Exam
Radiation protection expert on the level of coordinating expert

Nuclear Research and consultancy Group	NRG
Delft University of Technology	TUD
University of Groningen	RUG
Radboudumc	RUMC

exam date: May 10th 2021
exam duration: 13.30 - 16.30 hours

Instructions:

- **This exam contains 12 numbered pages and a separate attachment containing 10 pages of data. Please check!**
- Write your solutions and answers on the worksheets provided. You will also need to hand in any unused worksheets at the end of the exam.
- State **only your exam number** on the worksheets (so not your name and address).
- It is allowed to consult books, personal notes, and other documentation materials to answer the questions.
- When answering the questions, make sure you state which **calculation** and/or which **reasoning** helped you reach the solution.
- If you are unable to calculate part of a question and you need that answer to be able to solve the other parts, you are allowed to assume a fictional answer.
- For some of the questions you might not necessarily need to use all of the supplied data.
- You can acquire a total of 61 points if you correctly answer all of the questions. The points are distributed between the questions as follows:

  Question 1: 15 points
  Question 2: 18 points
  Question 3: 16 points
  Question 4: 12 points
- You will have passed this exam if you have obtained at least 55% of the total amount of points. This corresponds to a score of at least 33.5 points.

Question 1: Internal contamination with ^{131}I [15 points]

Therapeutic amounts of ^{131}I are prepared in a B-level isotope laboratory. The risk inventory and evaluation has shown that foreseeable unintended events can cause a significant increase in received dose due to internal contamination. Because of this, the exposed employees undergo monthly thyroid measurements. These measurements are performed on Monday morning, before new samples are prepared. A detector is held at 10 cm distance from the thyroid to determine the count rate. During one of these measurements, a net count rate of 89 cps is measured for one of the employees. It is presumed that this internal contamination is caused by inhalation of I_2-vapor.

Given:

- **Attachment pg. 3-4**: Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015), pg. 164-165; ^{131}I data
- **Attachment pg. 5**: Tissue weighting factors (w_T) ICRP-60 and ICRP-103
- Detection efficiency with detector at 10 cm distance from the thyroid: 9.5 cps/kBq ^{131}I

Question 1.1 [4 points]

Calculate the committed effective dose for the employee, if the I_2-vapor contamination would have taken place on the Friday morning of the previous week – at the start of the working day.

The committed effective dose for the employee is almost entirely caused by the activity in the thyroid gland.

Question 1.2a [2 points]

Use a calculation to estimate the absorbed dose in the thyroid, assuming the situation in question 1.1 and the tissue weighting factors from ICRP-60.

Question 1.2b [2 points]

Argue whether the absorbed dose from question 1.2a can lead to harmful tissue reactions.

The effective dose coefficients from the *Handboek Radionucliden* are based on the tissue weighing factors from ICRP-60. Question 1.3 considers how large the committed effective dose would be if the new tissue weighing factors from ICRP-103 would have been used.

In the case of inhalation of $^{131}I_2$-vapor this is relatively easy, because practically the entire committed effective dose is determined by the activity in the thyroid, and because the committed effective dose coefficient is mainly influenced by the changed tissue weighing factor of the thyroid gland. The relevant radiation weighing factors for ^{131}I have not been adjusted.

Question 1.3 [2 points]

Calculate what the value of the committed effective dose coefficient would be for the inhalation of I_2-vapor, based on the tissue weighing factors from ICRP-103.

The handbook does not supply data for a contamination which occurred more than 7 days prior. It does have data of the metabolic model.

Assume for the next question that the contamination occurred 30 days ago, and that a net count rate of 89 cps is now being measured.

Question 1.4 [5 points]

Calculate as accurately as possible the committed effective dose for the worker.

Question 2: Risk analysis nuclear physics experiment [18 points]

A radiation protection expert considers the radiation protection risks of a nuclear physics experiment. It concerns an experiment using one of the beamlines of a Van de Graaff accelerator, during which a target slide composed of a selenium-thallium alloy (molecular formula: SeTl) is irradiated with 5.9 MeV protons.

Neutrons are released during the irradiation of the target slide with protons due to the nuclear reaction ^{80}Se(p,n)^{80m}Br. The experimenter is <u>only</u> exposed to the neutron radiation produced during this reaction.

The experiment takes 7 days and is performed by one experimenter. There are two critical operations:

- Operation 1: aligning the proton beam
- Operation 2: replacing the nitrogen tank

Description operation 1: aligning the proton beam

The proton beam has to realigned once every 8 hours. During realignment, the experimenter is located at an average distance of 50 cm from the target slide.

Given operation 1:

- During beam alignment, the surveillance monitor in the hall indicates an ambient dose equivalent rate due to the neutrons of H*(10) = 0.1 μSv/h (alarm phase "green").
- The surveillance monitor is located at a distance of 15 meters from the target slide where the neutron radiation is produced.
- Alignment of the proton beam takes on average 30 minutes.
- H*(10) is a good indicator of the effective dose.

Question 2.1 [2 points]

Calculate the effective dose the experimenter is exposed to each time while aligning the proton beam.

The experimenter watches the target slide through a viewing window for on average 10 minutes during alignment. To calculate the equivalent eye lens dose due to neutron radiation, the neutron production during this time needs to be determined.

The following formula applies: $N_n = N_p \cdot N_{Se} \cdot \sigma \cdot yield$, where:

N_n = the number of produced neutrons
N_p = the number of protons incident on the target slide
N_{Se} = the number of selenium atoms per cm^2 in the target slide
σ = the cross section of the nuclear reaction in cm^2
$yield$ = the yield in number of neutrons per nuclear reaction.

Additional given operation 1:

- The mass thickness of the target slide is 1.2 $mg \cdot cm^{-2}$.
- The molar mass of SeTl is 284 $g \cdot mol^{-1}$.
- Avogadro's number is $N_{Avogadro} = 6.0 \cdot 10^{23}\ mol^{-1}$.
- The average beam current I = 50 nA.
- The elementary charge is $1.6 \cdot 10^{-19}$ C.
- 1 A = 1 C/s
- During irradiation the nuclear reaction $^{80}Se(p,n)^{80m}Br$ takes place. You may assume that this is the only nuclear reaction taking place.
- **Attachment pg. 6:** Cross section of the nuclear reaction $^{80}Se(p,n)^{80m}Br$.

Question 2.2a [6 points]

Calculate the number of neutrons produced in the target slide while the experimenter watches through the viewing window.

If you did not find an answer to question 2a, you may use $5 \cdot 10^{-7}$ neutrons for the following calculations.

Additional given operation 1:

- Assume the neutrons are emitted from the target slide isotropically.
- The distance between the target slide and the eye lens is 5 cm.
- The shielding effect of the viewing window is negligible.
- For the conversion of fluence to ambient dose equivalent for these neutrons (derived from fig. 6.14 from Bos et al.):
  $H^*(10) / \Phi_n = 500\ pSv \cdot cm^2$, with Φ_n the neutron fluence (in cm^{-2}).
- You may assume that H*(10) is a good indicator of the equivalent eye lens dose.

Question 2.2b [3 points]

Show through calculations that the equivalent eye lens dose the experimenter incurs during beam alignment is approximately 80 μSv each time.

Description operation 2: replacement of the nitrogen tank

A tank containing liquid nitrogen close to the accelerator needs to be replaced twice a day. The old empty tank is disconnected and the new full tank is connected.

Given operation 2:

- The surveillance monitor placed close to the accelerator measures a net ambient dose equivalent rate caused by the neutrons of H*(10) = 110 μSv/h (alarm phase "red"). This dose rate is an average for operation 2.
- H*(10) is a good indicator of the effective dose.
- Both connecting and disconnecting a nitrogen tank takes approximately 15 seconds;
- Moving the nitrogen tank from the entrance to the mount point takes approximately 60 seconds each time, and removing the empty tank also takes on average 60 seconds.

Question 2.3 [2 points]

Calculate the effective dose the experimenter incurs each time during replacement of the nitrogen tank.

This experiment, which lasts a total of seven days, is performed six times a year by the same experimenter. This person does not incur any additional occupational exposure.

Question 2.4 [5 points]

Conclude based on a calculation of the yearly effective dose and equivalent eye lens dose whether the experimenter should be classified as exposed worker, and if so, in which category.

Question 3: Shielding at an MRI-accelerator [16 points]

An MRI-accelerator is placed in a radiation bunker of a Radiotherapy department. An MRI-accelerator is a combination of a linear accelerator (irradiation device) with an MRI. The use of MRI-images enables very accurate irradiation of a tumor with the photon beam. The maximum energy of the photons in the beam is 6 MeV.

A radiation protection expert wants to calculate whether the shielding effect of the concrete walls and steel door is sufficient.

The photon beam of the MRI-irradiator can rotate 360º around the isocenter X. A 'beam stop' is located directly opposite the beam. This beam stop is a 30 cm thick steel plate which ensures that the beam is (practically) completely absorbed, see Figure 3.1

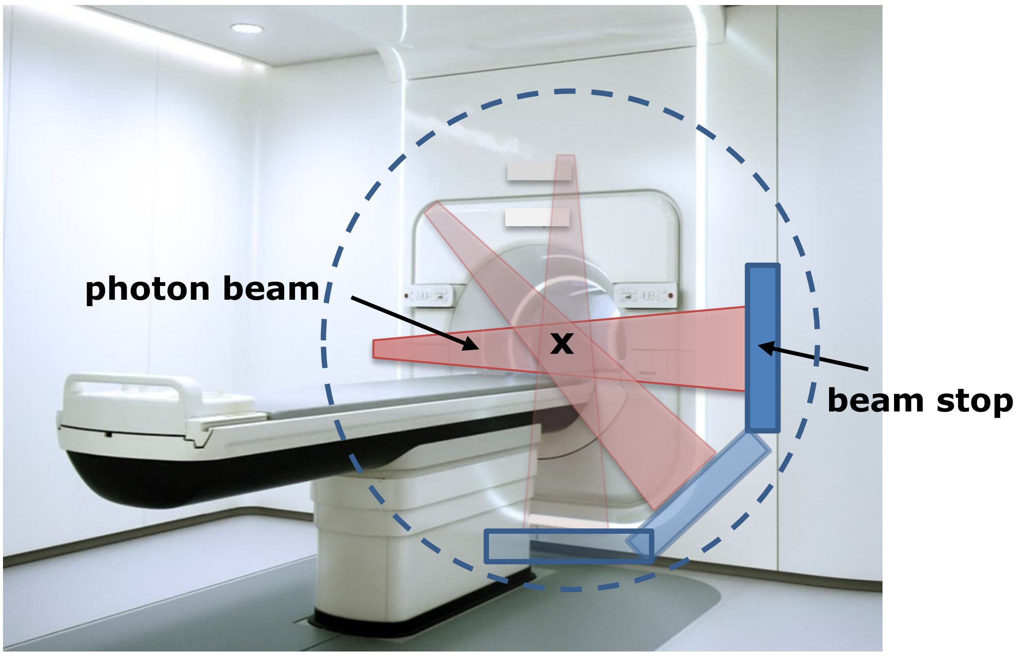

Figure 3.1 – MRI-accelerator with schematic representation photon beam and beam stop.

The manufacturer of the MRI-accelerator supplied measurement data about the air kerma free in air due to the amount of leakage and scattered radiation that is measured around the device during irradiation.

Given:

- Absorbed dose in the isocenter = 20 Gy per patient
- At 1 meter from the isocenter X, 0.1% of the absorbed dose in the patient is measured in air
- Assume for every calculation that all radiation measured around the device originates from the isocenter
- Workload = 8 patients per day, 250 days a year
- Distance isocenter X to point P1 in the control room is 5 meter
- Figure 3.2: map of the radiation bunker
- The thickness of the concrete wall between the irradiation an control room is 1.4 meter
- **Attachment pg. 7**: Broad beam transmission of photons (X-rays) through concrete
- $H^*(10)/K_a$ = 1 for the photon spectrum at an accelerator voltage of 6 MV
- The $H^*(10)$ is a good indicator for the effective dose in this situation

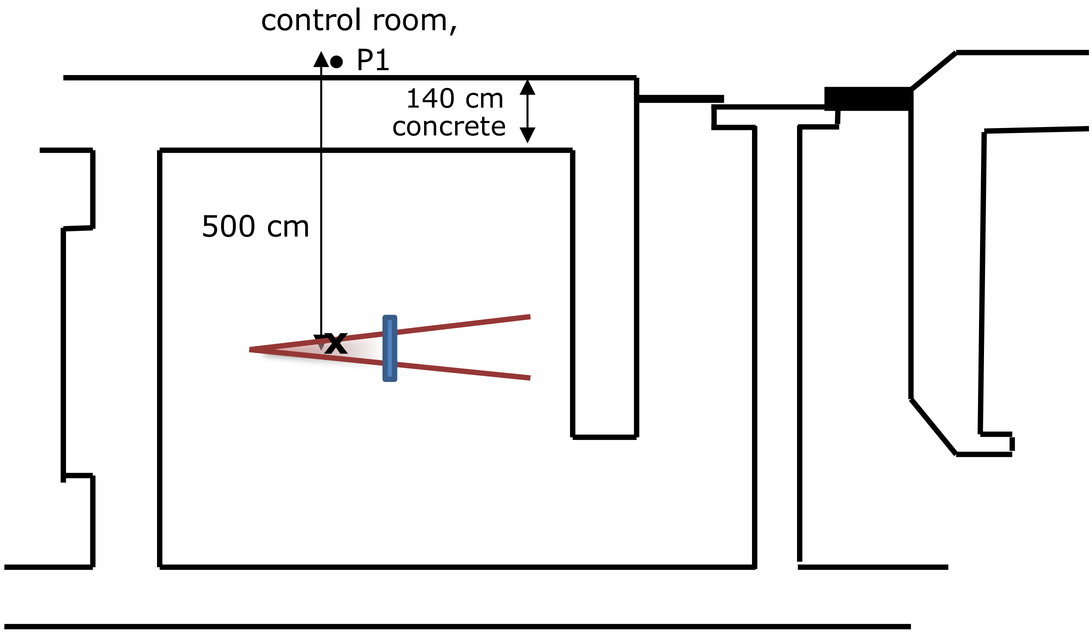

Figure 3.2 – Map of the radiation bunker

Question 3.1 [5 points]

Calculate the yearly ambient dose equivalent in point P1.

The radiation protection expert want to calculate the dose contribution in point P2 via route a. **Figure 3.3** shows this route.

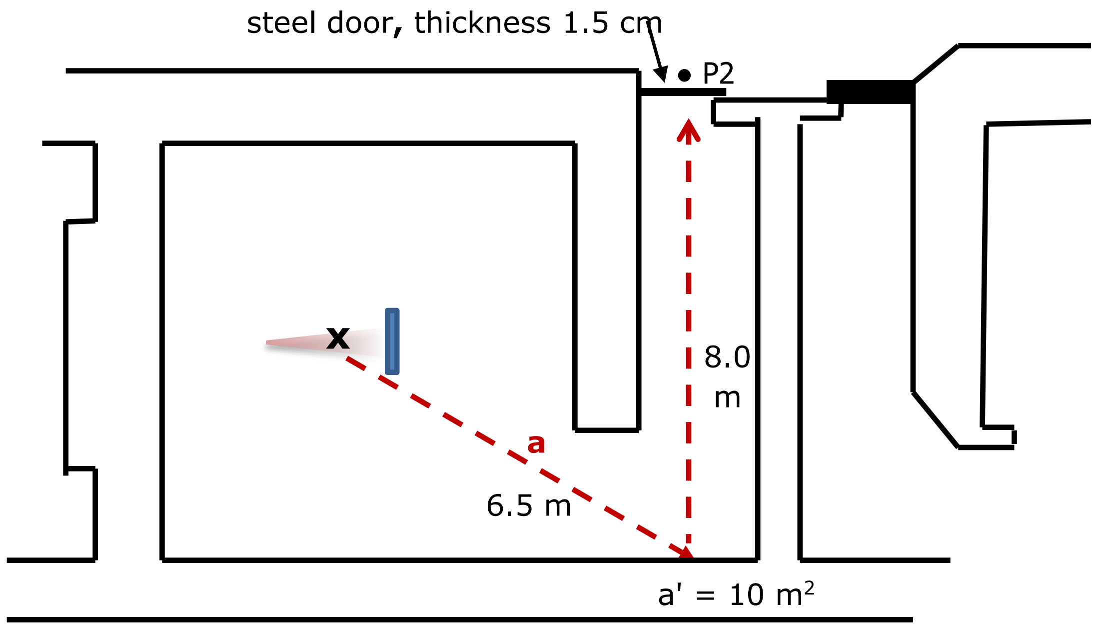

Figure 3.3 – Map radiation bunker; dose contribution point P2 via route a.

Additional given:

- **Attachment pg. 8**: Scattering patterns of divergent X-ray and gamma-ray beams incident perpendicular to a flat concrete wall (adopted from ICRP-33).
- To determine the fraction of scattered radiation you may use the graph from **attachment pg. 8**, even though the scattered photons are not incident perpendicularly.
- P2 is located directly behind a steel door, thickness steel door = 1.5 cm.
- The transmission of the scattered photons through 1.5 cm steel = 0.5
- Calculate using a scattering surface of 10 m^2 located at a'.
- Calculate using a photon energy of 6 MeV for scattered radiation.
- The scattering angle is 120 degrees.

Question 3.2 [6 points]

Calculate the yearly ambient dose equivalent in point P2 via route a.

The radiation protection expert considers the following event for the risk inventory and evaluation: an employee is still located in the bunker when the device is started. The mistake is detected quickly and the irradiation is interrupted. In this case the employee is exposed to an effective dose of 1.5 mSv. The radiation protection expert assumes that this situation happens no more than once per 20 years.

Question 3.3a [3 points]

Argue whether these workers should be classified as exposed workers, and if so, in which category.

Despite all safety measures the above mentioned event does take place, the exact exposure time is unknown. The radiation expert needs to decide whether this event should be reported as an incident to the Authority. Hereto he critically studies the definition of a radiation incident.

The definition of a radiation incident according to attachment 1 of the *Besluit basisveiligheidsnormen stralingsbescherming* (Decree basic safety standards for radiation protection, Bbs) is:

"*unintended event or situation or unwanted spreading where danger exists, or has occurred for:*

- *an exposure to ionizing radiation for members of the public exceeding 0.1 millisievert,*
- *a discharge onto or into the soil, the sewer, the surface water or air exceeding a by Our Minister determined value, or*
- *an exposure to ionizing radiation for workers exceeding 2 millisievert;"*

Question 3.3b [2 points]

Argue based on the definition of a radiation incident whether the radiation protection expert would need to report this event to the Authority as a radiation incident.

Question 4: Noble gas monitor [12 points]

In a radionuclide lab the noble gas ^{41}Ar is used to investigate the response of a noble gas monitor using different concentration of ^{41}Ar in the air. The measurement system (figure 4.1) consists of a gas measurement vessel containing a NaI-detector (cps), a noble gas detector (Bq/cm^3), a buffer vessel and various tubes. See figure 4.1 for a schematic representation. The system has a volume of 33.3 liter. The background radiation in this question may be considered negligible.

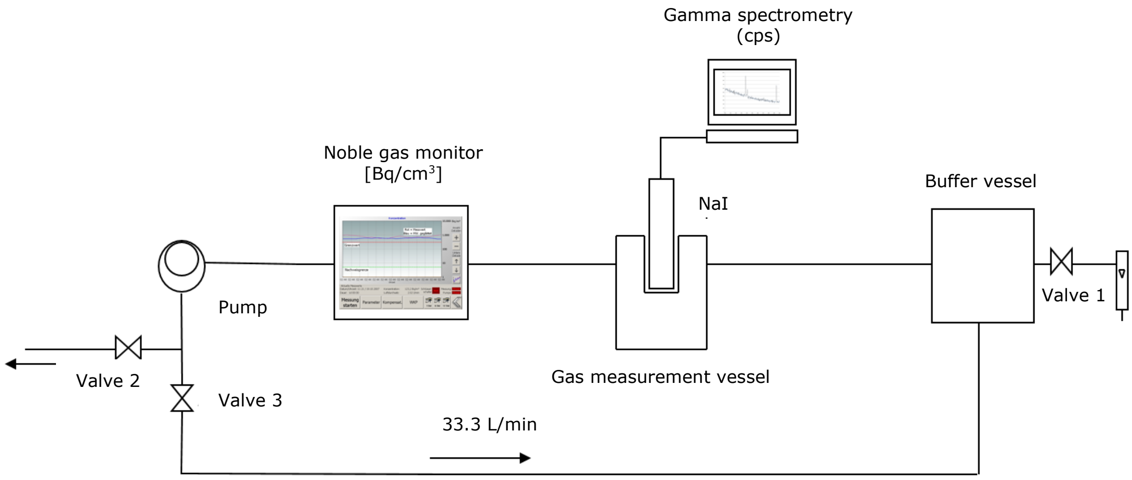

Figure 4.1: the measurement system.

Given ^{41}Ar:

- **Attachment, pg. 9-10:** Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015), pg. 40-41, ^{41}Ar data

Using the NaI-detetor, ^{41}Ar is measured in the air of the closed system. 4.0 MBq ^{41}Ar is inserted in the total volume of 33.3 liter. At t=0 the activity is uniformly (homogenously) spread within the system.

Throughout approximately 7.5 hours the net values of the ^{41}Ar photon peak are registered by the NaI detector. These measurements last for 1 minute each. See the net values in table 4.1.

The system turns out to be leaky, as the NaI-detector measurements indicate ^{41}Ar to disappear more rapidly than expected based on its physical decay.

T (h)	cps
0.000	1756
0.084	1696
0.167	1648
0.251	1586
0.334	1530
0.417	1491
...	...
2.754	587
2.838	567
2.921	552
3.004	532
3.088	516
3.171	497
...	...
7.093	97
7.177	95
7.260	92
7.344	90
7.427	86
7.511	83

Table 4.1

The system is proven to be leaky when the measured count rate falls outside 2 standard deviations from the count rate you would expect based on the physical decay after 3.004 hours.

Question 4.1 [4 points]
Prove using a calculation that the system is leaky.

Just like radioactive decay (characterized by the physical decay constant λ_{phys}) the removal of ^{41}Ar activity from the vessel can be described using a removal constant λ_{leak}. The total effective removal constant describing the overall decrease of ^{41}Ar-activity in the vessel is given by: $\lambda_{eff} = \lambda_{phys} + \lambda_{leak}$.

Question 4.2 [3 points]
Determine using the last measurement value the effective removal constant (h^{-1}) of the measurement system.

Question 4.3 [2 points]
Using a calculation show that the calibration factor for the gas measurement vessel based on the measurement at t=0 is equal to 0.068 Bq/cm^3 per cps.

After 7.5 hours, and the content of the measurement system is flushed for a duration of 10 minutes at a rate of 33.3 L/min. The argon-air mixture is discharged through a fume hood during this dilution.

Question 4.4 [3 points]
Calculate using the calibration factor of question 4.3 what the noble gas monitor indicates before and after this dilution, neglect the radioactive decay during flushing.