# Radiation safety at irradiation facilities

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**Abstract.** The radiation processing industry has been operating gamma and electron beam irradiators safely for more than 40 years. The annual radiation dose for facility personnel typically does not exceed the natural radiation dose from cosmic and terrestrial radiation. They wear normal, every day clothing and comply with standard health and safety regulations. Still, it is recognized that large quantities of radioactive material or high energy electron or X ray beams pose a potential hazard to workers, the general public and the environment. In order to achieve the necessary high degree of safety and reliability radiation processing facilities and their procedures are designed according to basic safety principles. They are operated in accordance with international, national and regional standards and regulations.

## 1. Introduction

Radiation processing is a regulated industry that has been operating safely for more than 40 years in usual commercial and business parks. The workers in these facilities wear normal everyday clothing and comply with standard health and workers safety regulations. Yet it is recognised that large quantities of radioactive material located at one place (for any purpose) or high energy electron or X ray beams pose a potential hazard to people (workers as well as general public) and environment, indicating the need to achieve a high degree of safety and reliability in the use of these sources. In view of this, the IAEA in collaboration with several international organizations (FAO, ILO, NEA of OECD, WHO and PAHO)[*] issued basic safety standards (BSS) for protection against ionizing radiation and for the safety of radiation sources in 1996 [1].The standards comprise basic requirements to be fulfilled in all activities involving radiation exposure. They are aimed to serve as a practical guide for public authorities and services, employers and workers, specialized radiation protection bodies, enterprises, and safety and health committees. These requirements are fulfilled by effective quality control procedures together with careful design, manufacture, transportation, installation, operation and decommissioning of the radiation sources.

In 2003, the IAEA published a report that provides information and guidance regarding design and safe operation of facilities to organizations intending to purchase and operate industrial irradiation facilities [2]. This information satisfies the requirements of the BSS in that a code is provided to ensure that radiation exposure of the workers and public is kept ALARA (as low as reasonably achievable) during normal operation, maintenance and decommissioning and in emergency situations. Earlier in 1992, IAEA had published a Safety Guide that provides device specific guidance regarding design, operation and regulation of industrial irradiators [3]. This applies to all types of irradiation facilities, whether operated on a commercial basis or for research and development purposes.

This paper is not a comprehensive work on radiation safety. It is really meant to give pointers where one can get more information, such as IAEA publications and other international guidelines. There are

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[*] FAO – Food and Agriculture Organization of the United Nations
ILO – International Labour Organization
NEA of OECD – Nuclear Energy Agency of the Organization for Economic Co-operation and Development
WHO – World Health Organization
PAHO – Pan American Health Organization

other safety regulations (local, national or international) in addition to radiation safety that will not be addressed in this paper.

## 2. Gamma sources and activated accelerator parts

### *2.1. Manufacturing*

Manufacturers of gamma irradiators follow established procedures that satisfy national and international regulations regarding the design and manufacture of radiation sources, such as those in ISO Standards [4].

### *2.2. Transport and disposal*

### *2.2.1. Gamma irradiators*

The design of the transportation containers for radioactive material (such as cobalt-60) as well as the transportation procedures are governed by the requirements of the IAEA Regulations for the Safe Transport of Radioactive Material [5] and any existing national legislation. These containers are heavily shielded as per stringent design specifications. Also, they are able to withstand significant impact and high temperatures without losing integrity. Figure 1 shows an example of a transport container for cobalt-60 pencils.

Transport regulations vary from country to country. When transportation involves crossing international borders UN regulations for safe transport apply. In general, the irradiation facility will not deal with all the details; it is the manufacturer and exporter of the source that take care of the shipping of radioactive material. The radiation processing facility however must have an appropriate licence to receive radioactive sources for its irradiator.

Sources may have to be disposed of at some later stage in the life of the facility. Typically they are disposed of by sending them back to the original manufacturer.

*FIG. 1. Type B(U) packaging container for cobalt-60 sources.*

### *2.2.2. Electron Beam and X ray accelerators*

Generally radiation from machine sources such as electron beam accelerators ceases when the electrical power to the machine is switched off. Only when the electron energy is high enough some parts of the accelerator may have been activated during factory testing of the machine. Depending on the level of activation, these accelerator and their components can be shipped as a non-radioactive shipment or not. Generally, accelerators with final electron energies up to 10 MeV are shipped as non-radioactive shipments. Care must be taken, when X ray converters have been extensively tested with electron beams at the manufacturing site; the converter material (typically tungsten or tantalum) may have been activated.

For normal operation of electron accelerators above 5 MeV, it is recommended to evaluate the activation of parts during maintenance. If activated parts have to be replaced, relevant regulations for storage, transport outside of the facility or disposal have to be followed.

## 3. Safety design principles

### *3.1. Dose rate limits*

Experience in many countries has shown that irradiation facilities can be designed and operated such that the annual exposure of workers is significantly less than 5 mSv, and that exposure of members of the public is less than 1 mSv per year. Most facility operators strive to ensure that workers are exposed to even less than 1 mSv per year, and therefore access of workers and members of the public is often restricted also outside of the radiation shield. In some countries, occupationally exposed workers are classified into category A and B, referring mainly to the annual dose limit of 20 mSv or 5 mSv, respectively. However there is really no reason why an occupationally exposed worker in an industrial irradiation facility should receive doses close to these limits.

Many countries regulate the method of calculating annual exposure depending on the occupancy of the relevant areas:

- Publicly accessible areas are those that are not under the authority of the irradiation facility operator. For these areas the average dose rate must be applied for a full year (approximately 8 700 hours) to determine public exposure.
- For all areas under the authority of the irradiation facility operator, which are not specifically restricted, one must assume working place conditions; hence, exposure is for approximately 2 000 hours per year.
- When areas under authority of the irradiation facility operator are not normal working places, it is permissible to estimate the total number of hours of exposure based on operational procedures. However, some countries limit the reduction factor to 10, hence a minimum of 200 hours must be considered for maintenance areas, hallways, storage areas etc.

Workers are typically classified to be exposed occupationally, only if their work duties include entering into the radiation shield, participating in maintenance of the irradiator, working close to or in restricted areas, or participating in source loadings. Other workers in the same facility are typically considered non-occupationally exposed, hence are treated the same as general public. From this consideration one infers that the *average dose rate* should be limited to the following values so as not to exceed *annual dose limits* mentioned above:

- work places and non-restricted areas: < 0.5 µSv/h (0.05 mrem/h)
- maintenance areas: < 5 µSv/h (0.5 mrem/h)
- public areas not under authority of the irradiation facility: < 0.1 µSv/h (0.01 mrem/h)

### *3.2. Biological shield design*

Many methods exist to perform radiation shielding calculations. All shielding calculations must consider two main radiation transport mechanisms:

- radiation transmission through the shielding walls, and
- scattered radiation through mazes and ducts.

Some irradiation facilities are not or very little shielded towards the sky. In this case, the sky-shine, the radiation that is scattered back from air molecules, must also be considered.

Typically the shielding calculations are performed by analytical methods. Wall thicknesses are determined using absorption values of the respective shielding material for the appropriate radiation type and energy combined with the inverse-distance-squared law. These methods are straightforward and are applied easily. Maze calculations however are much more complex. Methods differ for the type and energy of the respective radiation. Examples for shielding standards can be found for instance in NCRP 51, NCRP 144, and DIN 6847 [6–8].

Recently, numerical methods (such as, the Monte Carlo) have also been used when complex shielding situations are evaluated. These methods are based on computer codes that simulate radiation – particle by particle – and trace the respective particle to the outside of the shield. This method is time consuming as many codes still require defining the geometry in form of a text file in user unfriendly formats. Depending on the complexity of the geometry, a computer may well calculate for several weeks or months before a useful result is available. Mone Carlo codes that have been used extensively for this purpose include MCNP-X and Fluka.

### *3.3. Regulatory approval*

Before an irradiation facility can be constructed and operated, license from the national competent authorities is necessary. In some (federal) countries the responsibility for approval is delegated to its states or local government authorities. Depending on the type of installation (gamma, electron beam or X ray irradiator) and the energy level of the electrons in case of electron beam and X ray irradiators different licensing processes may be in use for the same country. The main difference amounts to the requirement to obtain a licence prior to shield construction or only prior to the first event where radiation is generated or isotopes delivered.

When licensing prior to construction is necessary the competent authorities primarily verify that the biological shielding is sufficient to protect the public, that radioactive emissions are under control (via exhaust air, ground water, and radioactive waste) and that the project team has general competence to design the irradiation facility according to the relevant safety standards [9–11]. All evaluations by the competent body take place based on documentation provided by the irradiation facility.

During the application process for an operating permit, the shielding calculations serve mainly as a guideline for dose measurements. Dose rates at relevant locations will be measured. The design of the personnel safety system will be audited and its function will be tested. The competent body typically has its own expectations on methods of safeguarding access to the irradiation room or other controlled areas. Thus, it would be wise to coordinate all relevant design steps with the responsible government authorities to avoid delay and additional cost near the end of the project.

### *3.4. Personnel safety system*

Operators and other workers at the facility are a critical group that could be potentially exposed to high radiation levels. This is prevented through interlocks and critical design features and operational procedures of the irradiator [9–11]. The main objectives for a safety system are

- keep people out of dangerous areas,
- warn people of hazards,
- define procedures, for example
  - to secure radiation rooms
  - to unsecure radiation rooms and allow access after a delay for ozone removal
  - for emergency stop and access violations
- provide safety even when a single fault is undetected.

These safety systems and devices are expected to meet certain criteria, including [3]:

- protection in depth – if one system fails there is yet another system (based on different principle) as a back up;
- redundancy and diversity – principal components should be duplicated;

- independence – fault in the irradiator should not impair the safety system; and
- fail-to-safe – failure of a safety system should always result in safe conditions.

Based on these criteria, several safety systems are incorporated in the design of an irradiator that either give early warning of any potential problems or prevent them from occurring. These systems are designed to protect product, facility, workers and in the worst case scenario the surrounding environment. Alarm signals from these safety systems are transferred to the control room and other relevant areas (for example product loading stations, staging areas, etc) for immediate attention of the operator.

### *3.4.1. Safety devices in a gamma facility*

- high temperature detector – it quickly recognises abnormal heat buildup, which could lead to product damage and the increased potential for fire
- pool water level sensor – it continuously monitors the water level in the storage pool and alerts the operator of unusually high or low levels
- radiation monitor – it continuously monitors radiation level and alerts the operator if there is abnormal level; two most likely locations for these monitors are: the product exit port and water deionizer tank. More radiation probes may be installed inside the irradiation room.
- source-down detector system – it provides direct indication of the position of each source rack when it reaches the bottom of the storage pool
- earthquake detector – it provides a means of automatically returning the source to the safe storage position in the event of a seismic event
- source guards and collision sensors – these serve primarily for jam detection and avoidance. In most published irradiator incidents jammed product or jammed source racks played a significant role.

### *3.4.2. Safety devices in electron beam or X ray irradiators*

- radiation monitor – it continuously monitors radiation level and alerts the operator if there is abnormal level; two most likely locations for these monitors are: the product exit port and if the accelerator is placed in a different room, near the exit or inside the accelerator room.
- if electron beam energies above 10 MeV are used, further radiation measurement systems may be needed to control the following potential hazards:
  - radioactive emissions via the exhaust air,
  - cooling water,
  - activated product.

It is however unlikely for sterilization facilities to activate product to a level above the detection level of normal dose rate monitors. Electron beam facilities with electron energies above 10 MeV and X ray irradiators with electron energies above 5 MeV shall consider possibility of product activation and define appropriate procedures and means to control product release.

### *3.4.3. Common safety devices*

- access control interlocks – these devices are typically redundant. Access doors are closed and locked until the irradiation or accelerator room is safe to enter. In the case of a forced entry, the safety system must shut down the accelerator or move  the radiation source to the storage room. Many such devices exist on the market; one example is shown in Fig. 2. The European Norm 954-1 presents a method for analysing the hazard to personnel and categorizes safety devices according to the hazard they need to safeguard against. Typically door interlocks to the irradiation room should be of category 3 or 4 according to EN 954-1 [12].

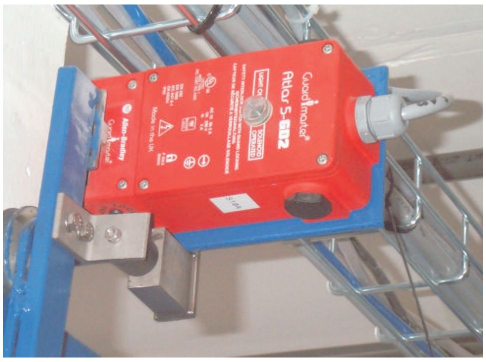

*FIG. 2. Example of a EN 954-1 Category 4 approved door switch with holding mechanism*

- ozone time delay – when air is exposed to ionizing radiation, ozone and other toxic gases are formed, which decay quickly and are removed by the ventilation system. This safety system prevents entry in the irradiation room for a short time period, after the source has been moved to the shielded position or the accelerator has been turned off, till safe level of these gases is reached
- smoke sensors – special attention has to be paid to radiation and ozone resistance of the components used in the facility.
- fire extinguishing systems – many fire alarms are caused by system malfunctions. Thus, it is important to build redundancy into the activation method for a fire extinguishing system. A single false activation of a water sprinkler system could cause more damage than the extra cost of a pre-action activation system or a gas extinguishing system.

### *3.5. Radiation measurement*

Radiation measurement equipment must be selected and used appropriately. The measurement range for instruments surveying workers areas should extend low enough to measure natural background radiation (0.1 µSv/h). If the dose rate exceeds several mSv/h, one would not expect to enter that area. Hence typical Geiger-Müller counters, proportional counters or ionization chambers will serve the purpose.

The measurement equipment must be robust enough for the intended use. When a radiation survey meter is attached to the main entry key of the irradiation room, the instrument must be able to withstand some rough treatment.

All instruments must be checked regularly for proper operation. In many cases, a check of proper operation is necessary before each use of the instrument (such as for entry into the irradiation room). A check source that is permanently installed at an appropriate location can ease the frequent operation checks. Many countries require calibration for all instruments serving personnel safety.

### *3.6. Personnel dosimetry*

The operators and workers wear radiation dosimeters (badges) during working hours to monitor the amount of radiation dose they receive. Typically, these badges are read every month to determine the dose received by the wearer of the badge. The IAEA in collaboration with several international agencies have set guidelines regarding safe limits of radiation dose that workers may receive [1]; these are based on ICRP recommendations [13]. The radiation badges are thus used to confirm that no individual is receiving dose above these limits. The design of the irradiator and the work procedures are such that individual doses are kept under limit.

## 4. Accident prevention

According to the IAEA, it is incumbent on the facility operator not only to keep the doses under the limits but also to reduce all individual doses to the level that can be reasonably achievable (called ALARA principle) [1]. Thus, generally, doses received by workers in radiation processing industry are well below these dose limits, almost close to the background levels.

Safety cannot be achieved by chance. Workers need to be aware of all hazards. They need to be competent to deal with their routine work as well as out-of-the-normal conditions. In order to be aware and competent they need to be trained, for example in accident prevention and safety procedures.

### *4.1. Safety procedures*

Safety procedures play an important role in preventing accidents. All radiation accidents have one feature in common: blatant disregard for procedures. Even an untrained worker (which should not exist) can work reasonably safe as long as he follows procedures set by the facility or the manufacturer of the irradiator and its safety systems.

Hence it is necessary for the irradiation facility to define procedures on working safely in the facility. The procedures should cover at the minimum the following issues

- management responsibilities for licensing, insurance, training, radiation safety organization
- duties of a radiation safety officer
- definition of controlled and restricted areas
- access procedures to irradiation areas
- work procedures in irradiation areas
- workers health and personnel dosimetry
- use of measurement equipment
- accident prevention programme
- responding to emergencies and incidents
- receiving and shipping of radioactive material (e.g. gamma source, activated accelerator parts, etc.)
- maintenance and equipment modification
- disposal of radioactive waste

### *4.2. Training*

The training syllabus has to be adjusted in content for the respective trainees. A training session for the radiation safety officers necessarily covers much more on basic physics, methods of measurements, regulatory requirements etc than for a worker in the warehouse.

At the minimum, the training syllabus should strongly emphasise the following messages

- follow procedures
- if in doubt, ask the radiation safety officer
- treat all alarms as if they were severe, until proven otherwise
- when entering the irradiation room, always use hand-held monitor and ensure its operation
- report all malfunctions to the radiation safety officer or the facility manager
- NEVER bypass safety systems.

The length of the training course depends on several criteria. Issues, such as how much hands-on exercises should be performed, who is trained, and if it is initial or recurrent training will play a role. The IAEA Safety Report Series No 20 describes various aspects of training in radiation protection [14] and is a recommended reading for trainers in radiation safety.

## 5. Conclusions

Safety is of paramount importance, and must be the first priority at any radiation processing facility. It is achieved through following standards and procedures for manufacturing and operations. The design of an irradiation facility must have built-in safety features and interlocks. National authorities will review the design and safety aspects of a facility. They may require additional safety features and grant licences based on their findings. A licence however can only be a snapshot of the safety situation at the time of issuing it. The best design may still be unsafe if the workers are not aware of the hazards and are not competent to deal with them, or if the maintenance is not performed correctly. Awareness and competence can only be reached by training. Hence initial and recurrent training is a must.

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