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Radiation protection in industrial applications of radioactive sources. Prevention of accidents in gammagraphy.

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Abstract

The use of radioactive sources in industrial applications continues to spread around the world. One of the main uses is industrial radiography, or gammagraphy, and this use accounts for many of the higher occupational exposure profiles and the largest proportion of radiation accidents. The consequences of such accidents can be significant, even fatal, and can impact on both workers and the public. This presentation will review the main causes of accidents, illustrated by examples, and cover the key elements of radiological protection actions to prevent accidents. It will look at the need for regulatory controls and their application, actions necessary by the employing organisations and those contracting radiography on their sites, the training of those involved, source security, the use of appropriate equipment and operational procedures..

1 Introduction

Although other Non-Destructive Technologies (NDT) are increasing in use, industrial radiography remains a wide spread and necessary use in the quality assurance of welds and structures. Industrial radiography encompasses X-radiography and gamma radiography (often referred to as gammagraphy). This paper will focus on gammagraphy but will also cover X-radiography as there is some similarity of issues.

Industrial radiography has shown itself to be prone to accidents and features prominently in the list of "Accidents with clinical consequences to occupationally exposed workers" (Table 40) in Annex E to the UNSCEAR 2000 report [1]. Also in the case of gammagraphy there have been cases where control of the radioactive sources has been lost and they have entered the public domain, sometimes with fatal consequences. This paper reviews the causes of accidents in this sector, their potential consequences and the safety and security arrangements necessary to prevent accidents and to keep doses to persons As Low As Reasonably Achievable (ALARA). It also look at the roles of those involved including regulators, clients, radiation protection experts, management and the radiographers themselves.

2 Types of Radiography and Equipment

This section reviews the different types of radiography and equipment; identifying some of the key safety requirements, and some of the common failures leading to accidents. This description is not exhaustive and more detail is given in guidance documents referenced in section 8.

2.1 Types of radiography

Industrial radiography falls into two broad types: enclosure and mobile radiography.

2.1.1 Enclosure radiography:

Here the radiography is carried out within a purpose built shielded enclosure that will have installed safety systems such as warning lights to warn persons of an exposure in progress or that an exposure is imminent; and door interlocks to prevent access during an exposure. For all X-radiography these systems should operate automatically. This is also possible for many gammagraphy situations but not all.

Enclosure radiography is inherently safer than mobile radiography, and should be used wherever reasonably practicable. However there is still the potential for failure of the radiography equipment and installed safety systems, which together with poor operating procedures can lead to accidents. Routine maintenance and testing of the installed safety systems is important. However a number of accidents have occurred during maintenance and immediately afterwards because those involved have not fully understood the procedures to be followed and that testing of the safety systems needs to be undertaken after maintenance.

Some designs of enclosure have open tops to allow easy movement by crane of heavy items to be radiographed. In such cases consideration has to be given to how to prevent the radiation beam clearing the top of the walls and exposing persons high up, such as crane drivers. Consideration also has to be given to "skyshine", radiation that has been multiply scattered up over the walls and back down to the occupied areas outside the enclosure. Minimising the size of the useful beam helps minimising exposure to persons.

2.1.2 Mobile radiography

Here the radiography equipment is taken to the item to be radiographed and this work is done within an area defined by temporary barriers. Portable warning and safety systems are used. The radiography may be carried out in places with poor egress or at heights with multiple access points that are difficult to control. The nature of these problem should be assessed before the work starts and solutions agreed with the site owners so that they can ensure cooperation to prevent their staff and those from other contractors on site interfering with the radiography or putting themselves at risk.

Mobile radiography is inherently more hazardous in that it relies heavily on procedures and cooperation with others on the site. The work is often undertaken in poor working conditions with other hazards around, possibly in inclement weather and often away from any supervision.

The profiles of dose rates around a radiographic examination are a function of a number of parameters. From a radiation protection perspective it is important that the source activities used are minimised to be consistent with the radiographic technique requirements and wherever possible collimation is used to limit the radiation beam dimensions to the minimum required.

2.2 Types of equipment

There is a range of radiography equipment that can be used in both types of radiography environments; including

2.2.1 X-ray equipment

Typically the X-ray equipment used in industrial radiography is in the range 100 to 300 kv and 3 to 15 mA; with radiation outputs of 30 to 300 mGy per minute at 1m.

These dose rates are significantly higher than from normal gammagraphy and exposure to the useful beam can result in clinical effects in a short period of time. However the collimation inherent in the design of X-ray sets and the likely movement of persons relative to the beam often serve to limit the effects of accidents. Nevertheless the dose rates in the useful beams necessitate the use of automatically operated safety and warning systems. In enclosure radiography these should be an integral part of the design of the enclosure. Also it is necessary inside the enclosure to have emergency stop buttons or emergency pull cords for use by anyone trapped inside. These should be strategically located so that anyone inside should not have to traverse a useful beam to use them or exit. Often legislation also includes a "search and lock up" requirement.

Many accidents occur because of poor design and maintenance of the safety systems coupled with lack of awareness and the use of poor operating procedures

2.2.2 Higher energy X-ray sets or linear accelerators

Typically these can be up to 8Mev. These are not common and are mainly used for specialised purposes in shielded enclosures but there are some that can be transported to locations and used as for mobile radiography. These units often have similarities to Radiotherapy units and can have outputs of the order of 4 Gy per minute at 1m.

These units can produce a fatal exposure in a relatively short period of time and it is essential that they have high quality safety and warning systems, and enclosures are well designed and adequately shielded. A higher degree of knowledge and experience is necessary for operators and for those carrying out regulatory inspections.

2.2.3 Gammagraphy or radiography source containers

The principal radionuclides used are shown in Table 1: the commonest being ^{192}Ir. There is an increasing use of ^{169}Yb and ^{75}Se, particularly the latter as its high specific activity allows physically smaller sources and smaller source to film distances. From a radiation protection perspective this results in smaller exclusion zones that are easier to manage: which is particularly important on congested sites, such as oilrigs. The shielding requirements for Cobalt-60 are such that containers are often not readily portable and the radionuclide is primarily used in shielded enclosures

Radionuclide	Energy (MeV)	Source output at 1m ($mGyh^{-1}$ per 37 GBq)	Half Life	Typical use for steel of thickness (mm)
Cobalt-60	1.17 and 1.33	13.0	5.3 y	50–120
Ir-192	0.2–1.4	4.8	74 d	10–70
Se-75	0.12–0.97	2.03	120 d	4–28
Yb-169	0.008–0.31	1.25	32 d	2.5–15

Table 1: Characteristics of principal radionuclides used in gammagraphy

There are a variety of source container designs that broadly fall into 3 categories:

2.2.3.1 *Shutter-type containers*

These consist of a block of shielding material at the centre of which the source is located. A portion of the shielding can be removed or rotated to expose the source, thus acting as a shutter. Due to the weight of shielding, this type is only practicable for use on site with relatively low energy or low activity sources.

The solid angle of the useful beam is not usually more than 60 degrees. Therefore this type of container offers a convenient method of limiting the useful beam. However, additional collimation may still be required to limit the useful beam to the minimum size necessary for radiography.

Accidents have occurred when the shutter mechanism has not been fully locked in the closed condition and with movement, such as during transportation, it has rotated into the open position. In one case this occurred whilst the container was on the passenger seat of a van with the beam port facing the driver.

2.2.3.2 *Manual extraction or torch type containers*

These consist of a source within a cylindrical shield (about the size of a torch) below a detachable handle. In the safe position the torch is located within a further shielding container with a bayonet fitting. The source normally resides a few millimetres back from the open end of the cylindrical shield, so that once the torch is removed from the shielding container, a narrow beam of radiation is produced. To carry out a radiograph a locating device, which provides a small degree of extra shielding and collimation, is fixed to the item to be radiographed and the torch is placed in its bayonet fitting. This action pushes back the spring loaded cylindrical shielding to produce a wide angel beam. In theory the radiographer then retires to a safe distance until it is time to end the radiograph.

Because of the necessary proximity of the radiographer, the use of this type of container often results in high cumulative doses to the radiographer. To speed up the rate of radiography (and often increase income) it has been known for radiographers to dispense with the use of the locating device and hold the torch in place with the cylindrical shield held or wedged back. There have been several instances of radiographers having radiation burns to their finger tips from acute and chronic exposure.

The use of Torch containers is now significantly reduced and is prohibited in some countries.

2.2.3.3 *Projection-type (or remote exposure) containers*

These typically consist of an outer steel case containing a depleted uranium shield in which there is an S shaped internal tube. In the shielded position the source capsule sits in the centre of the S shaped tube, so there is no direct beam of radiation. At one end of the tube is a locking mechanism to keep the source in its safe position; and at the other end a shielded transport plug can be put in place. The source pellet is typically 3.0 mm by 2.5 mm and is double encapsulated. This capsule is physically attached to a flexible cable about 15 cm long, often known as a 'source pigtail' or source assembly. This is designed to be coupled, typically with a spring assisted ball and socket joint, to a flexible drive cable with a crank handle that allows the operator to be at a safe distance when exposing the source. In use, a guide tube is attached to the front of the container and the source pigtail is pushed down it to the required position by winding out the drive cable.

Poor maintenance, incorrect coupling, obstructions in the guide tube or kinking it can all lead to extreme pressures being placed on the various linkages and eventually to the source becoming decoupled from the drive cable. This poses an immediate threat to the radiographer who must monitor after every exposure to ensure the source has fully returned to the safe shielded position. Failure to do so has lead to serious exposure of the radiographer and the source dropping out of the equipment unnoticed. To other workers and members of the public who find such radiography sources, they look like intriguing items and can easily be picked up and carried back to the family home; often with lethal effects as described in section 3.3.

In recent years significant improvements have been made to the design and tolerances of locking mechanisms to ensure that the sources assembly must be correctly connected to the drive cable before it can be projected into an exposure position. However the nature of mobile radiography inevitably means that the equipment is subjected to rough handling, making it extremely important that maintenance procedures are correctly followed. Disconnection of part of the source assembly still remains a major cause of accidents.

2.2.3.4 *Pipe crawler equipment*

These are a subset of mobile radiography. They are used to radiograph welds on pipelines. The machines carry either an X ray tube assembly or a gamma source on a mobile carriage which crawls along the inside the pipe. They are powered either by batteries on the carriage, an internal combustion engine or trailing cables from a generator. The crawler is activated and controlled by the radiographer from outside the pipe by using a control source which normally consists of a low activity caesium-137 sealed source mounted in a hand-held device and collimated. Radiation from the control source is received by a detector on the crawler. Typically, the control source is moved along the outside of the pipe to initiate the crawler to move in the desired forward or reverse direction. The control source is held against the outside of the pipe to make the crawler stop and wait, and an exposure begins automatically about 10 s after the control source is removed from the pipe's surface. Some X ray crawlers are fitted with a low activity 'tell-tale' radioactive source to help to identify the crawler's position in the pipeline. The radiography source does not leave the device during the exposure. Most are designed to "fail-to-safe" such that if power is lost, the source is automatically shielded. However, their safe use is strongly dependant on procedural controls and accidents have happened.

3 Accidents and their Causes

The previous section gave an insight into some of the design and operating features that need to be considered in the prevention of accidents and in keeping exposure from normal operations ALARA. However there are many other factors that can initiate or contribute to an accident or chronic exposure. This section reviews the more common causes of loss of control and inappropriate use of radiography sources.

3.1 Monitoring is Key

Whilst the main focus is on maintaining appropriate controls and prevention of accidents, the potential for incidents has to be addressed. A key element here is the ability of the radiographers to recognise an abnormal situation. This requires appropriate training, operating procedures and monitoring equipment.

APPROPRIATE MONITORING WITH A DOSE RATE METER IS ESSENTIAL

This has been emphasised because it is *the* most important action that will allow the radiographer to recognise an abnormal situation and prevent further uncontrolled exposure. The use of personal alarm dosimeters is strongly advocated, but they should be regarded as an adjunct or back-up for a dose rate meter, which should be the primary means of confirming that a source has fully returned to the safe position. It should be used after every exposure and taken to the front end of the container to check that the source is fully retracted into the safe position. Watching the doserate meter at the winding point, and seeing a reduction in doserate is not good enough. The source could have become decoupled close to the front of the container, such that the container was shielding the doserate meter from direct radiation. (see example in Appendix)

Essentially appropriate monitroing can make the difference between early recognition of a source decoupling (or other abnormality), that the radiographer can deal with using standard emergency procedures, and loss of control of the source into the public domain and potential fatalities.

3.2 Common causes of accidents

The causes for the loss of control of a source are many and varied. It may be due to a single catastrophic failure or more commonly a combination of events. Table 2 provides a list of some of the more common causes [2]. Here 'loss of control of a source' is taken to include failure of safety systems to control exposures, as well as the physical loss of a radioactive source.

Table 2. Common causes of loss of control of radioactive sources

Root causes

- Lack of, or ineffective
  - regulatory bodies
  - regulations
  - regulatory enforcement
- Lack of
  - national radiation protection services
  - awareness or training of management and workers
  - commitment by management to safety
  - an effective radiological protection programme in the organization

Specific causes

- Lack of, or inadequate
  - prior risk assessment
  - security during storage, transport and use
  - radiation surveys, e.g. failure to monitor after a γ-radiography exposure
  - supervision
  - emergency preparedness plans
- Design or manufacturing fault
- Inappropriate maintenance procedures
- Human error
- Deliberate avoidance of regulatory requirements
- Abandonment
- Catastrophic event, e.g. fire, explosion, flood
- Theft
- Malicious act
- Loss of corporate knowledge, due to:
  - loss or transfer of key personnel
  - bankruptcy
  - long term storage of sources
  - decommissioning of plant and facilities
- Death of owner
- Inhibitions to legal disposal, such as:
  - no disposal route available
  - export not possible
  - high costs of disposal

An effective regulatory infrastructure will incorporate measures to eliminate or minimize the above problems However even mature regulatory infrastructures cannot completely eliminate the threats. It also requires all the other "players" to do their part (see section 5).Periodically the effectiveness of the arrangements needs to be reviewed in the light of accidents and incidents that have occurred or might occur. One aspect of this might be to look at the possible threats through the life patterns of use of sources. Figure 2 provides a schematic representation of one such approach. In Section 3 examples are given of incidents and accidents that have arisen from some of the listed shortcomings.

One of the causes of accidents that deserves some explanation is "loss of corporate knowledge". Many industrial radiography companies are relatively small and it is not uncommon for them to go into bankruptcy. In some cases this has resulted in nobody with appropriate knowledge being left to take responsibility for the radiography sources. This can result in the sources ending up in the metals recycling industry or being left in a derelict building open to the public.

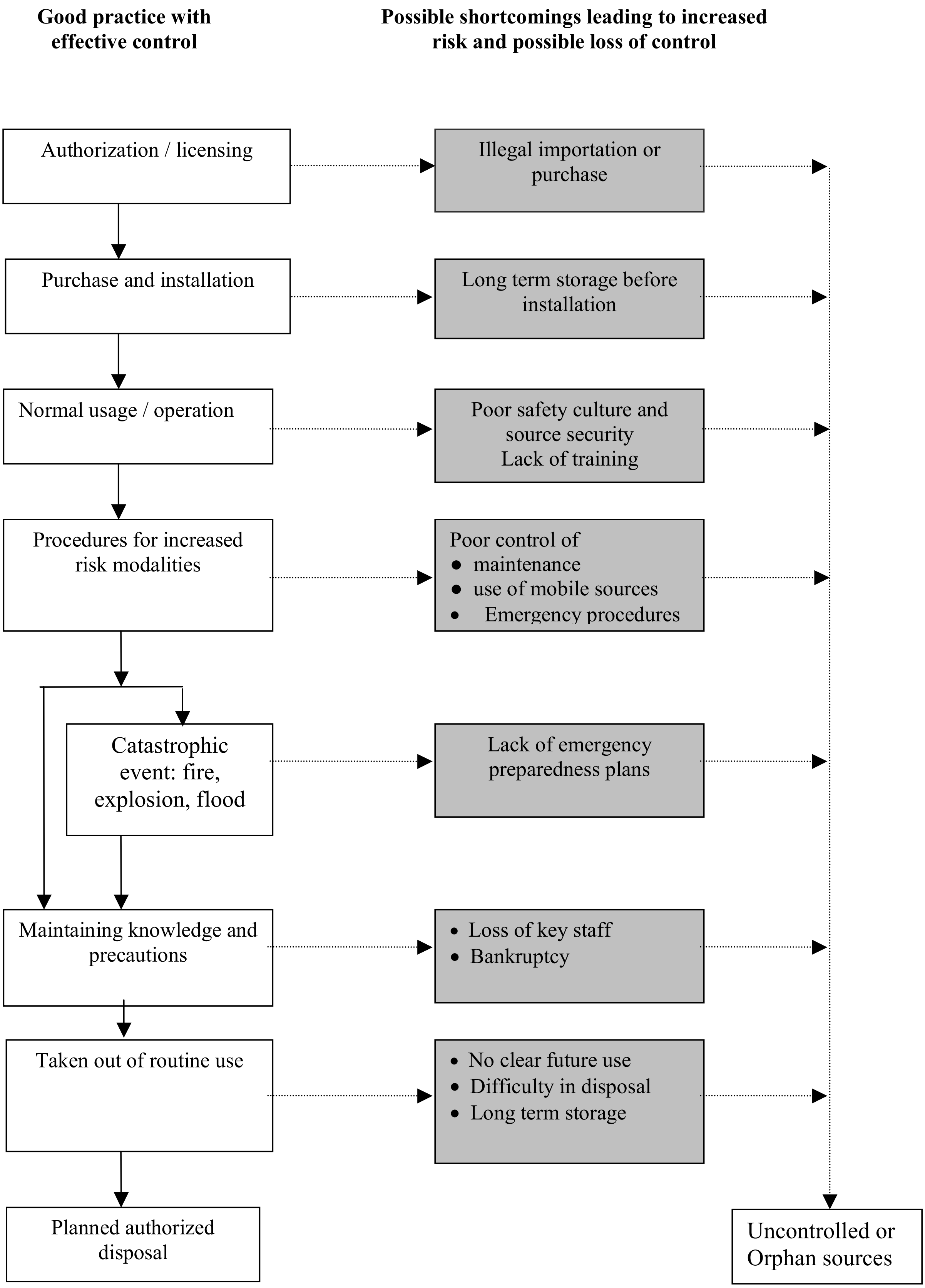

Fig 1 Challenges to good practice

3.3 Examples of consequences of serious radiography accidents

Mexico, 1962

Between March and September 1962, an engineer left a 200 GBq ^{60}Co source unprotected in the yard at a house in Mexico City. The source was found by a boy and subsequently taken to his home where it remained for approximately 4 months. The boy and his sister died following estimated protracted whole body doses of 47 and 28.7 Gy respectively. The children's mother and grandmother also died following doses estimated at 35 and 30 Gy respectively. The children's father survived, although he became permanently sterile, following an estimated protracted dose of 120 Gy [3].

Algeria, 1978

In May 1978, a 925 GBq ^{192}Ir source used for industrial radiography fell from a truck travelling on the road from Algiers to Setif. Two young boys found the source a few days later. Both boys handled the source and it was eventually placed in their home. It remained there for 5–6 weeks exposing the family to radiation under various conditions depending on the location and time spent in the kitchen. The two boys developed serious skin lesions; their 47 year-old grandmother and four females aged 14, 17, 19, and 20 years old, who spent most of their time in the house, were exposed to varying doses. The grandmother died in late June 1978. The foetus of the pregnant 20-year-old female also died during the haematological recovery period of the mother; and both boys required surgery for their skin injuries [4].

Morocco, 1984

In this serious accident, eight members of the public died from overexposure to radiation from a radiography source. A 0.6 TBq ^{192}Ir source became disconnected from its drive cable and was not properly returned to its shielded container. Later the guide tube was disconnected from the exposure device and the source eventually dropped to the ground, where a passer-by picked up the tiny metal cylinder and took it home, putting it on a shelf near his bed. The source was lost from March to June, and a total of 8 persons (the passer-by, members of his family and some relatives) died. It was initially assumed that the deaths were the result of poisoning. Only after the last family member had died was it suspected that the deaths might have been caused by radiation. The source was recovered in June 1984 [5].

Iran, 1996

In July 1996 industrial radiography was underway at the Gilan Combined Cycle Fossil Fuel Power Plant located 600 km north of Tehran. After making a series of radiographs, the radiography team did not notice that the 185 GBq ^{192}Ir source was missing from the container. A 33-year-old plant employee found the source, handled it and then placed the source into his shirt pocket for about 90 minutes. He demonstrated haematological depression and also developed lesions to the right thorax, right elbow, right thigh, and left palmar surface. His chest and thigh lesions were successfully treated and about 16 months after exposure, the skin lesions healed. The estimated whole body dose was 2–4 Gy, while the maximum skin doses did not exceed about 40 Gy [6].

Peru, 1999

In this accident gamma radiography using a 1.37 TBq ^{192}Ir source in a remote exposure container, was being carried out at the Yanango hydroelectric power plant. At some stage the 'source pigtail' became detached from its drive cable. A welder picked up the source, placed it in his right back pocket of his trousers and took it home, riding in a minibus. He changed his clothing, placing his trousers (with the source still in them) on the floor, and sought medical assistance related to pain in his right thigh. This was diagnosed as an insect bite. Meanwhile his wife had sat on the trousers while breastfeeding her 18 month old son. The loss of the source was noticed the same day and it was recovered within 24 hours.

However the dose received in this period was such that despite heroic medical treatment the welder lost one leg and had other major radiation burns. His wife and children were also exposed, but to a lesser extent [7].

Cairo, Egypt, 2000

This was a very similar incident to the one above. It involved a 1.2 TBq ^{192}Ir source that had been lost by a worker testing pipe welds. In May 2000 a farmer from a small village found the source and took it home; where he lived with a wife, sister, and four children. In the following weeks the source was handled by family members and moved to various locations within the family home. The 9-year-old son died in June, and death was reported to be due to marrow failure and inflammation, caused by a viral or bacterial infection. Other family members were also found to be sick with skin lesions, bone marrow failure and gastrointestinal symptoms, but the diagnosis again was incorrect. On 16 June the farmer died. On 25 June, a fact-finding mission detected high radiation levels at the family home and the source was recovered. Dose estimates were: father, 7.5–8 Gy; 9-year-old son, 5–6 Gy; five other family members, 3.5–4 Gy. Between 200 and 300 neighbours and relatives were monitored, and the affected family received continuing treatment/surveillance [8,9].

Bolivia, 2002

This accident involved a 0.67 TBq ^{192}Ir source in a remote exposure container being used for radiography of a pipeline in a trench. After the last radiograph the radiographer retracted the source and tried to disconnect the drive cable. However he could not turn the locking ring on the mechanical interlock that was necessary to be able to disconnect the drive cable. Because of the dirty environment in which he had been working he thought some dirt had entered the mechanism. However he had not used a dose rate meter to check the position of the source. It had in fact either become disconnected or never been connected properly. At this point the source was lying somewhere in the guide tube. He consulted his company's offices in La Paz. As a result he packaged up the container, guide tube and drive mechanism and arranged for them to be sent on a bus to La Paz (an 8 hour journey). The bus had 55 passengers, who were all exposed to some degree to the source in the luggage compartment below them.

Following the collection of the equipment from the bus station the next day, the fact that the source was exposed was discovered. However there were delays in reporting the incident to the authorities and in the emergence of the full details. Initial assessments suggested the potential for clinical effects. The Bolivian Authorities requested the IAEA to undertake an investigation and help with clinical follow up of the bus passenger (not all of whom could be traced). Fortunately a reconstruction of the incident was able to show that the maximum passenger dose was likely to have been about 0.19 Gy and chromosome aberration analysis tests on blood from the workers involved indicated that none were likely to have exceeded 0.2 Gy. [10]

4 Learning Lessons from Accidents

The Iranian, Bolivian and Peruvian accidents summarised above were all the subject of IAEA investigations and full reports were published [6,7,10]. In addition IAEA has published a Safety Series Report "Lessons Learned from Accidents in Industrial Radiography" [11]. These and other IAEA reports of accident investigations have contributed significantly to the process of learning from accidents. By their very nature they have concentrated on the more important accidents that need to be reported in depth, often having many facets such as regulatory control, system failures, emergency response and medical treatment of the radiation casualties. However it is not only the big accidents from which we can learn, we can also learn from the smaller accidents and near misses. This feedback is relevant to suppliers in improving the safety aspects of design, the management in developing radiation protection measures and the training of their staff, and to national and international authorities in helping them prioritise issues and resources to deal with them. Some examples of feedback mechanisms are given in the following subsections.

4.1 IRID

In 1996 in the UK, the then National Radiological Protection Board (NRPB – now part of the Health Protection Agency, HPA), the Health and Safety Executive (HSE) and the Environment Agency (EA) jointly established the Ionising Radiations Incident Database (IRID) and published its specifications [12].

The database has 23 alphanumeric fields which categorise the incidents and allow navigation through the database. However the 24th field is the most important field, being a text description of the incident, the causes, the consequences and the lessons to be learned. The description is anonymous and is designed to be used as training material. Some of the more interesting cases are reproduced in the appendix to this paper. In 1999 a first review of the first 100 cases reported was published [13] and it is accessible on the web, at
www.irid.org.uk

4.2 RELIR

The Qualified Expert Group of the French Radiological Protection Society has created an arrangement known as Retours d'Experience sur Les Incidents Radiologiques (RELIR) or in English, Feedback Experience on Radiological Accidents. This has now been undertaken in collaboration with CEPN and the case reports can be found on their website.
http://relir.cepn.asso.fr/

4.3 EAN

In 1996 the Eurpoean ALARA Network (EAN) was jointly established by CEPN and NRPB (now the Radiation Protection Division of HPA) with initial finanacial support from the European Commission. EAN's objectives are

- To promote the wider and more uniform use of optimisation techniques in the various fields of occupational application in Europe
- To provide a focus and a mechanism for the exchange and dissemination of information from practical experience
- To propose topical issues of interest that should be subject of European meetings, workshops or research projects.

EAN produces a twice yearly Newsletter in which it includes Lessons learned articles: these are accessible at http://www.eu-alara.net/index.php In addition EAN holds Annual Workshops on a range of topics: in particular "Industrial Radiography: Improvements in Radiation Protection", Rome, Italy, October 2001", the proceedings of which can be found on the above website. One of the recommendations from this Workshop was the establishment of an NDT ALARA Network to facilitate the promotion of the ALARA principle in industrial radiography. That network will especially give the opportunity to members of the European Federation for Non-Destructive Testing and EAN to work together.

4.4 RADEV and RAIS

IAEA originally designed RADEV (Radiation Event database) to be an international database similar in concept to IRID. However it has evolved to be a module within the Regulatory Authority Information System (RAIS) available from IAEA[14]. RAIS is targeted at developing countries and is a database created by the IAEA to help regulators track every parameter associated with their activities. RAIS combines the strengths of an extensive inventory and a detailed record of national expertise. It stores information on every radiation source and the facility in which it is used, including records of licenses and registration. It also provides a means of collecting accident data that can be used as feedback to radiation protection programmes.

5 Prevention of Orphan Sources

An Orphan Sources is defined as a radioactive source which is not under regulatory control, either because it never has been under regulatory control, or because it has been abandoned, lost, misplaced, stolen or transferred without proper authorisation [15]. The international community had collectively recognised the lessons from many incidents resulting in orphan sources, and with the additional threat of such sources being used in terrorist acts, identified that improvements needed to be made. IAEA took the lead in developing and getting international agreement on a Categorization of Radioactive Sources [16] ranking by category the threat from different types of use); and a Code of Conduct on the Safety and Security of Radioactive Sources [15].

Industrial radiography gamma sources are considered to be Category 2 sources according to the IAEA Categorization of Radioactive Sources. The Code of Conduct sets out guidance on the safety and security for such sources. Whilst the Code of Conduct is not legally binding on Member States, many have given an undertaking that they will implement its provisions. Examples of this for the US, EU and UK can be found in references [17,18 and 19] respectively. The overall requirement is that operating organisations (the radiography company) should ensure that gamma radiography sources are kept under proper control from when they are first acquired until when they are finally returned to the supplier or dealt with in another safe manner at the end of their working life. In general this requires that

- Sources shall be kept secure so as to prevent theft or damage
- Control of a source not be relinquished without compliance with all relevant requirements specified in the registration or licence and without immediate communication to the regulatory body, and when applicable to the relevant Sponsoring Organization, of information regarding any decontrolled, lost, stolen or missing source;
- a source not be transferred unless the receiver possesses a valid authorization; and
- a periodic inventory of movable sources be conducted at appropriate intervals to confirm that they are in their assigned locations and are secure.

Operating organisations therefore need to ensure that they obtain radioactive sources only from authorized suppliers, and that disused sources are returned to the original supplier or other authorised party. The import and export of radioactive sources should be consistent with the recommendations in the Code of Conduct [15] and its supplementary guidance on import/export controls [20].

6 Roles of the different "Players"

The overall responsibility for radiation safety lies with the operating organisation that is authorised to carry out industrial radiography. Specific duties and the day-to-day responsibilities for the safe operation of the equipment will, however, lie with a range of people including senior management, the radiation protection officer, industrial radiographers and assistants, qualified experts, and for site radiography - the client responsible for the premises where the site radiography is carried out. All have roles to play and must cooperate so that there is a clear understanding of their responsibilities. Also important is the regulatory framework within which they operate. It is not possible here to go into the detail of all the requirements and guidance: this information can be found in IAEA documents [21] and the websites of national regulatory authorities [22,23]. However a few generic points are made below and duties should be agreed to by all relevant parties and identified in writing.

6.1 Regulators

An effective regulatory infrastructure will incorporate measures to eliminate or minimise the above problems. However it has to be recognised that it is not just a case of having an appropriate set of regulations. The regulators have to have an appropriate knowledge and skills base (in short be trained) and need the support of a radiation protection infrastructure with a critical mass. By their regulatory enforcement programme, the regulators can set the tone of user compliance. Together with input from Qualified Experts (from the radiation protection infrastructure) this strongly influences the development of the safety culture amongst users. Safety culture is an intangible but readily recognisable characteristic that takes time to develop. The consequence is that although many countries are making significant steps forward to develop a regulatory infrastructure, the development of a safety culture will lag behind and threats to the safety and security of sources will remain an issue for some time to come.

6.2 Radiation Protection Qualified Experts

The operating organisation may consult with one or more qualified experts on matters relevant to radiation safety, such as the design of radiography facilities, radiation shielding calculations, testing and maintenance of radiation survey meters, etc. The responsibility for compliance with national regulations cannot be delegated to the qualified expert and must remain the responsibility of the operating organisation. Qualified experts do not have to be employees of the operating organisation - they may be appointed on a part-time basis or for specific projects. The primary requirement is that the qualified expert satisfies the appropriate national qualification or certification criteria.

Qualified Experts will often not be employees of the operating organisation, but be consultants dealing with a range of radiation users, seeing both developments in best practice and lessons from incidents. Also they are likely to have experience of interface with the regulators on the development of guidance and standards. With this broad network of experience, Qualified Experts are well placed to have a positive influence on how radiation protection is put into practice.

6.3 Management

The operating organisation, through its managers, is responsible for the establishment and implementation of technical and organizational measures needed to ensure protection and safety, and compliance with all relevant regulatory and legislative requirements. In some cases it may be appropriate to appoint other people from outside the organization to carry out tasks or actions related to those responsibilities, but the operating organisation retains the ultimate responsibility.

A senior manager should be nominated to have overall responsibility for overseeing radiation safety, and that industrial radiography is carried out in accordance with national regulations and authorisations. Responsibilities for radiation safety are required to be established, and they should be agreed to by all relevant parties, and written down. Managers should also ensure that procedures are in place to protect both workers the public, and to ensure that doses are kept as low as reasonably achievable (the ALARA principle). Appropriate training must be a key aspect of the management programme. All policies and procedures should be documented and be made available to all staff and the regulatory body as appropriate.

Managers are required to foster a safety culture within their organisation to encourage a questioning and learning attitude to protection and safety and to discourage complacency. A good safety culture is promoted by management arrangements and worker attitudes, which interact to foster a safe approach to the performance of the work. Safety culture is not confined to radiation protection; it should also pervade conventional safety. Operating organisations with good safety culture do not assign blame when incidents happen, they learn from their mistakes, they foster a questioning attitude and they seek continuous improvement in the safety of work processes.

The operating organisation should appoint at least one employee as a radiation protection officer (RPO) to oversee the day-to-day implementation of the radiation safety programme and to carry out duties required by the programme. Some countries have different titles for the “RPO” but the duties are similar and might include:

- Supervision of industrial radiography operations;
- Maintenance of source accountancy records;
- Inspection and maintenance of engineering controls, safety and warning features;
- Overseeing access controls to controlled areas;
- Establishment and periodic review arrangements for personal dosimetry;
- Supervision of workplace monitoring arrangements;
- Establishments and periodic review of local rules;
- Periodic reviews of training and refresher training requirements:
- Investigation of higher than normal exposures, and overexposures.

6.4 Radiographers

While the primary responsibility for radiation safety lies with the operating organisation, radiographers (including assistants and trainees) have a responsibility to work safely and take all reasonable actions to restrict their own exposure and those of other workers and members of the public.

Radiographers should:

- Follow the local rules and any other relevant procedures;
- Properly use radiation monitors – as identified in section 3.1 this may be the most important factor in ensuring an abnormal situation is recognised early on and does not go on to become a serious accident;
- Wear their individual dosimeters, at the correct location at all times during radiography and source handling;
- Co-operate with the RPO and qualified expert on all radiation safety issues;
- Participate in any training concerning radiation safety;
- Abstain from any wilful action that could put themselves or others in situations that contravene the requirements of national regulations.

The radiographer should promptly inform the RPO about any incident or circumstances that could result in higher than normal radiation doses to themselves or other persons. This could include failures or observed deficiencies in safety and warning systems, errors in following procedures, or inappropriate behaviour.

Good safety performance is a factor that should be incorporated into the daily routine of performing radiography by all personnel so that the job can be performed properly. Radiation safety performance should be a factor by which the safety performance of the whole operating organisation is judged.

6.5 Clients

The client is the organisation or person responsible for hiring the operating organisation to do the industrial radiography. The client has duties relating to the safety of contractors, such as industrial radiographers, working on their sites. They are also "paying the bills" and as such can have a significant influence on the standard of radiation safety achieved. Much of the work of companies undertaking mobile radiography comes from the petrochemical, construction and nuclear industries (if a country has a nuclear programme). Many regulators are aware of this and encourage these industries to actively look for and require high standards from radiography contractors. In the UK, the HPA provides Qualified Expert services to both radiography companies and clients. To help the clients, guidance documents have been produced to help them know what to look for from their contractors [24].

The client should always use an operating organisation that is authorised according to national regulatory requirements for industrial radiography.

The client should provide the operating organisation with sufficient lead-time to plan and to carry-out the work safely and to enable compliance with any advance notifications required by the regulatory body.

The client should not to impose contractual conditions or limitations that would hinder the operating organisation from performing radiography in a safe manner. Regulatory and safety requirements take precedence over commercial requirements. The client should ensure that radiography is co-ordinated with other work on site to minimise the risks from site specific hazards to the radiographers and radiation exposures to other workers. Special co-ordination is needed if more that one radiography organisation is working on the client's site at the same time. A permit-to-work system can facilitate communication and co-ordination of different jobs on the same site.

The client is responsible for providing a safe working environment for the radiographers, including the provision of scaffolding, adequate lighting and safe arrangements for working in vessels, confined spaces, trenches, or other places where access might be needed. The client is also responsible for informing and/or providing any training on site-specific safety issues to the visiting radiographers.

If radioactive sources are to be stored temporarily on the client's site, both the client and the operating organisation should ensure that such stores are safe and secure and that any necessary authorisations are obtained from the regulatory body. The procedures for gaining access to the source store should be clearly defined between the client and the operating organisation.

7 Emergency response

Although prevention is the first defence, emergencies can still happen, therefore operating organisations must have pre-prepared emergency plans to be able to respond quickly and safely to mitigate the situation. After the emergency is over, a report should be prepared which includes a critical review of how well the procedures were implemented and what lessons can be learned to prevent similar emergencies and incidents in the future and how response plans might be improved.

The operating organisation's safety assessment should identify potential emergencies and incidents that could affect workers or members of the public. This should be used as a basis for preparing emergency plans and procedures for responding to emergencies. A qualified expert may be consulted if needed, when drawing up emergency plans and procedures.

Emergency preparedness can be regarded as comprising several stages, each of which should be addressed by the operator:

- Identification of potential emergencies and incidents during industrial radiography, followed by an evaluation of the associated risks.
- Development of emergency plans and procedures to deal with the identified hazards.
- Specification and acquisition of emergency equipment.

- Training to implement the emergency plan and procedures, including necessary training in the use of emergency equipment.

- Exercises at appropriate intervals to test and evaluate the implementation of the emergency plan.

- Periodic reviews and updates of the emergency plans.

- Reports and notifications of incidents and emergencies.

8 Guidance material

Guidance material on safety and security in industrial radiography is available on the websites of national authorities of many of the countries with developed radiation protection infrastructures [22, 23]. In addition the IAEA has available a number of documents covering lessons identified [7,10,11], and safety guides [21]. A new safety guide "Radiation Safety in Industrial Radiography" is in preparation and has recently been through a consultation process with the Member States

9 Training

Appropriate training, including refresher training, underpins radiation protection safety in industrial radiography and is relevant to all the various groups with responsibilities in this sector. Guidance on the content of training courses may be available from national authorities but is also available in IAEA publications [24,25]. In addition IAEA provide courses covering "Training for Regulators on Authorization & Inspection of Radiation Sources in Industrial Radiography" [26].

10 Conclusions

It is clear that industrial radiography, and particularly mobile radiography, provides significant potential for accidents. Sadly that potential has been realised on many occasions, sometimes with fatal consequences. Equally clearly there is documentation of the lessons to be learned and ample guidance on safe working practices plus the well developed training material. What is required are appropriate regulatory frameworks and commitment by the "players" involved; that is managements of operating organisations, radiographers, clients, regulators and qualified experts; to practically implement safe working practices and develop the safety culture in the industrial radiography sector.

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APPENDIX: Case studies from IRID

IRID Case Number: 0001/74	**Category:** D.3.1
Equipment: Gamma site radiography	**Nature:** Lost source

A remote exposure radiography container, containing a 550 GBq iridium-192 source, was being used to examine a circumferential weld on a steel vessel. On completion of the exposure, the winding mechanism was used to return the source to its container. During this procedure the portable dose rate monitor located at the winding position recorded a drop in the external dose rate from the source, and this was assumed to mean that the source had been returned to the container. However, when the equipment was used five days later the resulting radiographs were all blank, revealing that the source was missing from the radiography container; obviously the source had been lost. After a search the source was found near the location at which it was last used.

Later investigation showed that the source had become detached, for some unknown reason, and had fallen from the guide tube during dismantling. The dose rate monitor had not been used correctly to ascertain that the source had fully returned to its container. The noted drop in dose rates at the winding position had arisen because the source had become detached from the drive cable close to the source container, which shielded the dose rate meter from direct radiation from the source.

The source was recovered in a controlled manner by the Radiation Protection Supervisor.

Doses

It was found that during the five days since the source had been lost 78 persons had been irradiated to some degree. Their estimated doses (effective dose equivalent) are given below.

Number of staff	Dose range (mSv)
2	100–150
4	30–100
9	11–30
63	< 11

The source was in a readily accessible position and had it been picked up during the five days it was missing this would have led to radiation burns and, possibly, fatalities.

Lessons

1 The monitor should have been taken up to the container to verify the source was fully in the safe position.

2 Monitoring should have been carried out when the container was returned to the source storage location. This would have identified the source as missing a lot sooner.

IRID Case Number: 0001/82	Category: D.3.2
Equipment: Gamma site radiography	Nature: Leaking source

A purpose-built source holder containing a 20 GBq thulium-170 source (in the form of thulium oxide inside an encapsulation) was being used to inspect tube welds on a steam generator being constructed inside a very large clean room facility. Work continued round the clock in three shifts. At the end of one shift the source was inadvertently left in a tube (possibly as a result of pressure of work) whilst the radiographs were processed. The radiographs indicated that this tube had a faulty weld. Not realising that the source was still in the tube, two workers were told to drill out the faulty weld. During this procedure the source capsule was accidentally destroyed, releasing large amounts of thulium-170 into the tube and working environment. The situation was made far worse by the lack of knowledge of the resident Radiation Protection Supervisors on the nature of the source and of techniques to prevent contamination from spreading. The driller recognised that there had been an obstruction in the tube, removed the source holder and showed the damaged source to the shift RPS. The latter's training had led him to believe that sealed sources could not be damaged. Also there were no contingency plans to deal with the situation. The matter was left to the RPS on the next shift. Dose rate measurements identified the presence of numerous 'bits' of the source. The RPS decided to use an industrial vacuum cleaner, which was not fitted with a fine particulate filter, to clean up the area. This had the effect of further dispersing the activity over the whole facility.

It was not until 24 hours after the accident that a senior RPS was informed and expert advice sought. In the interim some 200 workers had been in and out of the facility. Most had contamination on their skin and clothes. The contaminated staff and paperwork from the facility, together with the ventilation system, provided routes for the activity to spread throughout the factory. Although isolated contamination was found in some cars and homes there was no significant spread outside the factory.

It took eight persons three months (twelve hours per day) to clean up the contamination. This, together with lost production, resulted in a significant economic penalty to the company.

Doses

External whole body doses were negligible.

Extremity/skin doses were calculated from the level of fixed contamination and duration:

Number of staff	Dose range (mSv)
1	3800
1	150
2	80–100
1	60–80
5	40–60
20	10–40

Intakes of radioactive material were assessed by whole body monitoring:

Number of staff	Dose (Bq)	% of annual limit on intake (ALI)	Committed dose (mSv)
1	4.5×10^4	0.4	0.200
1	6.0×10^3	0.05	0.025
1	4.5×10^3	0.04	0.020
5	3.0×10^3	0.03	0.015

Lessons

1 Sources must always be removed to a safe location when not in use.

2 The failure to plan for contingencies and to train staff adequately, especially RPSs, can turn a significant incident into one which has very serious consequences.

3 Whilst there were failings of individuals to follow written procedures, these need to be seen against a background of the overall management of the work and the inherent safety culture. There is a clear lesson of the need to give appropriate priority to the management of health and safety at work.

4 In addition to radiation hazards, accidents can be very costly, in both financial terms and public image terms.

IRID Case Number: 0002/88	**Category:** D.2.1
Equipment: Gamma site radiography	**Nature:** Damaged/defective equipment

A two-man team was carrying out site radiography on a construction site using a 1.85 TBq iridium-192 gamma source in a remote exposure container. A set of three exposures had been completed before radiation monitoring by one of the radiographers revealed that the source had remained at the end of the guide tube after the final rewinding. At the end of each exposure, the end of the guide tube would have been repositioned and the films changed. The lead radiographer would have been very close to the source whilst repositioning the guide tube and changing the films. The contingency plan to recover the source was put into action by the radiographers. Both operators were wearing personal dosemeters but not alarm monitors.

Subsequent reconstruction of the incident indicated that the likely cause of events was that the source pigtail had not been connected to the wind-out cable by the radiographer and had simply been pushed to the end of the guide tube where it had remained for all three exposures. Connection of the wind-out equipment to the source container should not be possible in situations where the pigtail is not connected to the wind-out cable. With this particular wind-out equipment this was not the case, although the dimensions of the ball and shank were within the manufacturer's specifications for maintenance checks and both appeared to be in good condition.

Doses

Whole body doses were taken to be those recorded by personal dosemeters worn by the two radiographers. A reconstruction of the incident was carried out in order to estimate doses to the hands:

Lead radiographer	Whole body 43.3 mSv	Hands 200 mSv
Second radiographer	Whole body 2.9 mSv	Hands 2.7 mSv

Lessons

1 Radiation monitoring MUST be carried out after every exposure. Had this been carried out, doses would only have been received during implementation of the recovery exercise, and would have been significantly lower.
2 Care must always be taken when connecting the source pigtail to the wind-out cable and reliance should not be placed upon interlocking or similar mechanical mechanisms.
3 Personal alarm monitors should be worn during site radiography.
4 Routine maintenance must be carried out of all mechanical parts and interlocks.

IRID Case Number: 0005/90	Category: D.2.1
Equipment: Gamma radiography site	Nature: External whole body exposure

During night-time site radiography in the boiler house of a power station a radiographer (A) slipped on a stairway whilst carrying the source container in one hand and a cardboard box of loose items in the other. The source container housed a 65.2 GBq iridium-192 source and had the guide tubes connected to the container with the shutter locking key left in the lock. A second radiographer (B) came to the aid of the first. He removed the guide tubes from the source container and placed them and the scattered items back in the box. Two first aiders (C and D) arrived on the scene to attend to the radiographer's injury. Neither the radiographers or the first aiders were wearing personal alarm dosemeters, although they had been available to the radiographers.

When a third radiographer arrived 1.5 hour later to take over from the injured man (A) his personal alarm dosemeter sounded. Using radiation monitors they discovered that the source had slid out of the container in the fall and was now lying unshielded in the cardboard box. As a consequence of the incident, all four persons (A, B, C and D) were exposed to the unshielded radiation source.

Investigations found that the very loose operation of the shutter mechanism and dust fouling the source pigtail retaining mechanism undoubtedly contributed to the accident. The shutter locking key was found to be bent and the lock in the unlocked position. The source container and associated equipment had not been examined for some time prior to the incident for signs of wear and damage. It was concluded that the radiographers had not received specific instructions on the operating procedures for the equipment they were using.

Doses

Estimates of the doses received by the two radiographers (A and B) came from the personal dosemeters they were wearing at the time. The doses to the first aiders (C and D) were calculated following a reconstruction of the incident. Fortunately, the source appears not to have been directly handled.

Worker	A	B	C	D
Whole body dose (mSv)	1.8	9.2	0.8	0.8
Skin dose (mSv)	0.0	11.3	–	–

Lessons

1 Radiography source containers and associated equipment must be regularly examined for signs of wear and damage.

2 Source containers should always be transported with the shutter mechanism locked closed and the key removed.

3 It is not advisable for a person carrying a source container to carry other bulky items.

4 If the radiographers had been wearing personal dose rate alarms then they would have been immediately alerted to the exposed source. Alarm dosemeters should always be switched on whenever working in the vicinity of a radiography source, including times when radiography is not being directly carried out.

5 Radiographers must receive adequate instruction in the use of the equipment.

IRID Case Number: 0003/91	**Category: D.2.1**
Equipment: Gamma radiography facility	**Nature: External whole body exposure**

Two radiographers were carrying out gamma radiography using a remote exposure container housing a 160 GBq iridium-192 source. In order to save time due to pressures of work, and against the instruction of the Radiation Protection Supervisor, the work was performed in a permanent facility in which the safety features had yet to be fully installed (including fixed gamma alarms and interlocked doorway to the shielded enclosure). Five radiographs were taken with radiographer 1 manually replacing the film and repositioning the end of the guide tube each time. On each occasion, radiographer 2 had not approached within 3 m of the source. Upon completion of the fifth exposure, one of the radiographers noticed that the radiation monitor had been switched off throughout and promptly switched it on. Monitor readings indicated that the source was not in its exposure container as expected and they immediately left the enclosure and wound it in.

It was concluded that the incident had occurred because of confusion as to whether the source was in or out during each winding. Neither radiographer was wearing a personal alarm monitor. Radiographer 2 was wearing a personal dosemeter (TLD) but radiographer 1 had forgotten to wear his personal dosemeter.

Doses

It was concluded, by calculation, that radiographer 1 had received the following doses.

Whole body 4.0 mSv Hands 300 mSv

Chromosome aberration analysis of a blood sample from radiographer 1 gave a best estimate of the average dose as 0 mSv. The TLD worn by radiographer 2 recorded zero dose.

Lessons

1 A radiation monitor is vital in verifying the source position whenever projection type radiography is performed. After each exposure it should be used to confirm that the source has fully returned to the safe position.

2 In accordance with the Ionising Radiations Regulations 1985, whenever possible, radiography must be carried out in a fully functioning facility with appropriate safety features. The presence of an automatic gamma alarm or door interlock preventing access to the enclosure whilst the source is exposed would have prevented the occurrence of the accident.

3 All industrial radiographers should wear personal alarm monitors whenever performing radiography.

4 Personal dosemeters must be worn at all times by classified persons performing industrial radiography.

IRID Case Number: 0013/92	Category: D.4.1
Equipment: Gamma site radiography	Nature: Damaged/defective equipment

Night-time radiography work was being carried out using a 370 GBq iridium-192 source in a remote exposure container when the wind blew a steel bar over on to the guide tube. The source was in the exposed position at the time and the bar slightly crushed the tube from the shielded container such that when retraction of the source was attempted, the source became lodged near the crushed section. One of the radiographers received a radiation overdose during a badly executed recovery of the source. The radiographer attempted to reshape the guide tube by lightly hammering the flattened section until the source could be withdrawn into the shielded container. A bag of lead shot was used to try to shield the source during the hammering, but unfortunately this was incorrectly positioned and had little or no effect in reducing dose rates. The recovery operation is alleged to have taken less than five minutes although the subsequent investigation casts some doubt on this. The incident was not reported at the time and only came to light following the routine assessment of the radiographer's dosemeter.

The whole recovery operation was ill-conceived and demonstrated a lack of contingency planning and understanding of the situation.

Doses

The doses recorded on the radiographer's TLD were:

Whole body	373 mSv
Skin	2662 mSv

Chromosome aberration analysis of a blood sample gave an estimated whole body dose of:

130 mSv (95% confidence interval 20–340 mSv)

The investigation concluded that the TLD doses should remain on the dose record. No reliable assessment of his hand dose could be made, but it was probably well in excess of the whole body dose.

Lessons

1 Attempts to retract a stuck source forcibly through a kinked guide tube will, almost inevitably, result in the worst possible situation, with the unshielded source becoming lodged at the damaged part of the tube.

2 The recommended recovery option at this point is to CLEARLY IDENTIFY the position of the stuck source, apply local shielding, then cut out the portion of the guide tube containing the source and deposit it in a suitably shielded emergency container.

3 Contingency plans should require the presence of a suitable emergency container on site, together with long handled tools, as the lack of access to such a container will severely limit the acceptable recovery options. These plans should be rehearsed so radiographers are practised in the necessary procedures if an emergency should arise.

4 Instruction and training of radiographers and others who work with powerful sources should make clear the hazard of the very high dose rates present at small distances from the source and the need to avoid close contact with such a source.

IRID Case Number: 0009/93	**Category:** D.1.1
Equipment: X-ray site radiography	**Nature:** External whole body exposure

Two teams of industrial radiographers were working on a new installation radiographing welds using 160 kV industrial X-ray machines. One worker started to set up a new exposure. He manipulated the X-ray head of the machine into position. Unknown to him, his colleague, some distance away at the control point, had energised this machine and it was emitting X-rays. This colleague had heard a shouted request to switch on the X-ray set, although he did not know it was from the other team. The affected radiographer received, as a consequence, radiation doses to the whole body and to his hands.

Doses

The radiographer's dosemeter recorded a whole body dose of 3.1 mSv and the dose to his hands was estimated to be 90 mSv.

Lessons

1 Special care should be taken when two teams of radiographers are working on the same plant to ensure there is effective means of communication between those who initiate exposures and those who set up the equipment and change films.

2 Formal procedures should be adopted to avoid inadvertent exposure of staff.

3 Adequate supervision of industrial radiography should be exercised over site radiography activities.