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- no animals were harmed in the writing of this essay.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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Table of Contents

Academic integrity declaration.....	ii
List of Equations.....	iv
List of Abbreviations	iv
1 Why is ^{60}Co a suitable isotope?.....	5
2 Dosimetry calculations	5
2.1 Source activity	5
2.2 Unshielded dose rate	6
2.3 Shielded dose rate	7
2.4 Effective dose	7
2.5 Comparison	8
2.5.1 Measured effective dose	8
2.5.2 Comparison with calculated dose.....	8
2.5.3 Possible sources of discrepancy	9
3 Discuss any health implications from the radiation exposure in this incident	11
4 Assess compliance with the Ionising Radiations Regulations 2017.	13
4.1 IRR17 Para. 9	13
4.2 IRR17 Para. 11	13
4.3 IRR17 Para. 19	14
5 Evaluate the event against ONR Safety Assessment Principle EKP.5 Defence in Depth and two other SAPs of your choice.....	15
5.1 EKP.5.....	15
5.2 EKP.3.....	16
5.3 EDR.2	16
6 Propose proportionate improvements, justified on ALARP grounds, that would reduce the likelihood or consequences of a similar event.	18
6.1 Radiation readouts.....	18
6.2 Door interlocks.....	19
6.3 Warning Signs and Sirens	19
6.4 CCTV	19
7 Conclusion.....	21
References	22
Appendix A – Incident Dossier	24

List of Equations

Equation 1 - Activity at a given time 5

Equation 2 - Decay constant 5

Equation 3 - Dose rate from a point source 6

Equation 4 - Dose rate accounting for shielding 7

Equation 5 - Effective dose..... 7

List of Abbreviations

ALARP	As Low as Reasonably Practicable
EPD	Electronic Personal Dosimeter
TLD	Thermoluminescent Dosimeter

1 Why is ^{60}Co a suitable isotope?

Gamma irradiation is a popular method of industrial sterilisation (Chmielewski, 2023), as – compared to other methods such as steaming or gas - gamma rays can sterilize objects through packaging without leaving potentially harmful residue. ^{60}Co is especially suitable for sterilization as it decays at an appropriate rate (National Academies of Sciences, Engineering, and Medicine, 2021) and is readily available, being easily produced in nuclear reactors (International Irradiation Association, 2006).

2 Dosimetry calculations

2.1 Source activity

The activity of a radioactive source at a given time is calculated using equation 1:

$$A_t = A_0 e^{-\lambda t}$$

Equation 1 - Activity at a given time

Where:

A_t = Activity at (time) (Bq)

A_0 = Initial activity (Bq)

λ = Decay constant (s^{-1})

t = Time (s)

Original activity of source: 0.95 PBq, or 9.5×10^{14} Bq.

Elapsed time: 2.414016×10^8 s.

The decay constant for ^{60}Co can be calculated using equation 2:

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

Equation 2 - Decay constant

Where:

λ = Decay constant (s^{-1})

$t_{1/2}$ = Half life (s)

Half life of ^{60}Co : 1.66×10^8 seconds (International Commission on Radiological Protection, 2008).

$$\lambda = \frac{\ln(2)}{1.66 \times 10^8}$$

$$\lambda = 4.167 \times 10^{-9}$$

$\therefore$

$$A_t = 9.5 \times 10^{14} \cdot e^{-4.167 \times 10^{-9} \cdot 2.414016 \times 10^8}$$

$$A_t = 3.47 \times 10^{14} \text{ Bq}$$

2.2 Unshielded dose rate

The dose rate from a point source is calculated using Equation 3, below:

$$D = \frac{A\tau}{r^2}$$

Equation 3 - Dose rate from a point source

Where:

D = Dose rate (mSvh^{-1})

A = Activity of the source (MBq)

τ = The gamma ray constant ($\text{mSvh}^{-1} \text{MBq}^{-1}$)

r = Distance from source (m)

Gamma ray constant for ^{60}Co : $3.062 \times 10^{-4} \text{ mSvh}^{-1} \text{MBq}^{-1}$ (Peplow, April 2020)

Activity at source: $3.47 \times 10^8 \text{ MBq}$

Distance from source: 1.5 m

$$D = \frac{3.47 \times 10^8 \cdot 3.062 \times 10^{-4}}{1.5^2}$$

$$D = 4.72 \times 10^4 \text{ mSvh}^{-1}$$

2.3 Shielded dose rate

The dose rate, accounting for shielding, can be calculated using Equation 4:

$$D_t = D_0 e^{-\mu t}$$

Equation 4 - Dose rate accounting for shielding

Where:

D_t = Shielded dose rate (mSvh^{-1})

D_0 = Unshielded dose rate (mSvh^{-1})

μ = The linear attenuation coefficient of the shielding material (m^{-1})

t = The thickness of the shielding (m)

Dose rate: $4.72 \times 10^4 \text{ mSvh}^{-1}$

Half value layer: 0.23 m

Thickness of shielding: 0.6 m

$$D_t = 4.72 \times 10^4 \cdot e^{(-0.23 \cdot 0.6)}$$

$$D_t = 4.11 \times 10^4 \text{ mSvh}^{-1}$$

2.4 Effective dose

The effective dose is calculated using Equation 5:

$$E = D_t t$$

Equation 5 - Effective dose

Where:

E = Effective dose

D_t = Dose rate (mSvh^{-1})

t = Time (hours)

Dose rate after attenuation: $4.11 \times 10^4 \text{ mSv h}^{-1}$

The incident dossier, contained within Appendix A, suggests that the technician was in the vicinity of the source for a duration of between 8 and 15 seconds, equivalent to 2.22×10^{-3} and 4.17×10^{-3} hours respectively. These figures can be used to calculate the effective dose following an 8 second exposure (best case scenario) and a 15 second exposure (worst case scenario).

Best case scenario:

$$4.11 \times 10^4 \cdot 2.22 \times 10^{-3} = 9.14 \times 10^1$$

Effective dose in 'best case' scenario: 91.4 mSv.

Worst case scenario:

$$4.11 \times 10^4 \cdot 4.17 \times 10^{-3} = 1.71 \times 10^2$$

Effective dose in 'worst case' scenario: 171 mSv.

2.5 Comparison

2.5.1 Measured effective dose

The maintenance technician was wearing an Electronic Personal Dosimeter (EPD) at chest level, as well as a Thermoluminescent Dosimeter (TLD) at waist level. Post-incident dosimetry produced the following measured doses:

- An EPD dose of 27.6 mSv
- An EPD peak dose rate of 8.5 Sv h^{-1}
- A TLD dose of 33.4 mSv

2.5.2 Comparison with calculated dose

The measured doses compare to the calculated doses as follows:

- The EPD dose is significantly lower (27.6 mSv) than the calculated best-case dose (91.4 mSv).

- The EPD peak dose rate is significantly lower (8.5 Sv h^{-1}) than the calculated dose rate (41.1 Sv h^{-1})
- The TLD dose is higher than EPD dose, however remains significantly lower (33.4 mSv) than the calculated dose (91.4 mSv).

2.5.3 Possible sources of discrepancy

The figures for victim exposure time, victim distance from the source and the depth of the parked source are based on post-incident reconstruction. While the methodology of this reconstruction is not given, it is assumed that the figures are based on accounts from the victim and the operator. The author considers it unlikely that CCTV footage of the incident exists as this would significantly reduce uncertainty regarding the duration of the exposure.

As the reconstruction relies entirely on eyewitness accounts, it is reasonable to assume that there is some inaccuracy regarding the figures provided, specifically the distance between the victim and the source and the depth at which the source was parked beneath the water.

2.5.3.1 Operator distance

The dossier states that the victim's torso was 'approximately 1.5 m' from the source. The effective dose for an 8 second exposure at 1.5 m has been calculated to be 91.4 mSv. Allowing for a 60% margin of error and increasing the distance to 2.4 m gives an effective dose of 35.7 mSv, comparable with the whole-body TLD dose recorded (33.4 mSv).

While 60% is a significant margin of error, the very significant difference between the calculated effective doses at 1.5 m and 2.4 m illustrates the influence of source distance on the dose received by the victim and consequent importance of this figure in post-incident investigations.

2.5.3.2 Thickness of shielding

It is stated in the dossier that the source was 'approximately 0.60 m' below the surface of the water. The application of even a significant margin of error (100%)

results in an effective dose which is significantly higher (79.6 mSv) than the whole body TLD dose recorded (33.4 mSv).

2.5.3.3 Combination of factors

If a 50% margin of error is applied to both victim distance and the depth of water shielding, the calculated effective dose becomes 37.9 mSv, which is broadly comparable with the measured effective dose (33.4 mSv).

It is likely that the figures provided by the incident dossier regarding victim distance from the source and the depth of the source itself are inaccurate, and that these inaccuracies contribute to a calculated effective dose which is pessimistic when compared to the effective dose measured by personal dosimetry.

3 Discuss any health implications from the radiation exposure in this incident

In 2004, workers in an irradiation plant in China were exposed to a ^{60}Co source with an activity of 1.42×10^9 MBq (Radiation Biology Centre, Kyoto University, n.d.), with lethal consequences for both (Yao, et al., 2010). While the source in the incident discussed within this essay is not as active (3.47×10^8 MBq), the incident highlights the dangers of ^{60}Co as a radioactive source.

The incident dossier within Appendix A states:

“The maintenance technician reported a metallic taste in the mouth, dizziness and nausea as he waited for the arrival of the RPA. The following day he reported headaches and blurred vision.”

The severity of radiation poisoning is commonly scored using the European system Medical Treatment Protocols for radiation accident victims (METREPOL) (British Institute of Radiology, 2001), which scores the intensity and frequency of symptoms to establish the severity of radiation poisoning.

While a metallic taste in the mouth is not in itself a symptom of acute radiation poisoning, it is a common effect of radiation exposure, regularly observed in radiotherapy patients (Yamashita, et al., 2006), and confirms exposure to high levels of ionising radiation.

The patient displays the following symptoms of acute radiation sickness:

- **Dizziness and nausea.** While the intensity of this is not provided, the early onset - within less than an hour of exposure – suggests significant radiation poisoning (Lopez & Martin, 2011).
- **Headaches.** The intensity of these are not given, but headaches of a ‘tolerable’ intensity are a common symptom of moderate radiation poisoning (Lopez & Martin, 2011).

Considering the symptoms listed, it is highly likely that the technician was suffering from acute radiation poisoning justifying hospital admission and

observation, along with blood tests to establish the severity of the radiation sickness.

While the blurred vision is not a symptom of radiation sickness, it is indicative of serious damage to the eyes from radiation exposure (Hamada, et al., 2020) and tests should be undertaken to assess the extent of this damage.

Concerning the longer term health effects of this exposure, research suggests (Cardis, E. et al, 2005) that the excess relative risk of leukaemia from exposure to ionising radiation is 1.93% per Sv, and the relative risk of other cancers is 0.97% per Sv. Considering the comparatively minimal exposure in this case (roughly 40 mSv, or 0.04 Sv), the author considers the likelihood of this exposure resulting in the development of leukaemia or other cancers to be minimal.

4 Assess compliance with the Ionising Radiations Regulations 2017.

As the site is carrying out work involving ionising radiation, it is subject to the Ionising Radiation Regulations 2017 (IRR17) (UK Government, 2017). This essay will now identify the sections of IRR17 relevant to the incident here examined and assess the compliance of the site.

4.1 IRR17 Para. 9

“9. —(1) Every employer must, in relation to any work with ionising radiation that it undertakes, take all necessary steps to restrict so far as is reasonably practicable the extent to which its employees and other persons are exposed to ionising radiation.” (UK Government, 2017)

The irradiation chamber was separated by a door and a maze, restricting the access of employees to areas where radiation hazards were present. Further steps could have been taken to both indicate dangerous levels of ionising radiation within the chamber, and restrict access to the chamber while radiation levels were dangerously high. The author considers that such steps were necessary to prevent employee exposure to ionising radiation, and that in failing to take these steps, the site was non-compliant with the above paragraph.

4.2 IRR17 Para. 11

“11.—(1) An employer who provides any engineering control, design feature, safety feature or warning device to meet the requirements of regulation 9(2)(a) must ensure—

(a) that any such control, feature or device is properly maintained; and

(b) where appropriate, that thorough examinations and tests of such controls, features or devices are carried out at suitable intervals” (UK Government, 2017)

A key safety feature of the irradiator system is the source hoist, which uses a motor to lower the source to a sufficient depth beneath water to provide shielding

while the irradiator system is shut down. The parking of the source at depth is the single safety feature, with no other shielding present in the system.

While no mention is made of regular maintenance of the source hoist motor, it is stated that in the lead up to the incident occasional minor issues regarding the motor had been mentioned without any formal defect being declared. Per para. 11 above, the employer had a responsibility to ensure that the hoist, being a key safety feature, was properly maintained and tested. As an issue was able to develop and then persist, ultimately leading to a serious incident, the author concludes that the employer *did not comply* with IRR17 para. 11.

4.3 IRR17 Para. 19

“19.—(1) Every employer who designates any area as a controlled or supervised area must ensure that any such designated area—

(a) is adequately described in local rules; and

(b) has suitable and sufficient signs displayed in suitable positions warning that the area has been so designated and indicating the nature of the radiation sources and the risks arising from such sources.

(2) A controlled area must be physically demarcated or, where this is not reasonably practicable, delineated by some other suitable means.” (UK Government, 2017)

Plans show that the irradiation area is physically demarcated by a maze and a door, with warning signs positioned at two points within the maze. The author therefore considers that the site is *compliant* with IRR17 para. 9.

5 Evaluate the event against ONR Safety Assessment Principle EKP.5 Defence in Depth and two other SAPs of your choice

5.1 EKP.5

EKP.5 states the following (Office for Nuclear Regulation, 2020):

“Safety measures should be identified to deliver the required safety function(s).

Safety should be secured by characteristics as near as possible to the top of the list below:

(a) Passive safety measures that do not rely on control systems, active safety systems or human intervention.

(b) Automatically initiated active engineered safety measures.

(c) Active engineered safety measures that need to be manually brought into service in response to a fault or accident.

(d) Administrative safety measures (see paragraph 446 ff.).

(e) Mitigation safety measures (eg filtration or scrubbing).”

- **Passive safety measures.** The design of the irradiation system includes a barytes concrete maze and a heavy steel door. When the apparatus is lowered, the water also acts as a passive safety measure.
- **Automatically initiated safety measures.** The door was is interlocked with the parked source, not an in-chamber dosimeter. Under normal operation this would prevent access to the chamber in dangerous conditions, however the failure to interlock the door to the in-chamber dosimetry equipment permitted access to the chamber during fault conditions.

The in-chamber dosimeter was connected to the radiation warning signs, all of which were placed inside the maze and therefore not visible to the operator.

- **Active engineered safety measures.** No active safety measures are mentioned in the incident dossier.

- **Administrative safety measures.** There is evidence of a routine maintenance program which, if effective, would have reduced the likelihood of faults developing with the apparatus. The fact that both the source hoist and the conveyor developed simultaneous faults suggests that the maintenance program was not effective.

The author considers that the design of the apparatus was *partially compliant* with EKP.5.

5.2 EKP.3

EKP.3 states the following (Office for Nuclear Regulation, 2020):

“Nuclear facilities should be designed and operated so that defence in depth against potentially significant faults or failures is achieved by the provision of multiple independent barriers to fault progression.”

The design of the irradiator system includes the following barriers:

- A heavy duty door
- A barytes concrete maze
- Water acting as radiation shielding. The hoist, which lowers the source to a safe depth below the water, is integral to this shielding.

The heavy duty door was interlocked with the hoist; two of the three barriers were therefore not independent but rather connected, with the result that a fault with the hoist (failure to lower the source to the correct depth) resulted in a fault with the door (allowing access during dangerous conditions in the chamber).

To make the door an independent barrier, it would need to be interlocked either directly with the in-chamber dosimeter, or with the radiation warning signs which were themselves connected to the dosimetry equipment. The author therefore considers the design *non-compliant* with EKP.3.

5.3 EDR.2

EDR.2 states that (Office for Nuclear Regulation, 2020):

“Redundancy, diversity and segregation should be incorporated as appropriate within the designs of structures, systems and components.

It should be demonstrated that the required level of reliability for their intended safety function has been achieved.”

The design of the irradiation system includes a hoist which lowers the source to a safe depth under water. While it is unknown whether the hoist had been demonstrated to be reliable, the incident dossier suggests that this hoist was the only mechanism capable of lowering the source to a safe depth. This represents a lack of redundancy in the shielding system.

A more robust safety system might include either a second hoist which would function when a fault was detected within the first, or a secondary shielding system of lead-filled steel baffles which could be lowered in front of the source as a mitigation during a fault event.

6 Propose proportionate improvements, justified on ALARP grounds, that would reduce the likelihood or consequences of a similar event.

Reducing a risk to As Low as Reasonably Practicable (ALARP) refers to the reduction of the risk of an accident without incurring unacceptable cost (UK Health and Safety Executive, n.d.), either through the cost of resources or a reduction of the efficiency of work to the point where an activity is no longer financially tenable.

For example, while possible flaws with the design of the apparatus has been identified, the author does not consider that a complete overhaul of the design of the system (to further isolate the carrier mechanism from the source, or to install further shielding) would be practicable.

The following is a list of measures which the author considers would be practicable ways to reduce the likelihood of a similar event, or to aid in the investigation of future incidents:

6.1 Radiation readouts

The incident dossier suggests that nobody outside the chamber was aware of the radiation levels within, and that investigation of the radiation levels exposed personnel to dangerously high levels of radiation. The author therefore proposes that readouts for the in-chamber dosimeter are displayed in the following locations:

1. Beside the door to the maze
2. At the operators console

There should also be redundancy in the in-chamber dosimetry, with at least two devices present in the chamber to reduce the chances of a single failure resulting in a loss of dosimetry.

6.2 Door interlocks

Despite the in-chamber dosimeter detecting dangerously high levels of radiation, the maintenance technician was able to enter the chamber. The author proposes that the maze door be interlocked with the in-chamber dosimeter(s) to both restrict entry if radiation levels are high, and ensure operator awareness of dangerous conditions.

6.3 Warning Signs and Sirens

The in-chamber dosimeter was connected to two warning signs which, the dossier suggests, are illuminated when radiation levels inside the chamber are dangerously high. The wording of these signs, "*Radiation Warning – Danger of Death*" does not explicitly convey dangerously high radiation levels, and they are not accompanied by any audible warning such as sirens or recorded messages. The maintenance technician ignoring these signs was a major contributing factor to the severity of the incident.

The author suggests the following improvements to ensure operators are aware of high radiation levels:

1. The wording of the signs should be changed to convey the presence of dangerously high radiation levels.
2. The signs should be accompanied by flashing red lights.
3. The signs and flashing lights should be accompanied by an audible warning.

6.4 CCTV

Neither the operator nor the technician was aware that the source was improperly parked; had the operator been aware of the position of the source, it is likely that they would have been aware of the dangerous conditions within the chamber. The author proposes that CCTV be installed inside the chamber, and that this be viewable from the operators console. This would provide the following benefits:

1. Prior to allowing the entry of personnel to the chamber, the operator would be able to visually confirm that the source was safely parked.

2. If high radiation levels are indicated within the chamber, the operator will be able to establish the reason and possibly remedy the situation through resetting the lowering mechanism.
3. In the event of an incident, review of the CCTV footage would enable investigators to establish both the positions of the source and any victim with more certainty.

7 Conclusion

An industrial irradiation system developed a severe fault which, through neglect by plant personnel, developed to a point where a maintenance technician was exposed to dangerously high levels of ionising radiation. This technician developed symptoms of serious radiation poisoning which required hospitalisation.

The incident was due to a flawed irradiator design which was not compliant with IRR17 or the ONR SAPs. The author has proposed improvements to the design of the system to reduce the risk of personnel to ionising radiation exposure to ALARP.

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Appendix A – Incident Dossier

Equipment: Pool-Type Industrial Sterilisation Irradiator

Location: Commercial Packaging Sterilisation Facility

A.1 The Radioactive Source Assembly

Source Type: Sealed cobalt-60 source pencils arranged in a panoramic source rack.

Isotope: Cobalt-60.

Original Activity: 0.95 PBq certified on 22 June 2017.

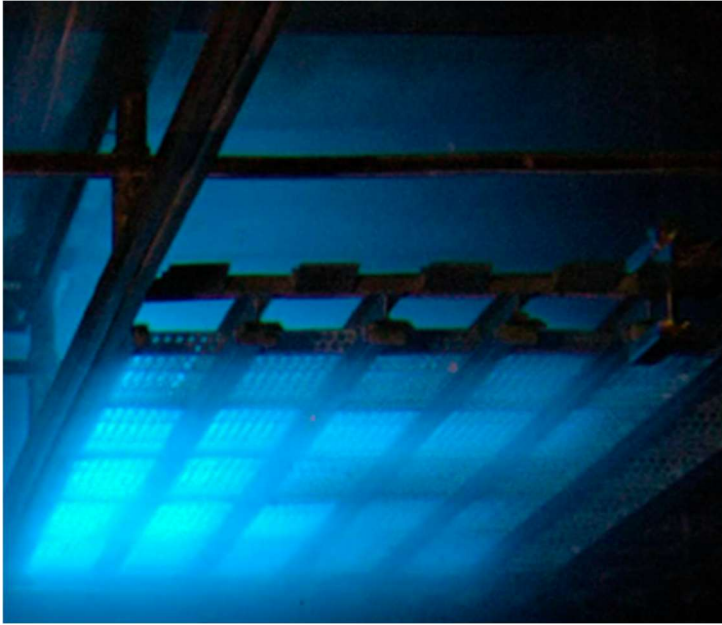
The source rack consists of multiple doubly encapsulated cobalt-60 pencils arranged to provide a high-intensity gamma field when raised into the irradiation position.

The decay of cobalt-60 produces two principal gamma photons of energies approximately 1.17 MeV and 1.33 MeV, making it suitable for industrial sterilisation.

For the purposes of this assignment, internal attenuation within the source rack may be neglected.

A.2 Engineering and Irradiator Design

The irradiator comprises a 5 m deep water shielding pool in which the source rack is stored when not in use. During operation, the rack is raised into the irradiation chamber by a motor-driven hoist mechanism.



When the source rack is fully parked, the pool water provides the principal biological shielding.

Lead filled steel baffles are used to limit direct radiation shine paths.

Product carriers are transferred through the irradiation chamber by an automated conveyor. Maintenance access is prohibited unless the source rack is confirmed to be fully lowered into the pool and the plant is in a safe state.



A.3 Maintenance and Operational Background

In the period leading up to the incident, operators had reported occasional hesitation in the final stage of source-rack lowering. The events cleared without intervention and no formal defect was declared.

The conveyor system had also developed intermittent transfer faults, including occasional obstruction of a carrier guide rail within the chamber.

Routine maintenance entries had previously been carried out following shutdown and confirmation of the parked source condition.

A.4 The Incident — 14 February 2025

At the end of a production run, the source rack was commanded to lower into the shielding pool. Because of a developing hoist defect, the source rack stopped with its upper edge approximately 0.60 m below the water surface, rather than at the normal fully parked depth.

The plant indication was interpreted as showing that the source was safely parked.

A maintenance technician entered to clear a jammed carrier mechanism from a position near the pool edge.

The maze entrance door was interlocked to the parked source so allowed entry.

The maintenance technician noticed the EPD was flashing and exited to consult with the operator.

The operator then took the dose rate meter and walked into the maze. On approaching the first bend the dose rate climbed to $100 \mu\text{Sv h}^{-1}$. The operator retreated and contacted the RPA.

The maintenance technician reported a metallic taste in the mouth, dizziness and nausea as he waited for the arrival of the RPA. The following day he reported headaches and blurred vision.

A.5 Dosimetry

The technician was wearing:

- an electronic personal dosimeter (EPD) on the chest
- a whole-body TLD at waist level

Post-incident dosimetry indicated:

- EPD dose: 27.6 mSv
- EPD peak dose rate: 8.5 Sv h⁻¹
- TLD dose: 33.4 mSv

The ADS reported the overexposure to the HSE.

A.6 Post Incident Investigation

The RPA carried out an investigation which was reported to the HSE.

The operator reported that she used a dose rate survey meter outside the maze as a double-check before allowing the entry of the maintenance technician. She reported that she could see on the meter an above background reading when the source was exposed and on this occasion the meter was reading background, consistent with the parked source. She stated that she was aware of the ability of the apparatus to give a lethal dose in a minute.

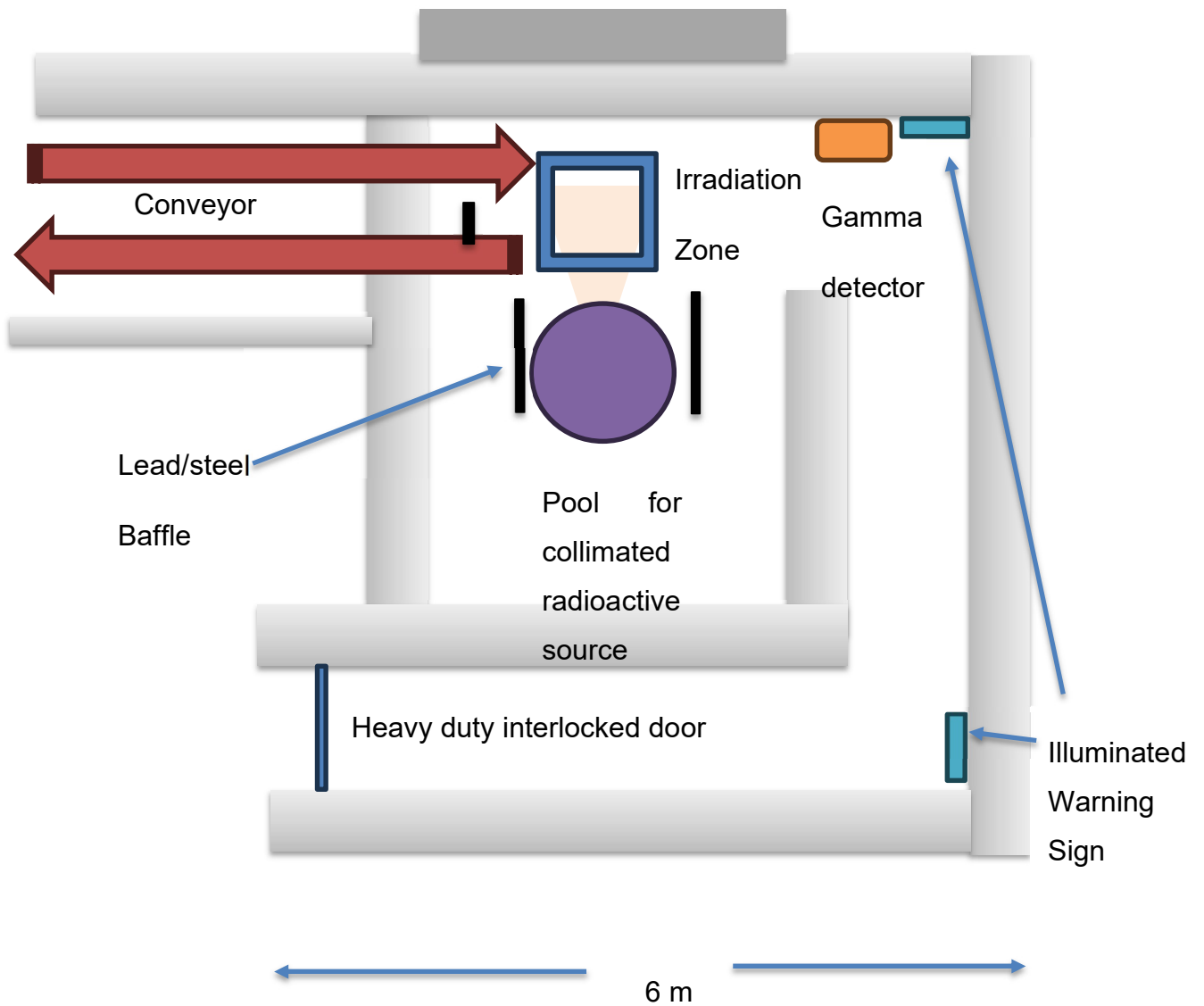
The two illuminated warning signs-connected to the in-chamber dose rate meter-were lit with “Radiation Warning- Danger of Death” when the maintenance technician made the entry and, hence, he must have either failed to notice or ignored the signs.

Post-incident reconstruction indicated that:

- the technician’s torso was approximately 1.5 m from the effective source position
- approximately 0.60 m of intervening water lay between the source and the technician for most of the exposure
- the technician remained in this position for approximately 8–15 s

Irradiator System-

Plan View- not to scale



Walls are 1.5 m thick barytes concrete