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Overview of Radiation Accidents at Industrial Accelerator Facilities

Helena Janžekovič
Slovenian Nuclear Safety Administration
Litostrojska 54
1000 Ljubljana, Slovenia
helena.janzekovic@gov.si

ABSTRACT

Industrial irradiators have been used for decades for various reasons. In the last decade sterilisation of products, e.g. medical products or food, became an important part of many industries. The required dose rates in order to make an efficient sterilisation might be up to hundred thousand of Gy/s. Due to such extremely intense radiation fields, defence in depth shall be implemented in the design of irradiation facilities and strong safety culture shall be in place. The facilities are based either on a use of radioactive materials, i.e. Co-60 or Cs-137, or accelerators. In the last decade irradiators with radioactive sources became obsolete in order to avoid security issues as well as handling a disused source.

The use of sources in industrial sterilisation facilities is related to numerous safety features assuring safe operation of facilities as sources are linked to high risks to human health in case of an accident. In the available open literature, the accidents related to industrial irradiators using radioactive sources are well described including detailed analyses of accidents with fatalities, e.g. in Kjeller 1982 and in Nasvizg in 1991. Much less information is available when industrial accelerator facilities are involved in accidents although the first accident related to industrial sterilisation happened in 1965 in USA where accelerator was involved resulting in amputation of worker's leg and arm. The literature reveals only five reported cases i.e. demonstrating that accident with health consequences are very rare. But except in one case all exposures of workers required extensive medical treatment, e.g. amputation of limbs.

The present very first analysis based on a short description of reported cases, identification of initial events and contribution factors as well as lessons learned could help the regulatory bodies, designers, suppliers, installers, operators, maintenance companies and others involved in radiation safety of industrial accelerators to identify design flaws as well as human errors leading to such dreadful accidents. The analysis demonstrates that three of five cases were related to so-called "dark current" showing that there was a clear lack of understanding technical characteristics of accelerators and the risks associated with such facilities.

1 INTRODUCTION

Radiation overexposure accidents are relatively rare but can have "severe long-term health consequences" as stated in [1]. While some accidents are well known and results published in open literature, e.g. as analysis of the Chernobyl accident, other accident are much less known to the general public despite their consequences, e.g. as the accident in Spain in 1990 resulted in 18 deaths from radiation related to clinical linear accelerator as given in Table 2 in [2]. Several databases of accidents exist nowadays, e.g. IAEA News and RELIR/OTHEA. They enable exchange of lessons when using radiation sources. In particular, such databases can be a useful learning tool when preparation of safety assessment for very new practice in the state is under way.

The use of industrial irradiators using accelerators for sterilisation or other purposes is becoming a new practice in many countries. It is related to numerous safety features assuring safe operation of facilities. A use of accelerators is somehow replacing a use of radioactive sources of Co-60 or Cs-137 of sources of Category I according to the IAEA [3]. Such sources can pose a significant risk if not safely managed or securely protected as stated in [3]: "The sources if not safely managed or securely protected, would be likely to cause permanent injury to a person who handled it or who was otherwise in contact with it for more than a few minutes. It would probably be fatal to be close to this amount of unshielded radioactive material for a period in the range of a few minutes to an hour." The replacement mentioned is based on security issues, i.e. in particular regarding Cs-137 radioisotope, as well as on a fact that once irradiation time needed for sterilisation becomes too long due to radioactive decay the source should be stored, reused or sent to the manufacturer using strict safety and security measures. The database of gamma irradiation facilities was prepared in 2004 and is given in [4]. Such database related to accelerators used for sterilisation is not available. It should be also noted that due to development of technology experiences related to accelerators designed decades ago might not be of limited use today. Despite this the analysis of accidents related to a use of industrial accelerators might help regulatory bodies, designers, suppliers, installers, operators, maintenance companies and others involved in radiation safety of industrial accelerators to identify design as well as human errors.

Due to such extremely intense radiation fields, i.e. up to thousands Gy/s, defence in depth shall be implemented in the design of irradiation facilities, either using radioactive sources or accelerators. The details of the safety guides are given in [5].

- When constructing a facility special attention shall be given to shields of a source. Shielding calculations require detailed knowledge of the technology applied as thick concrete shields of few meters might be necessary in order to assure safety operation of such irradiators, all penetrations shall be protected and sky shine shall be taken into account. Detailed and updated information on calculation of shielding is given for example in [6] and references therein.
- The safety systems installed, such as interlocks, shall be carefully designed and shall be based on independence, diversity and redundancy. As a rule, few tens of safety systems shall be in place. Their daily, weekly and yearly testing and maintenance as appropriate shall be assured in line with the *Program of testing and maintenance*. In particular, due to very intensive radiation fields due attention shall be taken to safety systems which might be degraded or destroyed by such intense fields very quickly, e.g. cameras and electrical connections.
- Safety procedures of all involved and in particular of the licensee of the irradiator shall demonstrate high level of safety culture in particular high level of understanding of risks associated with a use of irradiators and technical characteristics of a facility.

As pointed in [2] the design of irradiation facilities is based on the probability that an accident will happen is extremely low, i.e. 10^{-6} per entry.

2 ANALYSIS OF ACCIDENTS

In this very first attempt to analyse accidents related to industrial irradiators the list of databases analysed includes:

- IAEA document on lessons learned from accident in industrial irradiation facilities [7],
- Database given in Table 1 in [8],
- UK IRID database [9],
- OTHEA/RELIR database [10]
- presentation Accelerator Health Physics, 2008 HPS [11].

In the *Radiation Accidents and other Events causing Radiation Casualties-Tabulated Data* compiled by Wm. R. Johnston from 2014 available on the http://www.johnstonsarchive.net/nuclear/radevents/radaccidents.html eight events are related to irradiators using accelerators. However, these data were not included yet in the analysis.

The search for accidents with industrial irradiator reveals that a list of accidents related to industrial irradiators using radioactive sources is, as a rule longer than the list of accidents where accelerators were involved, e.g. in the document IAEA from 1996 [7] three of eight cases are related to accelerators. It should be pointed out that all eight cases were related either to fatal consequences or severe radiation injuries but fatal consequences were not related to a use of accelerators.

In general, accidents with radiation sources used in industrial irradiators are well described including detailed analyses of accidents with fatalities, e.g. one fatality was a consequence of the Kjeller accident in Norway in 1982 as well as of the Nasvizg accident in Belarus in 1991 [8]. Much less information is available when industrial accelerator facilities are involved in accidents although the first accident related to industrial sterilisation happened in 1965 in USA where accelerator was involved resulting in amputation of worker's leg and arm [8].

However, it must be pointed out as already given in [1] that reporting methodology might be an issue when comparing the databases. Namely, international databases are based on voluntary basis while national databases can be based on different criteria. For example, looking to Figure 4 given in [1] it seems that majority accident in South East Asia are related to orphan sources, i.e. sources outside a regulatory control, and while majority of overexposures in Russia are related to industry. On the other hand, the UK IRID database [9] does not report on any accident related to gamma irradiators or use of accelerators in industry. The OTHEA/RELIR database contains two accidents, both happened in France.

It can be concluded there are much less reports on accidents related to industrial accelerators than to irradiators using radioactive materials as safety features installed enable easier maintenance of safety in such facilities than in facilities using radioactive sources. In addition, collimated fields used at accelerator's facilities contribute to partial exposure to bodies in case of an accidents, e.g. in general amputation of limbs could be required in worst-case scenario.

A short overview of event reported based on the available open literature is structured in a table 1 in a way to compare these very few accidents which happened with accelerators used in industry. In all cases:

- the exposure time was short, e.g. of the order of one minute,
- as a rule, amputation of one or more limbs or skin grafting of exposed persons was necessary.

In one particular case a person was 6 weeks in coma and placed in a sterile chamber, while in another case a complete bone marrow transplant was necessary. Just in one case no such extensive medical procedures were required.

The literature given above contains also accidents related to the research facilities, e.g. such as “Hanoi accident”, Vietnam, in 1974 [12], where a physicist was a victim of an accident related to somehow old accelerator from Dubna. All such somehow research-related accidents are not included in the analysis.

The literature did not contain any information related to any standards to be used at the time of the accident. Today the ANSI N43.1. from 2011 on radiation safety for the design and operation of particle accelerators can be used.

Table 1: Accidents related to industrial accelerator facility

Case 1: Linear accelerator with a 10 MeV beam, Illinois (USA), 1965	
Initial Event	The worker entered to the irradiation room via a gap under the door, i.e. without tripping the interlock, during the irradiation. Up to 2400 Gy were received by various parts of his body.
Contributing Factor	The gap under the door enabled violation of operator’ procedures.
Responsibility	The operator did not follow the rules to be used when entering the irradiation room. The gap under the door used to accommodate the convey belt was not closed, i.e. the licensee was responsible for this error.
Lessons Learned	The designs of the facility shall not be a changed by any modification which can jeopardise the safety. The operators shall understand and follow the procedures.
Case 2*: Van de Graaff linear accelerator with a 13 MeV beam, Illinois (USA), 1967	
Initial Event	The workers were irradiated when entering the irradiation room. The maximum whole body dose was approximately 6 Gy.
Contributing Factor	One interlock was not working and several interlocks were taped.
Responsibility	Licensee should assure functioning of interlocks. (A note: A role of workers in this case is not known.)
Lessons Learned	The licensee shall assure functioning of interlocks, taping interlocks shall not be tolerated.
Case 3: Linear accelerator with a 3 MV potential drop, Maryland (USA), 1991	
Initial Event	The maintenance worker, i.e. operator in this case, was conducting maintenance when the filament current was off. He was unaware of the risk of existing so-called “dark currents” also called “cold currents” producing the dose rates up to 13 Gy/s. The estimated doses were up to 55 Gy.
Contributing Factor	The interlock systems and other safety features were not designed in line with safety rules, e.g. independence, redundancy and diversity,

	allowing the entrance to the irradiation room when dose rates in the room were high. The maintenance worker did not follow the rules.
Responsibility	The maintenance staff did not have enough knowledge to provide maintenance of the accelerator and to understand the importance to follow the procedures. The safety features shall be redesigned, i.e. the licensee was responsible for this error.
Lessons Learned	The designs of the facility shall enable safe maintenance. The maintenance staff shall be trained to follow rules.
Case 4: Linear accelerator with a 2.5 MV, maximum current of 35 mA and maximum dose rate 80 000 Gy/s, Forbach (France) 1991	
Initial Event	The part-time workers entered to the irradiation rooms in order to provide maintenance of auxiliary equipment. “Dark current” caused dose rates up to 0.1 Gy/s. The whole body doses were up to 1 Gy and doses to the skin up to 40 Gy.
Contributing Factor	The second-hand facility had equipment which was not designed for such high exposure fields. The licensee did not have enough knowledge about safety requirements for such facility.
Responsibility	The licensee using second-hand facility did not assure safety measures to be in place due to a lack of understanding. The licensee did not assure the competence of the workers. The workers did not follow safety procedures.
Lessons Learned	The maintenance of the facility should be in line with the safety precautions. In particular, all auxiliary equipment and materials, e.g. oils, shall be resistant to high radiation field. The operators shall be trained to follow rules, as two of the workers were classified as workers of “category B” according to the 2013/59/Euratom Directive their competence was not assured.
Case 5: Linear accelerator with a 800 kV and maximum current of 100 mA (France) date not known	
Initial Event	Three workers entered to the irradiation rooms in order to check ventilation system when the operator started with irradiation. The effective doses received were between 30 to 35 mSv.
Contributing Factor	Safety procedures were not in place. The persons involved in the accident did not have appropriate retraining.
Responsibility	The licensee did not assure safety features and appropriate retraining of the personnel.
Lessons Learned	Safety features must be upgraded in line with international standards. Retraining of personnel shall be in place. Safety procedures shall be in place.

* The accelerator was used for soil irradiation.

As noted from the table the accidents were related to a set of violations of basic safety rules, e.g. among others a person entering the irradiation room should always have appropriate equipment to measure dose rates, should have an alarm dosimeter and have a possibility to observe clear display of the status of the radiation field in the irradiation room. Any unauthorized modification or negligence of interlocks in intolerable. In addition, despite the fact that the irradiation can be quite routine procedure this does not mean that competence of the personnel involved shall not be regularly verified as clear understanding the risk is the first step in safe operation of such facility. Poor understanding of acceleratory technology and in particular "dark current" phenomena and lack of exchange operational experiences were contributing factors to the reported accidents. In particular, two of five accidents, both related to "dark current", are almost identical.

3 CONCLUSIONS

The very first analysis of accidents leading to overexposure of humans at industrial accelerator facilities shows that the number of such accidents is much lower than the number of accidents in industrial facilities with irradiators using radioactive sources. The accidents related to accelerators are actually extremely rare. However, it must be pointed out that, as a rule, the exposures of only few minutes in irradiation room can lead to amputation of limbs of the exposed worker.

The present analysis of reported accidents might help the regulatory bodies, designers, suppliers, installers, operators, maintenance companies and others involved in radiation safety of industrial accelerators to identify design flaws as well as human errors leading to such rare but dreadful accidents. The analysis demonstrated that two of five cases were related to "dark current" showing that there was a clear lack of understanding technical characteristics of accelerators and the risks associated with such facilities.

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