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NSEDA Assignment F

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Nuclear Safety ACDA5023

Academic Year: 2023 - 2028

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August 2026

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1 Introduction

This report will investigate an incident involving Iridium 192 (^{192}Ir) in an industrial gamma radiography source. The source became stuck inside the guide tube of a remote device during a weld inspection. Unknown to the staff, the source failed to return to its shielded position, and they approached the source, resulting in a significant radiation exposure. This report will analyse the radiological consequences as well as the effectiveness of the engineering and safety controls in place.

2 Iridium-192 as a radiography source

Iridium-192 excels as a radiography source in this scenario due to its ability to emit gamma energy sufficient to penetrate dense materials such as steel. This enables the inspection of welded joints and other structural components for internal defects, including cracks and voids, without causing damage to the material (GammaBuana, 2024). As the gamma rays produced by Iridium-192 are so high, it means the operation requires smaller quantities of the source and therefore makes it easier to store and operate. Additionally, Iridium-192 has a half-life of 73.83 days. This gives a practical balance between a source maintaining the ability to produce effective radiographic images as well as being replaced periodically (National Library of Medicine, 2016)

3 Source Activity

Source activity refers to the rate at which unstable atoms decay within a radioactive isotope; the SI unit in which this process is measured is becquerels (Bq), where one Bq represents one decay per second. As a radioactive isotope continues to decay, the number of unstable atoms decreases, resulting in a reduction in activity over time. All radioactive isotopes have a half-life; this is the time required for half of the unstable atoms in a radioactive source to decay (Renneboog, 2015). As mentioned, Iridium-192 has a half-life of 73.83 days.

The brief provides the original activity as 16 TBq, and the delta time between the source activity and the incident is 134 days. Using Equation 1 (LibreTexts Physics, n.d.), the source activity on the day of the incident can be calculated.

$$A = A_0 \left(\frac{1}{2}\right)^{t/T_{0.5}}$$

Equation 1 - Source Activity Equation

Where:

A = Current time activity (TBq)

A₀ = Initial activity (TBq)

t = Time delta (Days)

T_{0.5} = half-life (Days)

The source activity on the day of the incident is:

$$A = 16TBq \left(\frac{1}{2}\right)^{134/73.83}$$

$$=4.55TBq \text{ or } 4.55 \times 10^{12} \text{ Bq}$$

4 Dose Rate

4.1 One Metre Dose Rate

This section of the report focuses on the dose rates associated with the Ir-192 source during this incident. Dose rate refers to the quantity of radiation received per unit of time and is most commonly expressed as Sv/h, mSv/h or µSv/h (LexisNexis, 2026).

The unshielded dose rate at 1m is shown. In this scenario, it is treated as a point source, meaning the radiation is all exiting the source from a single point, equally in all directions.

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

Equation 2 - Dose Rate Equation

Where:

D= Dose Rate

τ = Gamma Constant

A= Activity Source

R= Distance from source

4.55TBq = 4550 GBq

Gamma constant = 0.13 mSv/h (Massoud, 2013)

Distance from source = 1 metre

$$D = \frac{0.13 \times 4550}{1^2}$$

= 591.5 mSvh per hour

Because this is treated as a point source, the answer is reliable given the small size of the Ir-192 pellet and the 1 m distance from the source. However, the brief notes that during operations the source was contained in a shielded exposure device, as well as the use of a projection sheath and guide tube. These mitigations could reduce or alter the radiation reaching the worker, and the calculated value is therefore a worst-case at 1m.

4.2 Initial Recovery Dose Rate

There were two key stages of interaction during this event: the initial recovery phase and the hands-on intervention phase. During the initial recovery phase, the radiographer remained approximately 0.8m from the source. The radiation field at the torso is estimated to have corresponded to approximately 20–30% of the nominal unshielded field at that distance.

To estimate the dose rate during this phase, the nominal unshielded dose rate was first calculated at 0.8m using the previously calculated activity and gamma constant.

Distance to source at initial recovery = 0.8m

$$D = \frac{0.13 \times 4550}{0.8^2}$$
$$= 924.2 \text{ mSv/h}$$

As the brief states that the torso received approximately 20-30% of the nominal unshielded field, the estimated dose rate during the initial recovery phase is between the two calculated values:

$$924.2 \text{ mSv/h} \times 0.2 = 184.8 \text{ mSv/h}$$

$$924.2 \text{ mSv/h} \times 0.3 = 277.3 \text{ mSv/h}$$

4.3 Hands-On Intervention Dose Rate

Following the initial recovery attempt, the radiographer moved closer to the source to investigate the crank housing and guide tube connection. During this assessment, the radiographer was approximately 0.5m away from the source. At

this closer distance, the shielding provided by the exposure device was less effective, and there was less obstruction between the radiographer and the source. The radiation field at the torso was therefore estimated to be 40-60% of the nominal unshielded field.

To estimate the dose rate during this phase, the nominal unshielded dose rate was calculated at 0.5m using activity and the gamma constant for Ir-192.

Distance to source at hands-on intervention = 0.5m

$$D = \frac{0.13 \times 4550}{0.5^2}$$

= 2366 mSv/h

The increased radiation field at the torso to 40-60% due to the closer distance shows the worker was exposed to the following dose rates:

2366 x 0.40 = 946.4 mSv/h

2366 x 0.60 = 1419.6 mSv/h

The results from these calculations demonstrate the inverse square law, where the dose rate increases as the distance from the source decreases (Ionactive, 2024). This occurs as the radiation emitted spreads over an increasingly larger area as it travels from the source until it interacts with the worker. The estimated dose rate increased from 591.5 mSv/h at 1m, to 924.2mSv/h at 0.8 to finally reaching 2366mSv/h at 0.5m. This demonstrates the importance of safe distances when working with radioactive materials and that distances can dictate greater exposure than time spent near a source.

In addition to closing the distance to the source, the worker became less shielded as they progressed closer to the source, increasing the unshielded field to the worker's torso. As a result of this, the dose rate significantly increased from the initial recovery to the hands-on phase, demonstrating that both distance and shielding are essential to keeping workers safe and risk As Low As Reasonably Practicable (ALARP) in line with IRR 2017 (UK Statutory Instrument, 2017).

5 Effective Dose

5.1 Initial Recovery Effective Dose

During the initial recovery phase, the radiographer remained approximately 0.8m from the effective source for 60-90 seconds. As shown above, the estimated dose rate to the torso was between 185 - 277mSv/h. To calculate the effective dose received during the radiographer's interaction, the exposure time must be converted from seconds into hours, as the dose rate is expressed in mSv/h.

Exposure time = 60 - 90 seconds (divide by 3600 to get into hours)

= 0.0167 – 0.025 hrs

$185 \times 0.0167 = 3.08 \text{ mSv}$

$277 \times 0.025 = 6.93 \text{ mSv}$

Overall exposure to the radiographer during initial recovery is 3.1 – 6.9 mSv/h.

5.2 Hands-On Intervention Effective Dose

During the hands-on intervention phase, the radiographer crouched and handled the crank housing and guide tube connection for approximately 10–15 seconds. At this stage, the dose rate increased due to the inverse square law and reduced shielding, giving a dose rate of 946-1420 mSv/h.

Exposure time = 10-15 seconds (divide by 3600 to get into hours)

= 0.00278 – 0.00417 hrs

$946 \times 0.00278 = 2.63 \text{ mSv}$

$1420 \times 0.00417 = 5.92 \text{ mSv}$

Overall exposure to the radiographer during hands-on recovery is 2.6 – 5.9 mSv.

Therefore, the estimated total effective dose to the radiographer across both phases was approximately 5.7 – 12.8 mSv. The value is a broad range because both exposure events and the unshielded percentages were not exact and were estimates within the case study.

$$3.1 + 2.6 = 5.7\text{mSv (lower limit)}$$

$$6.9 + 5.9 = 12.8\text{mSv (upper limit)}$$

Unlike the dose rate, the effective dose rate received by the radiographer was higher during the initial recovery phase. This was primarily due to the longer exposure time to the source. Although the dose rate was lower at 0.8m, the fact that the radiographer stayed there for 60-90 seconds resulted in a greater overall effective dose compared to the shorter time at 0.5m.

5.3 Dose Rate Comparisons and Discrepancies

The estimated effective dose rate for the radiographer was calculated to be approximately 5.7- 12.9 mSv/h. This is reasonably accurate to the readings on both the EPD (8.6mSv) and the TLD (11.4 mSv). The difference is likely to be due to the estimated dose being calculated on approximate distances and exposure times, as well as shielding levels. Each of the dosimeters was located in different areas of the body, with the EPD on the chest and the TLD on the waist. As the radiation field varied depending on the position of the radiographer, and they changed position throughout the exposure during the incident, the two dosimeters would have been exposed to different levels of radiation, providing conflicting results.

Additionally, the dosimeters used in this case serve different roles. The EPD provides real-time dose and dose rate measurements and can alert the user with an alarm when a specified level has been reached (Gamma Data, n.d.). The TLD, on the other hand, does not display the dose values in real time. It uses a crystalline material within the reader to trap and store the radiation, which is then

sent to a lab for further analysis to understand the exposure levels (Passmore, 2026).

6 Health Implications

6.1 Short-Term Effects

Short-term effects detailed in the report are that the radiographer felt faint and nauseous. These are signs of acute radiation syndrome, which generally requires a whole-body dose of at least 700 mSv in a short space of time. In this case, the highest level recorded by the dosimeters was 11.4mSv, very far away from the required 700mSv (Mallika Singh, 2024). These effects on the radiographer are likely psychological impacts of experiencing a high-stress event, where they may feel a level of uncertainty about the impacts it may have on their life, such as cancer, leading to an influx of anxiety and feeling unwell (OSHA, n.d.).

6.2 Long-Term Effects

The main long term effect of radiation exposure is the increased likelihood of cancer. This is known as a stochastic effect, where the likelihood of developing cancer increases with the increase in radiation dose. ICRP 103 provides the cancer detriment for both workers in this field and the whole population. The cancer detriment is calculated through the following equation: Fatal cancer + loss of life weighting factor for non-fatal cancers. ICRP 103 states the detriment-adjusted nominal risk coefficient for cancer in adult workers is 4.1% per Sv (ICRP, 2007). The increased likelihood of cancer in this incident using the highest dose level measured is shown below:

$$11.4 \times 3 \times 10^{-3} \times 4.1 = 0.047\%$$

However, this is an estimate based on the entire population, and other factors such as age, weight and other factors can alter results slightly.

7 Ionising Radiation Regulations 2017 Compliance

The brief indicates that although several controls suggested within the Ionising Radiation Regulations 2017 (IRR 17) were in place during the event, the overall process did not adequately prevent radiation exposure so far as reasonably practicable, as required, as stated in Part 1 Section 9 (UK Statutory Instrument, 2017). The regulation states that employers must complete risk assessments, restrict exposure, maintain equipment, and rehearse contingency plans should an incident occur.

The report states that the source was shielded by an exposure device which was remotely operated, as well as sheathing to restrict exposure to the workers further. Additionally, personnel were instructed to wear an EPD and TLD to understand the dose rates they were exposed to, as well as alerting them when they had reached the maximum exposure limit through the EPD. Although IRR17 does not specify the requirement for a dosimeter, they are a very effective way to understand the current exposure levels to the staff and help reduce the risk of high exposure levels through the active monitoring and alerting system found in an EPD.

However, significant failures in compliance with IRR17 are visible throughout. Firstly, stiffness within the source retraction had been reported in the months before the incident, whilst the guide tube was routed in an unusual route, creating tighter bends than appropriate. This implies that appropriate risk assessments had not been carried out where required, and as required in Part 1, Section 11 of IRR17, it suggests that they failed to comply with “where appropriate, that thorough examinations and tests of such controls, features or devices are carried out at suitable intervals.”

The event also appears to be non-compliance with Part 1, Section 13, which states that contingency plans are required where a radiation accident is likely to occur. The brief states that the radiographer approached the source and corrected the fault before the position of the source had been confirmed. HSE specifically states in their guidance that a contingency plan is required if a radiography source becomes stuck in order to reduce risk to the staff (Health and Safety Executive, 2026).

Overall, it is appropriate to say there are major non-compliances with IRR17 which could have significantly reduced the exposure to the staff. The poor maintenance schedules also played a critical role in allowing the scenario to occur.

8 Office of Nuclear Regulation Safety Assessment Principles

8.1 EKP.3 Defence in Depth

EKP.3 requires nuclear facilities to have multiple layers of safety to prevent faults and failures. If prevention fails, EKP.3 aims to ensure detection, limit potential consequences and stop escalation (Office for Nuclear Regulation, n.d.).

In this scenario, the system had several barriers related to the shielded container, remote operation, and radiation detectors on the workers. However, these barriers were not sufficiently independent. Once the source failed to retract, the operator assumed it had functioned as required and approached the source, effectively defeating the procedural barrier and exposing themselves to increased doses of radiation. The incident demonstrates poor defence-in-depth because a single mechanical failure, in addition to human error, was sufficient to bypass the whole Swiss cheese model of defence.

Level	Objective	Defence/Barrier
Level 1	Prevention of abnormal operation and failures by design	Conservative design, construction, maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels
Level 2	Prevention and control of abnormal operation and detection of failures	Control, indication, alarm systems or other systems and operating procedures to prevent or minimise damage from failures
Level 3	Control of faults within the design basis to protect against escalation to an accident	Engineered safety features, multiple barriers and accident or fault control procedures
Level 4	Control of severe plant conditions in which the design basis may be exceeded, including protecting against further fault escalation and mitigation of the consequences of severe accidents	Additional measures and procedures to protect against or mitigate fault progression and for accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive material	Emergency control and on- and off-site emergency response

Figure 1 - Defence in Depth Level

Using Figure 1, the ONR states that there are 5 levels to demonstrate effective compliance with EPK.3. This scenario failed at only level 2 due to the fact that they were unable to detect any failure until it was too late and the workers had become exposed.

8.2 EDR .1 Failure to Safety

EDR.1 requires a nuclear facility to ensure equipment is inherently safe or fail safely, with unsafe failure modes identified. In this incident, the source retraction equipment failed in an unsafe manner. The machinery was not designed to alert staff to a failure, and therefore no automatic response was in place to warn staff of the hazard and prevent them from approaching the source. This demonstrates very poor compliance with EDR.1 (Office for Nuclear Regulation, n.d.).

8.3 EMT.2 Maintenance, Inspection and Testing

EMT.2 requires structures, systems and components to receive regular and systematic examination, inspection, maintenance and testing as defined in the safety case.

Although access is not provided to the safety case, it is known that recent performance issues, such as stiffness, had been reported, but no action was taken. This is in clear violation of EMT.2, as required maintenance has not been completed and staff were aware of the issues. This poses a massive threat and is likely the first failure of the scenario, and should the repairs be made, the incident could have been prevented entirely (Office for Nuclear Regulation, n.d.).

9 Suggested Improvements to Achieve ALARP

Firstly, clear contingency plans should be implemented in line with HSE guidance to ensure complete shutdown of operation and situational awareness of the hazard is maintained (Health and Safety Executive, 2026). The contingency plan should look to remove workers from the area, restrict access to only those needing to be there, and survey the incident from a safe location where the dose rate is as low as reasonably practicable. Assistance in the contingency plan can be provided by the Radiation Protection Adviser (RPA), whom the worker had contacted post-incident; it is required in IRR17 that all nuclear facilities should consult an RPA (UK Statutory Instrument, 2017). They can reconstruct scenarios and understand the risks involved, allowing detailed plans to be created from this.

Secondly, the remote drive, guide tube and associated machinery should undergo inspection, maintenance and testing routinely. Should equipment show any signs of stiffness or loss of performance, it should be removed immediately and not used again until further inspections have been completed. This is particularly important due to the ignored stiffness before the incident, leading to the failure of the task. This would also support EMT.2 as well as EPk.3, where it would help rise above level 2 and demonstrate greater robustness to failure (Office for Nuclear Regulation, n.d.).

Finally, although the failure was specified as due to equipment failure, human factors led to the exposure to the radiographer. There is mention of operating in a congested workspace, working late into the shift as well as poor set-up of equipment. All of these factors may have increased pressure on workers as well

as tiredness, leading to a lapse in judgment of the risks, especially in the case of the radiographer assuming the source had retracted. To reduce the effects of human factors, workers should receive appropriate training to treat any abnormal resistance in equipment as a potential radiation hazard and confirm the source has returned using a survey meter from the beginning. Regular emergency drills could help enforce the correct response. In addition to this, fatigue and shift management could be introduced to ensure staff remain fit and healthy for the entirety of their shift to reduce the risk of human-caused incidents.

Overall, these improvements help achieve ALARP risk as they directly address the causes of the incident and should be implemented to follow existing guidance as well as legislation such as that in IRR17. Although other improvements can be made, implementing the first two suggestions would help significantly reduce the likelihood of machine failure and potential consequences of a similar incident, in combination with a greater understanding of the effect of human factors to help reduce the likelihood of personnel causing the incidents.

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