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LESSONS LEARNED FROM ACCIDENT INVESTIGATIONS

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Abstract

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Accidents in three main practices — medical applications, industrial radiography and industrial irradiators — are used to illustrate some common causes of accidents and the main lessons to be learned from them. A brief description of some of these accidents is given. Lessons learned from the accidents described are approached bearing in mind: safety culture, quality assurance, human factors, good engineering practice, defence in depth, security of sources, safety assessment and monitoring and verification compliance.

1. INTRODUCTION

Over the years, many lessons have been learned from accidents and systems of control have been improved accordingly. Although the retrospective approach to safety requirements is not the only approach, reviewing the key lessons from previous accidents can help in clearly identifying the need for and form of safety requirements.

The selection focuses on the larger accidents involving fatalities and other serious consequences. Yet the principles derived from these events are equally applicable to other situations involving smaller activities.

2. LOSS OF SECURITY OF SOURCES

2.1. Ciudad Juárez, Chihuahua, Mexico, 1983 [1]

A teletherapy unit with a 30 TBq ^{60}Co source was purchased and imported without notifying the Regulatory Authority. The source was improperly shipped in the head of the teletherapy unit, but was not put into use and was stored in a general warehouse for six years. Except for security provided by the warehouse, the user had no control over and could not exercise any surveillance of the source. A maintenance technician loaded the cylinder and other metal parts from the unit onto a pick-up truck, drove to a scrapyard and sold the cylinder and parts. Before arriving at the scrapyard however, he deliberately ruptured the cylinder containing the source, allowing a large quantity of radioactive material from the source to be deposited onto the bed of the vehicle. The truck was then left parked on the street, in the suburbs of the city, for 40 days due to mechanical problems. After this time, it was moved to a different street where it stayed parked for a further ten days.

In the scrapyard, when the cranes moved the cylinder together with other pieces of metal, the ^{60}Co pellets were spread all over the scrapyard, were attracted by the crane's magnetic field and got mixed with the other metal materials. Within two weeks, scrap contaminated with ^{60}Co had been used by steel production plants at foundries and, shortly thereafter, reinforcing rods for construction and metal table frames manufactured with contaminated material were exported.

The accident was discovered when a truck containing items made from the contaminated steel triggered radiation alarms as it passed a radiation monitor installed on the side of the road adjoining a nuclear laboratory.

An extensive investigation established that 30 000 table frames and 6600 tons of reinforcing rods had been manufactured from the contaminated material. Aerial surveys of an area of 470 square kilometres were conducted, and visits were made to 17 636 buildings in order to determine whether contaminated material had been used in their construction. Readings at 814 buildings showed radiation levels which exceeded acceptable limits: these buildings were then subjected to demolition in whole or in part. It is estimated that the accident exposed close to 4000 people to radiation, and that some 80 persons received doses greater than 250 mSv. Five persons are believed to have received doses of 3 to 7 Sv over a period of two months.

2.2 Goiânia, Goiás, Brazil, 1987 [2]

A private radiotherapy institute moved to new premises, leaving behind a 51 TBq ^{137}Cs teletherapy unit without notifying the licensing authority. As a result of the partial demolition of the building, the teletherapy unit became totally unsecured and remained so for 2 years. At that time, two people entered and removed the source assembly from the radiation head. They tried to dismantle it at home, and in the attempt the source capsule was ruptured. The radioactive source was in the form of caesium chloride, which is highly soluble and readily dispersable. Contamination of the environment ensued, resulting in the external irradiation and internal contamination of many persons.

After the source capsule was ruptured, the remnants of the source assembly were sold as scrap to a scrapyard owner. He noticed that the source material glowed blue in the dark. Several persons were fascinated by this and over a period of days friends and relatives came and saw the phenomenon. Fragments of the source the size of rice grains were distributed to several families. This proceeded for five days, by which time a number of persons were showing gastrointestinal symptoms arising from their exposure to radiation from the source. The symptoms were not initially recognized as being due to exposure to radiation. However, one of the persons irradiated connected the illnesses with the source capsule and took the remnants to the public health department in the city. This action began a chain of events which led to the discovery of the accident and the subsequent mobilization of a major emergency response.

Many individuals incurred external and internal exposure and the emergency response had to deal with both this and major contamination throughout the city and beyond . In total, some 112 000 persons were monitored, of whom 249 were contaminated owing to the way they had handled the caesium chloride powder. Four persons died within four weeks of admission to hospital, having received total body radiation doses of 4.5–6 Gy.

Initial radiation surveys were conducted on foot over the contaminated areas. Seven main foci of contamination were identified, including the scrapyards concerned, some of them with dose rates of up to 2 $Sv \cdot h^{-1}$ at one metre. Aerial surveys were flown over 67 square kilometres. Of 159 houses monitored, 42 required decontamination. The decontamination programme lasted 6 months, involved significant resources and produced some 35 000 m^3 of active waste. The accident had a major economic impact on the area, depressing trade with other areas.

2.3. Tammiku, Estonia, 1994 [3]

This accident involved at least four separate events. First, a source was abandoned, scrapped, detected and recovered. Second, the same source was stolen from a waste disposal facility and one of the individuals took the source to his home. Third, during the recovery of the source from the home, the source was briefly touched by an individual in the recovery operation. Finally, approximately one year after the source had first been detected and a couple of months after the radiation injuries, a second source similar to the first was detected and recovered when a radiation expert happened to detect high radiation levels while travelling along the highway in a car.

The first event was the discovery in January 1994 of a radioactive source in a shipment of scrap metal. The scrap was routinely surveyed using a hand held dose rate monitor. The Estonian Rescue Board was notified and recovered the metal frame containing the source. The Rescue Board took the source to the national waste disposal facility at Tammiku. The radionuclide and activity of the source were not determined prior to disposal and the origin of the assembly containing the source was not established.

The suitability of the waste disposal facility was an important element in subsequent events. The design anticipated that higher activity gamma sources would be placed in a more highly shielded vault. However, the frame holding the source was too large to be placed into the vault through an S-tube provided for this purpose. Thus, the highly radioactive source was left in a relatively accessible and less shielded area of the disposal facility.

The second event took place in October 1994. Three brothers made an unauthorized entry into the waste repository and removed the frame. The source was dislodged and fell to the ground. One of the men put the source in his pocket and took it home. The source remained in the house for approximately one month, until the accident came to light. The man who picked up the source was hospitalized four days later and died about a week after that. He had injured his leg at the facility and based on his description of an injury while working in the woods, he was diagnosed as suffering from a "crush injury". The accident was discovered a few weeks later when the man's stepson was admitted with radiation burns to his hands after having picked the source up while working on his bicycle. The diagnosis of radiation burns was made and the police notified. In addition to the fatality, the man's two brothers, his wife, his stepson and the stepson's great-grandmother were estimated to have received doses exceeding 0.3 Gy and up to 2.7 Gy.

Security at the waste facility had included electric intruder alarms at the entrance gate and the door to the disposal pit, but these were easily overridden. The fence was in poor condition and was easily climbed over. The guards noted that a break-in had occurred and noted that measured dose rates had decreased. The reduced dose rates were attributed to changes in arrangement caused during the break-in and the facility operators took no action.

The police notified the Rescue Board after the stepson's injuries were diagnosed. Members of the Board confirmed high dose rates at the house and evacuated the house and 14 additional houses. A shielded box with a 3.5 cm coating of lead was obtained in order to recover the source. The staff involved in the recovery wore lead aprons and rubber gloves but did not have tongs or other handling tools to perform the task. One person picked up the source briefly with his hand to place it in the box. However, this person was not found to present any local injury following this manipulation.

A governmental commission was set up to assess the consequences of the accident and, on an inspection trip by car to a company, commission members happened to detect elevated radiation levels along the highway. A radiation source in a metal frame was located and identified to be ^{137}Cs. The first source was also identified as ^{137}Cs. Subsequently, a radiological survey of Estonia was made using a vehicle carrying a high pressure ionization chamber. No further radiation sources were found.

3. INDUSTRIAL IRRADIATION FACILITIES

The International Atomic Energy Agency (IAEA) publication entitled "Lessons Learned from Accidents in Industrial Irradiation Facilities" [4] describes eight accidents between 1975 and 1994 which caused five fatalities at operating facilities. Three of these are described below.

3.1. San Salvador, El Salvador, 1989 [5]

The irradiation facility was commissioned in 1975. Its initial complement of staff had been trained and were able to deal with abnormal occurrences. Nevertheless, over the years the trained staff left and training of the replacement staff was by word of mouth, rather than formal training. Also relevant was the fact that user instructions were not printed in the local language. The safety systems deteriorated. No preventive maintenance was carried out, the protective metal shroud to prevent interference with the movement of the source rack was not installed and key safety systems were not repaired; some were even removed and improper entry procedures used. The country had no regulatory control or any other form of radiological protection infrastructure.

On 5 February 1989, three employees entered the facility, using improper, but by now standard procedures, to deal with a jam in the transport mechanism. They were exposed for several minutes to the 0.66 PBq ^{60}Co source. One died from his radiation injuries and another had to have both legs amputated.

For a number of reasons, this serious accident was not recognized immediately and the facility continued to operate. However, the source rack had been damaged. Over the next two weeks and until the situation was recognized, source pencils fell out of the source rack, causing radiation exposure to other staff. There also existed a serious risk that one of the source pencils would be carried out of the facility through the transport system and thus enter into the public domain.

3.2. Soreq, Israel, 1990 [6]

Although a well developed regulatory and national radiation protection infrastructure was in place, there were a number of similarities with the San Salvador accident: the instructions were in English and not in the local working language (Hebrew); a metal source shroud to protect against interference from the transport system was not in place; and the same improper procedure was used to gain entry.

On the day of the accident, an operator was called in, outside normal working hours, to attend to a transport jam within the irradiation facility. Although he used the abnormal entry procedure, there were still two lines of defence left. At the entry point there were two warning signals, one indicated the source was in the unsafe position, while the other indicated it was safe. The former signal had occasionally been known to malfunction. He chose to ignore that signal and contrary to the local rules, proceeded to enter. He used the dose rate meter, but it was not working correctly on the dose range he used. He was exposed to the 12.6 PBq ^{60}Co source for 1 minute or so and received a radiation dose of 10–15 Gy. He died 36 days later.

3.3. Nesvizh, Belarus, 1991 [7]

A feature of the design of this irradiation facility was a pit at the entrance, which in theory required the operator to remove the main key from the control panel, go to a second position, draw a motor-driven, sliding floor section over the pit and thus allow access. From an operator's perspective, the entry sequence was long: this operator looked for a way of bypassing the procedure. The design was such that the drive motor for the movable floor was located in the pit. This motor could be stepped on and the pit crossed without the key being removed from the main control panel. There were no interlocks between the transport system, the radiation detection system and the source movement control. Thus, with the above improper entry procedure, the control panel was left in the 'ready' position, only one step away from exposure of the source.

On the night of the accident, the operator, while in a state of sleepiness, entered the irradiation chamber, using the improper procedure. At the time he must have assumed the source to be down, but while he was in the chamber, it came out of its store to the exposed position. This could have occurred due to faulty electrical contacts or accidental and unnoticed depression of the exposure button (several function buttons were close together). The operator was exposed to the 28 PBq source for close to a minute, receiving 10–15 Gy. He died 113 days later.

4. INDUSTRIAL RADIOGRAPHY

The IAEA publication entitled "Accidents in Industrial Radiography and Lessons to be Learned" [8] describes several examples of accidents in this area, where uncontrolled exposure occurs, often leading to deterministic effects.

4.1. Morocco, 1984 [9]

The accident originated at the construction site where ^{192}Ir sources were being used to radiograph welds. A 1.1. TBq ^{192}Ir radiography source became disconnected from its drive cable and was not properly returned to its shielded container. Subsequently, the guide tube was disconnected from the camera and the source eventually dropped to the ground, where a passing labourer noticed the tiny metal cylinder and took it home.

Within a relatively short period of time, during May and June of 1984, a total of eight persons, including the labourer and his entire family and some relatives, died with clinical diagnoses of "lung haemorrhage". It was initially assumed that the deaths were the result of poisoning. Only after the last family member died was it suspected that the deaths might have been caused by radiation. The source was recovered in June 1984.

4.2. Transportation accident between Korea and the United States of America, 1989 [10]

In 1989, a manufacturer received a 260 GBq ^{192}Ir source that had been cut off from the source assembly by the user and stored in a radiographic source changer for decay for disposal. This technique of cutting off sources and holding them for decay was commonly practised by this user. In this case, the source was not transferred from the source changer to the disposal container before return of the changer to the manufacturer. A radiation survey did not detect the source prior to transport. As a result, a container was shipped as not containing radioactive material while it did contain a source; the source was not secured to the source assembly and was free to move out of the shielded charger during transport.

The source changer took three weeks to arrive at the manufacturer's facility. Upon receipt, the source was detected because of high readings from a radiation monitor. The time at which the source became unshielded could not be determined. The highest potential dose to a member of the public was estimated to be 5 mSv and the highest potential dose to the transportation workers was 0.31 Sv.

5. MEDICAL RADIOTHERAPY

The IAEA has prepared an analysis of medical accidents in "Accidental Exposure in Radiotherapy and Lessons to be Learned" [11]. Many of these relate to accidents involving exposure of the patient to doses significantly greater than intended. Accidents involving patient exposure are not referred to here. Nevertheless, some of the accident scenarios also relate to loss of control of sources leading to uncontrolled exposure of workers and member of the public.

5.1. Indiana, Pennsylvania, USA [12]

A patient was prescribed three treatments using a high dose rate remote afterloading brachytherapy unit (HDR) loaded with 160 GBq ^{192}Ir. Five catheters were placed in the tumour and the source was stepped through the programmed positions in each catheter. During the first treatment, difficulty was experienced placing the source in the fifth catheter. An area radiation monitor sounded the alarm, but was disregarded because the HDR unit console indicated "safe". The area monitor was also used with an electron linear accelerator and had previously been observed to alarm when the accelerator was turned off. As in other accidents, the operator assumed the radiation monitor was malfunctioning. The source wire had actually broken and the source had remained in the patient.

The patient was transported back to the nursing home with the source still in the catheter. The source remained in the patient's body for almost four days, at which point the catheter containing the source fell out. The nursing staff placed the catheter in medical waste, which after storage was transferred to an incinerator company. A fixed radiation monitor at the incinerator alarmed and the package containing the source was identified and made safe. It was determined that the radiation exposure was at least a contributory cause of the death of the patient. It also resulted in the exposure of 94 individuals, including persons at the cancer clinic, people at the nursing home, ambulance staff and workers at the incinerator company.

5.2. Cincinnati, Ohio, USA [13]

In 1986, hospital personnel reused high activity ^{125}I seeds containing 1.5 GBq for several patients because of the relatively high cost of the seeds. The seeds were removed from old catheters and loaded into new ones for implant into other patients. During removal, one of the seeds ruptured. The rupture may have been caused by cutting the catheter to free the seeds with a sharp object, such as a razor blade or scissors. The user did not realize that a seed had ruptured. The seeds, including the ruptured seed, were implanted into a patient. As a result, the patient sustained a thyroid burden of about 20.7 MBq and a radiation dose to the thyroid of about 21 Gy.

Hospital personnel discovered that one or more seeds had ruptures when ^{125}I contamination was detected in a source/transport bucket stored in the brachytherapy source storage room one day following the implant into the patient. The storage room was not ventilated by a fume hood. Consequently, 60 hospital personnel, including those involved in cleanup operations, received thyroid uptakes of ^{125}I ranging from 1.5 Bq to 7.7 kBq. Family members were also exposed when visiting the patient. A proper radiation survey was used, but the high background radiation in the storage room masked the positive indication of contamination.

6. LESSONS LEARNED [14]

The range of the aforementioned accidents provides a fair indication of the severity of the accidents which might occur if effective control of sources is not maintained. The causes of these accidents are varied and need to be addressed by preventive radiation protection measures. However, some common lessons learned have been grouped under the following headings:

6.1. Safety culture

Failure to train staff in procedures and in the operation and purpose of safety equipment can cause workers to make serious errors.

- In San Salvador, the original operators had received thorough training but replacement operators did not.
- In Indiana, Pennsylvania, professional and technical staff were trained by the device manufacturer in the operation of the HDR device but not in the operation of, or the requirement to use, a hand held survey meter.

In response to management failures to maintain and repair equipment or fix known problems, workers may develop unsafe practices.

- Frequent product transport problems in San Salvador, Soreq, and Nesvizh resulted in worker practices to speed up entries and trick non-operational or poorly functioning safety systems.
- Installing a shroud to protect the source transport mechanism — as suggested by the supplier — could have prevented the accidents in San Salvador and Soreq.
- In San Salvador, the radiation monitor probe had failed and was removed rather than replaced.
- In San Salvador, the entry door became degraded, but a method of using a knife to slip the catch was adopted by workers.

6.2. Quality assurance

Significant deviations from local rules may occur if management does not have a programme to assure that requirements are satisfied.

- In Soreq and Nesvizh, tricking or bypassing safety systems had become frequent practice.
- In Indiana, Pennsylvania, the Radiation Protection Officer was normally at another facility and came to this facility about once a year.
- In Juárez and Goiânia, management failed to institute systems to monitor the status of sources in storage.
- In several accidents, management was either unaware that safety systems had deteriorated or deliberately chose to ignore the problems.

6.3. Human factors

Prior experiences with "false alarms" and misplaced trust in mechanical safety indicators may lead workers to ignore warning signals.

- In Indiana, Pennsylvania, the technicians had previous problems with the radiation monitor and did not believe the radiation alarm when another indicator said the source was "safe".
- In Soreq, the operator had two different indications about the source location. The mechanical sensors indicated the source was down but the gamma alarm indicated the sources were exposed. The operator believed the mechanical sensor and proceeded to fix the problem with the product transport jam.

Working conditions and the condition of the worker may affect worker judgement and lead to error.

- The three irradiator accident examples all happened at night and in at least one case the operator was tired and sleepy.

Workers may want to be seen as taking initiative and may hesitate and decide not to request help in unusual situations.

- The three irradiator incidents involved operators working alone who may have been reluctant to call in expert help. It is worth noting that in San Salvador and Soreq, instructions not to attempt to enter the irradiation chamber when signals indicating the presence of radiation were lit were in English, but not in the workers' native language.
- The worker in San Salvador who made the original entry was regarded as showing initiative and resourcefulness in solving the frequent maintenance problems at the facility.

6.4. Good engineering practice

Design, construction or materials features of radiation sources or equipment may initiate the sequence of events that leads to an accident.

- In Indiana, Pennsylvania, the source wire broke with the ^{192}Ir source inside the patient.
- In Morocco, industrial radiography sources became disconnected from drive cables.

Design, construction and materials features of the radiation sources may worsen the consequences of the accident and increase the difficulty of recovering the radiation source.

- In Juárez, the use of small pellets of ^{60}Co allowed the material to be dispersed and accidentally distributed to many recipients.
- In Goiânia, the use of a physical and chemical form (caesium chloride) that was dispersible and soluble contributed to the widespread contamination, internal exposures, and difficulties in recovering the material.

Design features of auxiliary production and safety systems can initiate accidents or fail to prevent accidents as intended.

- In San Salvador and Soreq, the design of the product transport system could cause the source return mechanism to jam with the sources exposed.
- In the same two accidents, the design of the circuits for the radiation monitor system permitted the use of a trick to send a false signal that background radiation levels had been detected.

- In Indiana, Pennsylvania, the design of the source return sensing device gave an indication that the source was in the 'safe' condition even when the radioactivity was still in the patient.

6.5. Defence in depth

Failure to provide multiple layers of defence between the radiation source and members of the public can lead to uncontrolled and very hazardous conditions.

- In Juárez and Goiânia, reliance upon secure storage in the normal course of warehousing or maintaining a facility was easily overcome by individuals with knowledge of the use of ordinary tools but no knowledge whatsoever of radiation sources.
- In Indiana, Pennsylvania, the failure to use a hand held radiation monitor combined with the failure to believe the fixed radiation monitor led to reliance upon a single position indicator to confirm (incorrectly) that the source had been returned from the patient to the shielded container.

6.6. Security of sources

Once a source is lost or stolen, the consequences to life, health and the environment are subject neither to timely control nor prompt mitigation.

- In Juárez and Goiânia, the shielding which was the primary safety barrier between the source and the public was thought to have economic value and was dismantled with unsophisticated techniques.
- In Juárez and Goiânia, the accidents were not detected until well after significant doses had been received and the radioactive material had been widely dispersed.
- In Mexico City and Morocco, fatal doses were received over relatively long periods of time and the missing sources were identified and recovered only as the result of the investigations of the deaths.

6.7. Safety assessment

Assessment and modification of facilities, equipment, and procedures taking into account accidents and lessons learned could have prevented later accidents.

- The accident at Soreq involved the same types of initiating events and human errors as had occurred earlier in San Salvador.
- The storage without surveillance and subsequent dismantling of the ^{137}Cs teletherapy head and source in Goiânia by a member of the public occurred under circumstances similar to the accident in Juárez involving a ^{60}Co teletherapy unit.

6.8. Monitoring and verification of compliance

Use, maintenance, calibration and testing of suitable radiation monitoring equipment would prevent most accidents.

- In San Salvador, Soreq and Pennsylvania, a required radiation monitor, survey meter or both was either inoperable, not functioning correctly or considered so unreliable as not to be believed.
- In Pennsylvania and San Salvador, required checks using portable, hand held survey meters were not carried out.
- When lack of security results in the loss or theft of a source, any type of monitoring was no longer likely until the loss was noted and reported.

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