A(t)$ of the radionuclide after the irradiation time t:

$$A(t) = A_\infty\left(1 - e^{-\lambda t}\right) \quad (3)$$

where λ is the decay constant of the product nuclide.

A.2 Radiation Shielding

The gamma radiation emitted from activated materials is potentially hazardous to radiation workers handling them. Radiation shielding is typically incorporated to reduce unnecessary exposure to radiation and protect people and the environment from its harmful effects. Radiation shielding materials are used to absorb or scatter radiation, thereby reducing the amount that can reach and harm living tissue. The effectiveness of the shielding depends on the type and energy of the radiation and the properties of the shielding material.

The Beer-Lambert law describes how a beam of photon radiation, like gamma or x-rays, with initial intensity I_0weakens as it travels through a shielding material. When a buildup factor B is incorporated, it accounts for the additional intensity from scattered radiation, providing a more comprehensive description of the radiation's behavior in real-world scenarios:

$$I = B I_0 e^{-\mu x} \quad (4)$$

In equation (4), I is the attenuated intensity of radiation after incorporating a shielding material with a linear attenuation coefficient μ and thickness x. The μ is the probability of photon interaction per unit thickness of a material and it varies with the type of material and photon energy. Equation (4) also accounts for scattered radiation that may potentially increase the I by including the buildup factor (B). This factor represents the additional intensity beyond what would be expected from direct attenuation alone, which is a case when $B = 1$. The buildup factor depends on the shielding material, radiation energy, and the mean free path (mfp) of the photon in the material, which is inversely related to the linear attenuation coefficient ($\mu = 1/mfp$).

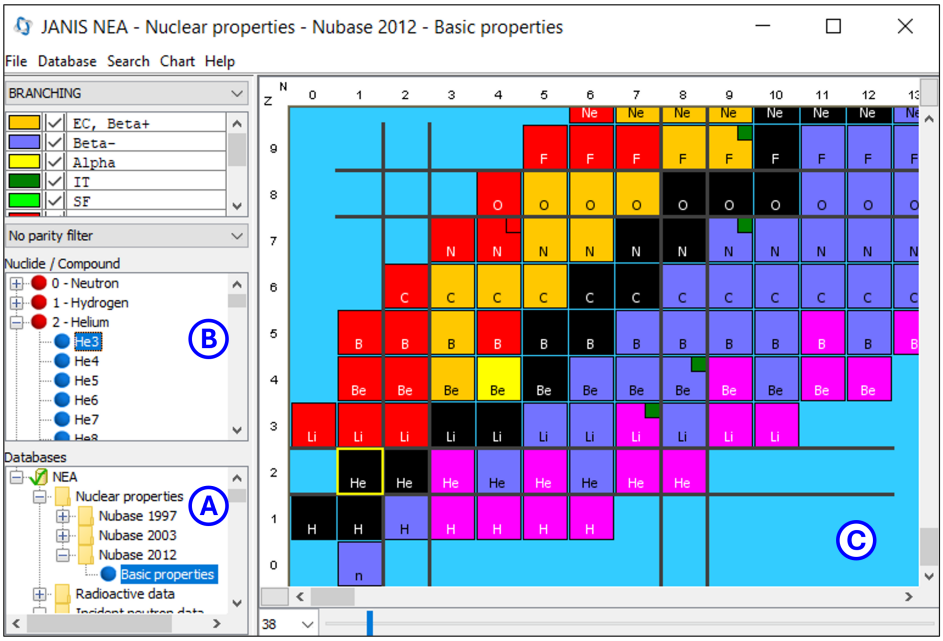
B. Software Description and Guide

B.1 JANIS (Java-based nuclear information software) is a software tool designed for managing and visualizing nuclear data. It provides an interface for accessing and analyzing various types of nuclear information, such as cross-sections, decay data, and fission product yields. JANIS is commonly used in nuclear physics and engineering for research, educational purposes, and data analysis, supporting various formats and sources of nuclear data.

Initiate the software by double-clicking or opening the **"Janis.jar – Shortcut"** in the desktop.

***Figure 1**. JANIS Icon*

Once the program is opened, the following window/interface should appear:



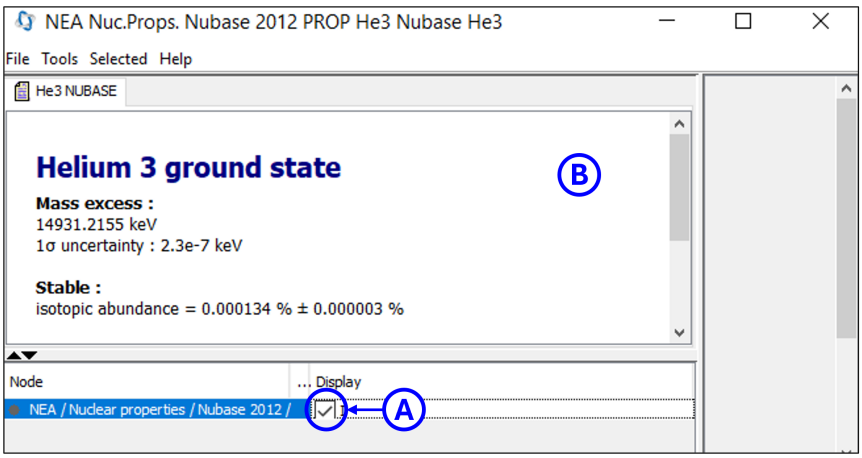
A **Database List.** Select the database you need here. Data include incident neutron cross-section data from different libraries (e.g. ENDF/B-VII.1, JEFF-3.0) and nuclear properties (e.g. Nubase 2012).

B **Nuclides/Compound selector.** The nuclide/ compound of interest may be selected here by "double-clicking"

C **Nuclide chart.** The nuclide/compound of interest may also be selected here by "double-clicking"

***Figure 2**. JANIS Interface*

When using the database for nuclear properties, after selecting a certain nuclide/compound, a new app window will be opened with an example shown in **Figure 3**.

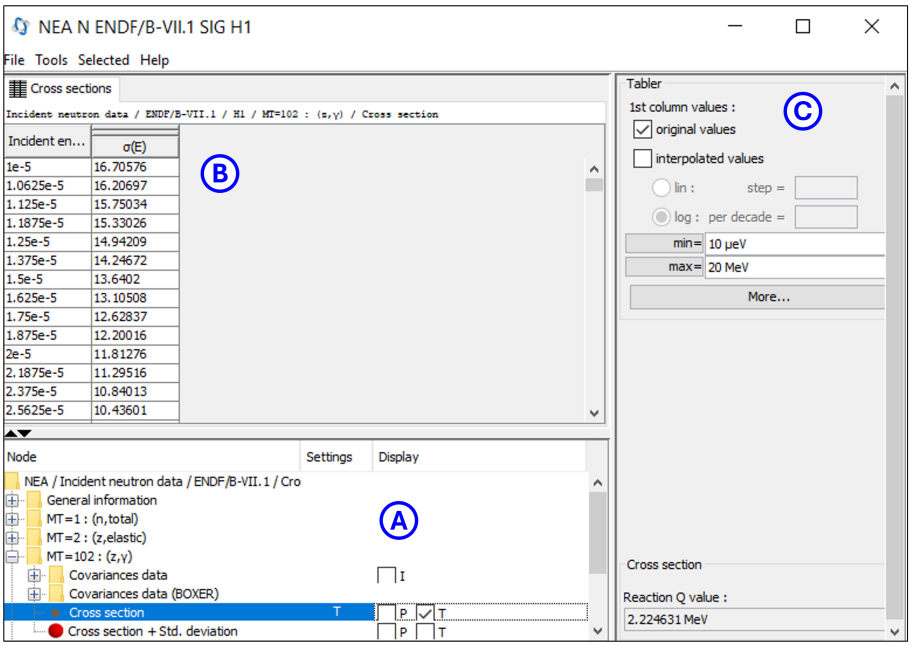


(A) Check this box to display nuclide/compound data.

(B) Nuclide/compound data display

***Figure 3**. Sample software window for nuclear properties.*

When using the database for incident neutron data, after selecting a certain nuclide/compound, a new app window will be opened with an example shown in **Figure 4**.



(A) List of reactions with nuclear data, in this example, incident neutron cross section for (n, γ) reaction (MT=102), with "T" checked in display to show the tabular view of the cross-section data.

(B) Tabular display of the incident neutron cross-section for (n,total) reaction across all energies available. The unit of cross-section are in barns.

(C) Tabler where you may input minimum and maximum value to limit the data displayed in the table.

***Figure 4**. Sample window for incident neutron data.*

B.2 EpiXS is a Windows-based application software developed by the Philippine Nuclear Research Institute. It provides a manageable database that can be applied for photon attenuation, dosimetry, and shielding. The software incorporates photo atomic data of EPICS2017 from ENDF/B-VIII.0 and EPDL97 from ENDF/B-VI.8. It features data library interpolation in the energy range of 1 keV to 100 GeV and can calculate various parameters such as: partial or total cross sections (σ), mass attenuation coefficients (μ/ρ), linear attenuation coefficients (μ), mean free paths (mfp), half-value layers (hvl), effective atomic numbers (Z_{eff}), and electron densities (N_{eff}).

Initiate the EpiXS software by tapping on the icon displayed below:

***Figure 5**. EpiXS Icon*

The main menu interface will be displayed and by selecting "**Agree and enter**", access to the main simulator is granted. Upon choosing "**Enter composition**" in the subsequent interface, a prompt will appear for the material type: **element, compound, or mixture**. This can be selected as illustrated below.

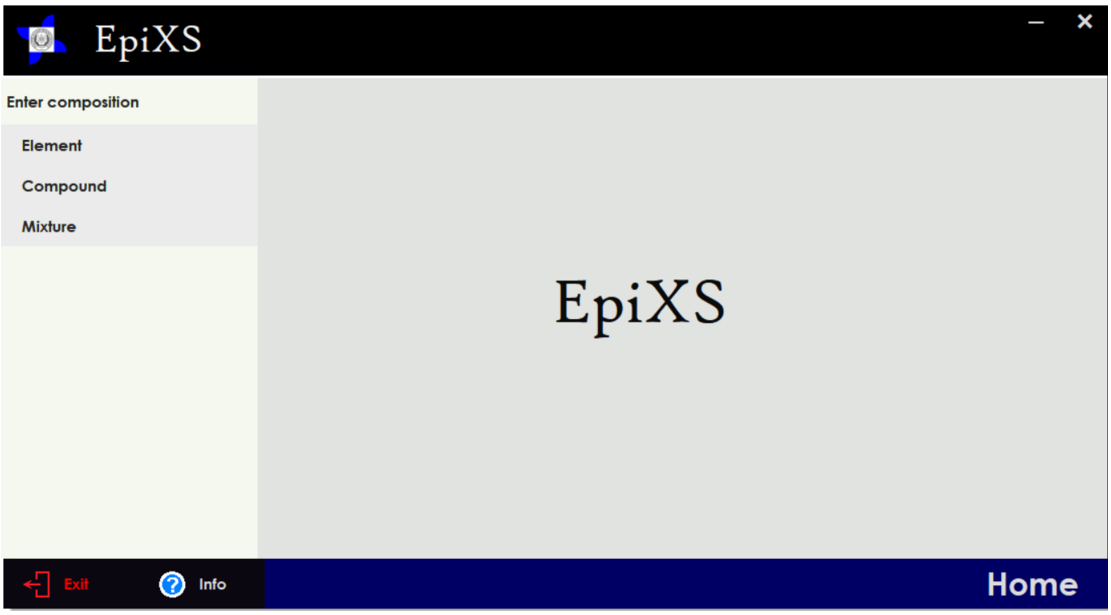


***Figure 6**. EpiXS Interface*

- **Elements** – Elements can be chosen either by their atomic number or their chemical symbol.
- **Compound** – For compounds, chemical formulas should be provided in standard chemical notation. Subscripts are required to be written in line. As an example, the formula for dihydrogen monoxide, commonly known as water, should be entered as H2O. Please note that the inclusion of parentheses, spaces, and dots is not supported by the software.
- **Mixture** – Mixtures can be composed of either "elemental" or "compound" components, or both. Users are required to provide the chemical symbol or formula (as outlined above), along with the weight fraction for each component in the format: *<compound><space><weight>*.

Once the material type is selected and all required information is entered in the appropriate format, the "**Proceed**" button can be clicked. It is important to note that providing the material's density is optional. However, without this parameter, calculations for the μ, mfp and hvl cannot be performed.

In the next interface, the computed parameters can be viewed either as a graph or as data, based on preference.

Experiment Scenario

Consider a 350 g stainless-steel sample that will be irradiated for 5 hrs in a material testing research reactor with a fully thermalized (average energy of 0.025 eV) neutron field with a flux of $\phi = 2.460 \times 10^{14}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The sample will be collected for characterization, and you are tasked to conduct a preliminary safety analysis in handling the irradiated sample. The elemental composition of the stainless-steel sample is provided in **Table 1** as well as the specific nuclides in the sample that will be most likely activated.

Table 1. *Elemental compositions of stainless-steel weight*

Composition	Weight Percent (%)	Target Nuclei	Molar Mass (g/mol)	Main Activation Product
Ti	0. 03			
Ni	8.12			
Cr	8.0	Cr-50	49.946	Cr-51
Mn	14.0	Mn-55	54.938	Mn-56
Fe	68.85	Fe-58	57.933	Fe-59
Co	1.0	Co-59	58.933	Co-60

Experiment Procedure

Part 1. Data Collection (1.5 pts)

Use the following databases from the JANIS Software: (a) Nubase 2012 to gather atomic and nuclear data, and (b) ENDF/B VII.1 library for the cross-section data of the nuclides of interest.

1.1	Complete the table by indicating the radiative capture (MT = 102) cross-section (σ) in barns, and natural abundance (f_i) in %, of the nuclides of interest (Cr-50, Mn-55, Fe-58, Co-59), at the specific incident energy. Linear interpolatation of data may be needed for the required incident energy. For the σ, give the answer in 3 decimal places.	**1.0 pt**

1.2	Retrieve the half-life of each main activation product (Cr-51, Mn-56, Fe-59, Co-60) in seconds. Write the answers in proper scientific notation with 4 significant figures.	**0.5 pt**

Part 2. Neutron Activation (2.25 pts)

In **Table 2**, the activation products and their corresponding gamma radiation are given.

***Table 2**. Main activation products and radiation emitted*

Main Activation Product	Gamma Radiation Emitted (MeV)	Emission Probability (%)
Mn-56	0.847	98.85
	1.810	26.9
Fe-59	1.099	56.5
	1.292	43.2
Co-60	1.252*	199.83*

**Co-60 emits 2 gamma photons 1.33 MeV and 1.17 MeV at 99.98% and 99.85% emission probabilities, respectively. For many applications, it is a common practice to treat these photons as a single photon with an energy of 1.25 MeV (average energy of the 2 photons) at combined emission probability of 199.83% to simplify solutions.*

2.1	Calculate the prompt activity (A) in Bq of the nuclides listed in **Table 2** after 5-hour irradiation of the sample. Write the answers in proper scientific notation with 4 significant figures.	**1.5 pts**

Using point source approximation, the photon flux (φ) at a certain distance r from a gamma source can be obtained from source activity (A) and the emission probability (p):

$$\varphi = \frac{pA}{4\pi r^2} \quad (5)$$

2.2	Using the point source approximation, what are the flux of the gamma radiation with energies 0.847 keV, 1.099 MeV, and 1.252 MeV, assuming that the point of detection is 0.5 meters away and no gamma radiation attenuation and scattering. Give the answers in scientific notation with 4 significant figures.	**0.75 pt**

Part 3. Radiation Shielding (3.0 pts)

Once the stainless-steel sample is retrieved, it must be stored in a container that effectively shields against the gamma radiation to prevent unnecessary exposure. There are three available containers made from different proportions of Iron (Fe), Chromium (Cr), and Nickel (Ni), as detailed in **Table 3**. The sample, when placed inside, is positioned 0.5 meters from the container wall. Neglect gamma radiation attenuation in the air. You are tasked to evaluate these three containers and determine which one offers the best shielding function.

Table 3*. Elemental compositions, thicknesses, and densities of the three containers.*

Containers	**Elemental composition (wt%)**			**Thickness (cm)**	**Density (g/cm^3)**
	Cr	Fe	Ni		
Alloy 1	18.0	72.0	10.0	2.1261	7.85
Alloy 2	21.0	46.5	32.5	2.0562	8.07
Alloy 3	25.0	55.0	20.0	2.1058	7.91

Use the EPICS2017 library of the EpiXS software. When extracting the parameters from the software, consider up to four decimal places for each value.

3.1	Asuming that there is no radiation buidup considered and all three containers have identical thickness. Determine the: **(a)** mass attenuation coefficient (probability of photon interaction per unit density of a material), **(b)** linear attenuation coefficient, and **(c)** mean free path of the container that provides the best shielding against a gamma energy of 1.099 MeV? Write all answers in 5 decimal places.	**0.9 pt**

3.2	If there is no buildup radiation considered and the activated sample is stored in the container that provides the best protection against gamma energy of 1.252 MeV, calculate the transmitted gamma radiation flux after this gamma energy passes through the container. Write the answer scientific notation with 4 significant figures.	**1.0 pt**

3.3	Assuming that there is no radiation buildup considered, find the ratio of the total transmitted to incident radiation after the three gamma energies have passed through Alloy 3 container. Write the answer in 3 decimal places.	**1.1 pts**

Part 4. Shielding Thickness Optimization (3.25 pts)

Radiation dose limits are established to protect people and the environment from the harmful effects of ionizing radiation by ensuring exposure remains within safe levels. Radiation workers have higher dose limits compared to the public because they are trained and monitored to handle radiation safely. The maximum permissible dose for radiation workers is $50\ \mathrm{mSv}$ in a year and a five-year average dose rate of $20\ \mathrm{mSv}\,/\,\mathrm{yr}$.

Radiation dose can be calculated from flux using flux-to-dose conversion coefficients. International organizations like the ICRP publish flux-to-dose conversion coefficients of different types of radiation based on dosimetry measurements and calculations. The table below shows the flux-to-dose conversion coefficients for gamma radiation.

***Table 5**. Flux-to-dose conversion coefficients for different gamma energies*

Gamma Energy (MeV	Conversion Coeff. (μSv/h)/(n/cm^2-s)
0.662	1.085
0.800	1.310
1.000	1.625
1.117	1.800
1.330	2.100

***Table 6.** Elemental composition and densities of the lead block and air*

Material	Elemental compoistion (wt%)	Density (g/cm^3)
Lead	100% Pb	11.348
Air	78% N; 21% O; 0.9% Ar	0.001225

4.1	Suppose a radiation worker is expected to handle activated samples for a total of $800\ \text{hrs}$ in a year. For the purpose of this problem, let's assume that the dose rate received by the worker during these $800\ \text{hrs}$ is constant. Calculate the maximum dose rate, in μSv/hr, that the worker can be exposed to without exceeding the five-year averaged dose limit.	**0.25 pt**

The buildup factor can be calculated for certain energies and will differ depending on the material used. The buildup factor can be calculated in different methods. One can solve the buildup factor as a function of μx, $B(\mu x)$, by using the Taylor's form given by:

$$B(\mu x) = Ae^{-\alpha_1 \mu x} + (1 - A)e^{-\alpha_2 \mu x} \tag{7}$$

where A, α_1, and α_2 are functions of energy, and x is the thickness. This function can sufficiently provide an accurate value for practical shielding problems. Values for A, α_1, and α_2 are different for each material and energies. Given in the table below is the values of A, α_1, and α_2 for lead. The parameters assume that the source is from a point isotropic source.

Table 7. *Parameters for the Taylor form of the Exposure Buildup Factor for Lead*

Energy (MeV)	A	$-\alpha_1$	α_2
0.5	1.677	0.03084	0.30941
1.0	2.840	0.03503	0.13486
2.0	5.421	0.03482	0.04379
3.0	5.580	0.05422	0.00611
4.0	3.897	0.08458	-0.02383
6.0	0.926	0.17860	-0.04635
8.0	0.368	0.23691	-0.05864
10.0	0.311	0.24024	-0.02783

Note: Linear interpolation should be applied for the flux-to-dose conversion coefficients corresponding to the energy of interest.

4.2 **(a)** Superimpose the two plots: **2.0 pts**

- Plot 1: The maximum desired gamma dose calculated from Question 4.1 (a constant value) as a function of μx.
- Plot 2: Calculated gamma dose being produced by the gamma source that has the highest contribution from Question 2.2 after it passes through a Pb block as a function of μx. Consider the contribution of buildup radiation.

Use μx values ranging from 17 to 19. Increment for μx may be as low as possible.

(b) Find the minimum thickness, in cm, of Pb that will provide the maximum allowed dose below the dose limit specified in Question 4.1. Give your answer in 3 decimal places. **1.0 pt**