



# Lessons Learned: a nuclear knowledge management tool for learning about radiation accidents

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## ABSTRACT

According to the International Atomic Energy Agency (IAEA), the lessons learned (LL) in a radiation accident are extremely important for the building of learning about accidents, identifying best practices and preventing new accidents from occurring. Thereby, it was noted that the LL identified from the accident analysis led to the adoption of a series of measures to make facilities safer and more prepared for such accidents. In this sense, the objective of this paper is to make a bibliometric review on the accidents involving radiation material, based in the main publications of the IAEA about LL. It is understood that, in relation to the dissemination of knowledge, the analysis of the LL as a tool for Nuclear Knowledge Management (NKM) is of extra relevance, not only for studies and learning in the area, but mainly for the prevention of accidents. So is evident that the analysis of the LL about radiation accidents is a powerful learning tool in the field of radiation protection, promoting the discussion about a wider knowledge over nuclear energy. It is then observed the importance of evaluating LL to strengthen the NKM.

**Keywords:** Lessons Learned, Nuclear Knowledge Management, Bibliometric Review, International Atomic Energy Agency, Radiation Protection, Radiation Accident.

## 1. INTRODUCTION

### 1.1. Presentation

According to the International Atomic Energy Agency (IAEA), the lessons learned (LL) in a radiation accident are extremely important for the building of learning about accidents, identifying best practices and preventing new accidents from occurring. In this sense, the IAEA included in the Safety Standards, stated in the Fundamental Safety Principles publication, the principles for the effective management of safety [1].

In particular, in the Fundamental Safety Principles, under Principle 3, which deals with leadership and management for safety, the publication states that “processes must be put in place for the feedback and analysis of ... accidents ... so that lessons may be learned, shared and acted upon”[1]. This point is also covered in GS-R-2, where it is stated that

...arrangements shall be made to maintain, review and update emergency plans, procedures and other arrangements and to incorporate lessons learned from research, operating experience (such as the response to emergencies) and emergency drills and exercises as part of the quality assurance programme. [1, p.7].

Thereby, IAEA, during the General Conference, in September 2011, in resolution GC(55)/RES/9, emphasized for all Member States that

...the importance...to implement emergency preparedness and response mechanisms and develop mitigation measures at a national level, consistent with the Agency's Safety Standards and further requested “the Secretariat to continue improving methods of exchange of knowledge and experience in the area of emergency preparedness and response and strongly encouraged Member States to participate actively in this exchange” [1, p.7].

So, LL have been learned from investigations into a relatively large number of accidents that have occurred in different practices. The retrospective study of accidents is essential to prevention, which is why the IAEA have devoted a considerable amount of resources to this area [2].

The body of knowledge gained from these investigations can, in general, be involved in accidents with: nuclear (power plants) and radioactive materials (as industrial radiography and radiotherapy) [2, 3]. In addition to published reports, another tool for dissemination of LL from accidents (LLA) is IAEA's international reporting system of unusual radiation events (RADEV) [2].

## 1.2. The importance of Lessons Learned to Nuclear Knowledge Management

It was verified the essential role that the study of LLA has in preventing accidents in different areas. And a practice also used by the IAEA in relation to radioactive activities is Nuclear Knowledge Management (NKM). So, to IAEA, the importance of NKM is in fact that building, collecting, transferring, sharing, preserving, maintaining and utilizing knowledge is essential to developing and keeping the necessary technical expertise and competences required for nuclear power programmes and other nuclear technology [4].

This is because, for the IAEA, knowledge is the most valuable asset for any radioactive installation, given that advanced and specialized knowledge in nuclear engineering and science is required for the safe and effective design, construction, licensing, commissioning, operation, maintenance and decommissioning of nuclear technology-based systems, which may have long life cycles in changing contexts [4].

According to IAEA, appropriate expertise must be developed and kept available throughout the nuclear technology life cycle, where effective Knowledge Management (KM) helps achieve this objective, so that the safe use of licensed nuclear facilities and technologies is reliant on the ongoing availability and maintenance of suitable knowledge and expertise, including an adequate understanding of related safety issues [4]. In this sense:

Recognizing the importance of nuclear knowledge management, the IAEA develops methodologies and guidance documents for planning, designing and implementing nuclear knowledge management programmes and facilitates nuclear education, providing support, networking opportunities and experience exchange. The IAEA assists Member States by providing products and services for maintaining and preserving nuclear knowledge and by promoting the use of state-of-the-art knowledge management technologies [4, n.p.].

In addition, it can be said that there is a direct relationship between LL and KM or NKM. For instance, radiation protection is a set of measures designed to protect humans, their offspring and the environment against possible undue effects caused by ionizing radiation from sources and technologically modified natural sources [5].

Then, when approaching learning in the face of tragedy, through the radiological accident in Goiânia, or example, one cannot fail to emphasize the importance of KM as a tool both for the training of human resources, but also in the legacies left from events of this nature [4, 6]. So,

The management of information and knowledge is a theme that has been widely discussed, in several spaces, in Brazil, especially in higher education organizations and institutions. This is a complex discussion that involves many aspects both because it is located at points of intersection between several fields of knowledge, notably Administration, Computer Science and Production Engineering, as well as the objective constraints of its organizational theories and practices [6, p. 55].

Thus, KM as a discipline started with information science and has since expanded to all other areas [7]. It can be inferred that:

The understanding of Knowledge Management according to the process by which strategic information is identified, analysed and interpreted with the purpose of generating new information and knowledge that support the processes of decision-making and action demonstrates that this process can be applied in other environments other than business. Information flows are established by all human activities and Knowledge Management can be applied, according to the purpose of each enterprise, whether scientific, business or political [8, p. 15].

In this sense, LL would be the key experiences that hold some relevance for future projects, and some author's present different definitions and conceptions of LL [9, 10]. Thus, the LL would be, in general:

- a. means to make knowledge explicit, to develop it and to increase its comparability, in order to contribute to learning [11];
- b. learning's obtained in the process of realizing a project, can be identified and registered at any time, to generate a knowledge base [12];
- c. a foundation for innovation, by identifying the root cause of successes and failures, helping to improve the process [4].

On the other hand, the relationship between LL and KM would have the main objective of transmitting empirical knowledge to an organization (be it operational, tacit or strategic), positively impacting the results of organization, making the LL stored in a knowledge base [7].

Thus, under the view of KM, any and all experience is knowledge, and should be explicit, shared and disseminated to add value to people and organizations, so that Km would be the management of activities and processes, promoting knowledge through the best use and creation of individual and collective sources of knowledge [8,10, 13, 14].

Therefore, the understanding of NKM as a process by which strategic information is identified, analyzed and interpreted in order to generate new information and knowledge that supports decision-making and action processes, demonstrates that this process can be applied in different

environments. In this sense, the objective of this paper is to make a general review of some LLA, so that, from the NKM, analyze the main legacies with respect to the issue of radiation protection and radiological emergency that can be carried out. In this sense, this paper provides an overview of the LL and specifically considers the human actions and omissions that have resulted in an accident, focusing on accidents that have occurred at nuclear (power plants) and radiological (as industrial radiography and and radiotherapy) levels.

## **2. MATERIALS AND METHODS**

Then, the mainly objective of this paper is to make a bibliometric review on the accidents involving radioactive materials, based on the publications of the IAEA about LL and LLA.

## **3. RESULTS AND DISCUSSION**

It will be now present the results regarding the research on bibliometric review on IAEA about LL, that is, the main LL publications related to accidents involving radioactive material and industrial radiography, irradiators and radiotherapy.

Thus, the results will be presented in 3 major groups of IAEA publications: 1. IAEA scientific and technical publications about LL ; 2. Accidents in industrial radiography, irradiators and radiotherapy; and 3. A brief history of the major accidents involving radioactive material.

### **IAEA SCIENTIFIC AND TECHNICAL PUBLICATIONS ABOUT LL AND LLA**

A total of IAEA scientific and technical publications can be searched by multiple parameters, as Topic and Type. Now, the publications about LL and LLA will be identified according to the Topic and Type of publications [15] :

#### **A) Topics**

The publications are classified into 14 Topics. The Topics (and their respective subdivisions) will be presented here. The total number of publications, the total number of publications on LL and

LLA are indicated in parentheses (T/LL/LLA). Only the publications on LL and LLA (in underlined) will be presented here. Some publications appear repeatedly or appear in different languages on different Topics:

- 1) Accident reports (16/0/0);
- 2) Department of Nuclear Energy (3/0/0);
  - 2.1) Division of Nuclear Power (2/0/0);
    - 2.1.1) International Project on Innovative Nuclear Reactors and Fuel Cycles Section (1/1/0) – “Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)” - 2009;
  - 2.2) Division of Nuclear Fuel Cycle and Waste Technology (1/0/0);
    - 2.2.1) Decommissioning and Environmental Remediation Section (1/0/0);
- 3) Nuclear power plant safety (3/1/0) – “Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL)” - 2015;
  - 3.1) Operation and maintenance of nuclear power plants (8/0/0);
  - 3.2) Construction and commissioning of nuclear power plants (2/0/0);
  - 3.3) Decommissioning of nuclear installations (2/0/0);
  - 3.4) Design of nuclear power plants (2/1/0) – “Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident” – 2016;
- 4) Management systems (2/0/0);
- 5) Nuclear safety and security (2/0/0);
  - 5.1) Emergency preparedness and response (EPR) (6/0/0);
  - 5.2) Radiation protection (2/0/0);
    - 5.2.1) Patients (1/0/0);
    - 5.2.2) Public (1/0/0);
    - 5.2.3) Workers (1/0/0);
  - 5.3) Radioactive waste and spent fuel management (1/0/0);
    - 5.3.1) Decommissioning of nuclear installations (2/0/0);
  - 5.4) Security of nuclear and other radioactive material (1/0/0);

5.4.1) Public events security (4/0/0);

5.4.2) Nuclear forensics (2/0/0);

6) Nuclear technology and applications (2/1/0) –“Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned” – 2011;

6.1) Energy (8/2/0) – “Lessons Learned from the Deferred Dismantling of Nuclear Facilities” - 2018; “Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)” – 2009;

6.1.1) Nuclear power reactors (10/1/0) –“Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL)”- 2015;

6.1.1.1) Fast reactors (1/0/0);

6.1.1.2) Small modular reactors (1/0/0);

6.1.2) Nuclear fuel cycle (4/1/0) –“Experiences and Lessons Learned Worldwide in the Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents” – 2014;

6.1.2.1) Nuclear fuel utilization (1/0/0);

6.1.3) Energy planning (2/0/0);

6.1.4) Nuclear power plant life cycle (2/0/0);

6.1.4.1) Operation and maintenance of nuclear power plants (8/0/0);

6.1.4.2) Construction and commissioning of nuclear power plants (2/0/0);

6.1.4.3) Decommissioning of nuclear installations (2/0/0);

6.1.4.4) Design of nuclear power plants (2/1/0) – “Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident” – 2016;

6.1.4.5) Siting of nuclear facilities (1/0/0);

6.1.5) Nuclear infrastructure (1/0/0);

6.1.5.1) Infrastructure development (2/0/0);

6.1.6) Research reactors (1/0/0);

6.2) Addressing environmental issues (1/1/0) – “Lessons Learned from Environmental Remediation Programmes” – 2014;

6.3) Food and agriculture (1/0/0);

- 7) Assessment of contamination in agriculture (1/0/0);
- 8) Chernobyl Nuclear Accident (1/0/0);
- 9) Department of Nuclear Safety and Security (1/0/0);
  - 9.1) Division of Nuclear Security (1/0/0);
  - 9.2) Incident and Emergency Centre (1/0/0);
- 10) Fukushima Nuclear Accident (1/1/0) – “Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident” – 2016;
- 11) Industrial applications (1/0/0);
  - 11.1) Environmental remediation for industry (1/0/0);
- 12) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) (1/1/0) – “Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)” - 2009;
- 13) Neutron activation analysis (1/0/0);
- 14) Nuclear waste treatment (1/0/0) – “Management of Disused Sealed Radioactive Sources” – 2014.

## B) Type

The publications are classified into 10Types. The Types (and their respective subdivisions) will be presented here. The total number of publications, the total number of publications on LL and the total number of publications on LLA are indicated in parentheses (T/LL/LLA). Only the publications on LL and on LLA (in underlined) will be presented here. Some publications appear repeatedly or appear in different languages on different Types:

- 1) TECDOC Series (35/9/0) - Spent Fuel Storage Operation — “Lessons Learned” – 2013; “Experience Gained from Fires in Nuclear Power Plants: Lessons Learned” – 2004; “Planning, Managing and Organizing the Decommissioning of Nuclear Facilities: Lessons Learned” – 2004; “Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident” – 2016; “Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)” – 2009; “Managing Human Resources in the



Nuclear Power Industry: Lessons Learned” – 2003; “Follow-up of delayed health consequences of acute accidental radiation exposure Lessons to be learned from their medical management” – 2002; “Nuclear Power Plant Organization and Staffing for Improved Performance: Lessons Learned” - 1998; “International Experience in the Implementation of Lessons Learned from the Three Mile Island Incident” - 1983;

2) Non-serial Publications (32/2/2) – “Lessons Learned from Accidents in Industrial Irradiation Facilities” - 1996; “Lessons Learned from Accidents in Industrial Irradiation Facilities (Russian Edition)” - 1998;

3) Nuclear Energy Series (22/5/0) – “Lessons Learned from the Deferred Dismantling of Nuclear Facilities” - 2018; “Experiences and Lessons Learned Worldwide in the Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents” - 2014; “Redevelopment and Reuse of Nuclear Facilities and Sites: Case Histories and Lessons Learned” - 2011; “Lessons Learned from Environmental Remediation Programmes” - 2014; “Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned” - 2011;

4) Proceedings Series (10/1/0) – “Lessons Learned from the Decommissioning of Nuclear Facilities and the Safe Termination of Nuclear Activities” - 2007;

5) Technical Reports Series (10/0/0);

6) Emergency Preparedness and Response (6/5/5) – “Lessons Learned from the Response to Radiation Emergencies (1945-2010)” - 2015; “Lessons Learned from the Response to Radiation Emergencies (1945–2010)” - 2014; “Lessons Learned from the Response to Radiation Emergencies (1945–2010)” - 2013; “Lessons Learned from the Response to Radiation Emergencies (1945–2010)” - 2013; “Lessons Learned from the Response to Radiation Emergencies (1945–2010)” – 2012”;

7) Safety Reports Series (6/4/3) – “Lessons Learned from Accidents in Industrial Radiography” - 1998; “Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL)” - 2015; “Lessons Learned from Accidental Exposures in Radiotherapy” - 2000; “Technical Approach to Probabilistic Safety Assessment for Multiple Reactor Units” - 2019;

8) Nuclear Security Series (3/0/0);

8.1) Implementing Guides (2/0/0);

9) TECDOC Series (CD-ROM) (2/0/0);

10) INSAG Series (1/0/0).

From the total of publications, one can infer the following relationships about LL and LLA:

A) Topic - 122/12/0, which corresponds to a relationship between the total publications and LL publications of 9.8% and the total publications and LLA of 0%, while the relationship between LL publications and LLA publications is 0%;

B) Type - 129/26/10, which corresponds to a relationship between the total publications and LL publications of 20.2% and the total publications and LLA publications of 7.8%, while the relationship between LL publications and LLA publications is 38.5%.

Then, the 6 publications on accidents are: 1) "Lessons Learned from the Response to Radiation Emergencies (1945-2010)" - 2015; 2) "Lessons Learned from Accidents in Industrial Irradiation Facilities" - 1996; 3) "Lessons Learned from Accidents in Industrial Radiography (1998); 4) Lessons Learned from Accidental Exposures in Radiotherapy" - 2000; 5) "International Experience in the Implementation of Lessons Learned from the Three Mile Island Incident" - 1983; 6) "Lessons Learned from the Three Mile Island Incident" - 1983 [15].

Three of these publications on accidents are briefly described, with a more general approach and the corresponding LL [15]:

I. "Lessons learned from accidents in industrial radiography" - 1998

This "Safety Report" discusses the issue of the use of ionizing radiation for technical development in medicine, industry and research. A long-established application of ionizing radiation is the use of X-rays and gamma for industrial radiography. In almost all IAEA Member States, industrial radiography is performed in companies ranging from multinational companies to small businesses, consisting of one or two people.

In addition, radiography is performed at thousands of sites, including shielded enclosures (fixed installations) and remote field sites, and covers many different applications. Industrial radiography accounts for about half of all accidents reported to the nuclear industry in both developed and developing countries.

This was the reason for a review of these accidents by a team of regulatory authorities, manufacturers and safety consultants. Based on a study of the circumstances of each accident and apparent deficiencies in safety, regulatory system, design and staff performance, a number of measures were identified that, if implemented, would improve safety performance.

This report contains the results of extensive research in terms of lessons that can be learned from accidents. The information contained in this report is intended to be used by regulatory authorities, operational organizations, workers, manufacturers and customer organizations responsible for radiation protection and safety in industrial radiography.

## II. "Lessons learned from accidental exposures in radiotherapy" - 2000

In this "Safety Series" it is argued that the medical use of radiation is unique in that patients are intentionally exposed to radiation. The goal of radiation therapy is two fold: delivering a dose and dose distribution suitable for tumor control, but also minimizing complications in normal tissues. In therapeutic applications, doses are high and a deviation from the prescribed dose can have serious or even fatal consequences.

Therefore, there is a strong need to ensure adequate radiation protection and radiation safety by verifying that all personnel involved are properly trained for their functions, that the equipment used meets the international specifications relevant to radiation safety and that the safety culture is embedded in routine activities in radiotherapy departments. Many people should interact and work together on highly technical measures and calculations, and therefore the potential for errors is great. A review of the errors shows that most are due to a human error.

The International Basic Safety Standards for Protection against Ionizing Radiation and Safety from Radiation Sources (IAEA Safety Series No. 115) require that an immediate investigation be performed whenever accidental medical exposure of patients occurs. The investigation report must be disclosed to the appropriate parties so that the lessons can be learned to avoid similar accidents or mitigate their consequences in the future.

This safety report is a collection of a large number of events that can serve as a checklist to test a facility's vulnerability to possible accidents and provide a basis for improving safety in the use of radiation in medical applications. Another objective of this report is to encourage readers to develop a questioning and learning attitude, to adopt measures for the prevention of accidents and to prepare the mitigation of the consequences of accidents if they occur.

## III. "Lessons Learned from the Response to Radiation Emergencies (1945-2010)" - 2013

In this report, it is said that the IAEA Statute authorizes the IAEA to establish safety standards to protect health and minimize the danger to life and property. According to the IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles, the fundamental safety objectives, safety

principles and concepts that lay the foundation for the safety standards and the safety aspects of the IAEA are established. Related requirements are set forth in the safety requirements publications, while guidance on compliance with the requirements is provided in the related Safety Guides.

The publication "Fundamentals Safety Principles" contains ten principles of safety and briefly describes its intention and purpose. Principle 9, for example, states that "arrangements should be made for emergency preparedness and response for nuclear or radiation incidents". Requirements for emergency preparedness and response to nuclear or radiological emergencies in any country are provided in the IAEA Standard Safety Series, GS-R-2, "Preparation and Response for a Nuclear or Radiological Emergency", prepared jointly by seven organizations of different countries.

Included in the safety principles set out in the publication "Fundamentals Safety Principles", they represent principles for effective safety management. In particular, in Principle 3, which deals with leadership and safety management, the publication states that "processes should be put in place for feedback and accident analysis so lessons can be learned, shared and acted upon." This point is also covered in GS-R-2, which states: "Arrangements should be made to maintain, review and update emergency plans, procedures and other arrangements and incorporate lessons learned from research, operational experience (such as emergency response). The IAEA General Conference of September 2011, in resolution GC (55) / RES / 9, emphasized for all Member States the importance for implementing emergency preparedness and response mechanisms and developing mitigation measures at the national level, in accordance with the Safety Standards and further requested.

The Secretariat should continue to improve methods of exchange of knowledge and experience in the area of emergency preparedness and response and encourage Member States to participate actively in this exchange. While the primary responsibility for safety must be with the person or organization responsible for facilities and activities that give rise to radiation hazards (Principle 1 of the Publication of Fundamental Principles of Safety), the IAEA also has a responsibility to assist its Member States in improvement. Firstly, under its Statute, it is authorized to provide for the application of its standards. Secondly, one of the tasks assigned to the IAEA in accordance with Article 5a. (ii) of the Convention on Assistance in Case of a Nuclear or Radiological Accident, the emergency is to collect and disseminate information from States Parties and Member States on available methodologies, techniques and research results related to the response to nuclear accidents or radiological emergencies.

This publication has been prepared to assist IAEA Member States in assimilating these lessons from past emergencies that reinforce the safety requirements given in the publication of GS-R-2 safety requirements. However, this report was written before the March 2011 earthquake in Japan and does not include consideration of the accident at the Fukushima Daiichi nuclear power plant at TEPCO.

## ACCIDENTS IN INDUSTRIAL RADIOGRAPHY, IRRADIATORS AND RADIOTHERAPY

The following analysis was based on investigations of individual accidents in the IAEA Accident Report Series [2]. Three summary tables will be presented: Table 1 on accidents involving radiotherapy patients, Table 2 on industrial accidents and Tables 3 and 4 on loss of sources that caused deaths or several injuries, respectively. Also, after each table, the main LL will be presented.

**Table 1:** Accidents involving radiotherapy patients

Country	Year	No of patients affected	Causes and main contributing factors
USA	1974-76	426	Co-60 dose calculations based on erroneous decay chart (varying overdoses); no independent verification of decay charts and dose calculations; More than two years without beam measurements; Physics manpower and attention shifted to others tasks, such as a new accelerator
Germany	1986-87	86	Co-60 dose calculations based on erroneous dose tables; varying overdoses; no independent determination of the dose rate
UK	1988	207	Error in the calibration of a Co-60 therapy unit (25% overdose); no independent calibration of the beam
UK	1988-89	22	Error in the identification of Cs-137 brachytherapy sources (-20 to +10% dosimetry errors); no independent determination of source strength
Spain	1990	27 (18 deaths from radiation)	Error in the maintenance of a clinical linear accelerator; Procedures for transferring machine from and to maintenance (informing physicists) not followed; Conflicting signals and displays ignored; Procedures for periodic beam verifications (QA) not implemented; Overdosage ranging from 200% to 700%
UK	1982-91	nearly 1,000	Inappropriate commissioning of a computerized Treatment Planning System (5-30% underdosage); No written proce-

			dures for commissioning and use
USA	1992	1 (death from radiation)	Brachytherapy source (High Dose Rate) left inside the patient; Source dislodged from equipment; Conflicting monitor signals and displays ignored
Costa Rica	1996	115 (at least 17 deaths from radiation)	Error in calculation during the calibration of Co-60 therapy Unit; lack of independent calibration and of QA; Recommendations from an external audit ignored

Source: [b].

As LL, a structured and systematic approach is needed of activities; licensing of a radiotherapy department should be conditional on a comprehensive quality assurance programme; embrace treatment prescription, planning and delivery, as well as the organization of the radiotherapy department; maintenance of radiotherapy equipment and the staff qualifications and training; maintain the level of safety over time, which means looking at indicators of slow degradation. For this purpose, inspectors should not only look for formal compliance, but also for early warnings of potential problems [b].

**Table 2:** Accidents involving industrial irradiation facilities

Year	Place	Type Facility	OfOutcome	Estimated Dose	Remarks
1965	Illinois,USA	Accelerator	One person - amputation of leg and arm	290-2400Gy	
1967	Pittsburg, USA	Accelerator	3 irradiated people, one of which required the amputation of both hands	1-6 Gy	Failure of interlocks
1974	New Jersey, USA	Gamma	1 person, Acute radiation	~4 Gy	
1975	Stimos, Italy	Gamma	1 fatality	~12 Gy	
1977	New Jersey, USA	Gamma	1 person, Acute syndrome	~2 Gy	Short exposure, because he realized that the source was exposed and left immediately
1982	Kjeller,	Gamma	1 fatality	~22 Gy	

	Norwat				
1989	San Salvador, El Salvador	Gamma	1 fatality	~8 Gy	Two other persons with whole body doses of 2.9- 3.7 Gy
1990	Soreq, Israel	Gamma	1 fatality	~10-20 Gy	
1991	Nesvizh, Belarus	Gamma	1 fatality	~11 Gy	
1991	Hanoi, Viet Nam	Accelerator	Amputation of one hand and fingers of the other	~10-50 Gy	
1991	Maryland, USA	Accelerator	Amputation of four fingers of each hand	~55 Gy	
1991	Forbach, France	Accelerator	Skin lesions	~40 Gy	

Source: [b].

As LL, long as technological safety barriers remain effective, the probability of an accident with an irradiator is extremely low; the operational safety programme should ensure that all safety interlocks remain effective over time, so that the overall probability is not increased by the removal of any of the layers; for irradiators, maintenance of these systems and trust in them is essential to the behaviour of staff; the recommendations given earlier for industrial radiography, with respect to illustrating the consequences with pictures for training purposes, praising safework rather than production, and close supervision with the objective of detecting early signs of degradation of safety, are also valid for irradiators; the recommendations given for industrial radiography with respect to licensing and inspection procedures are also applicable to irradiators; at the application stage the following issues should be addressed: What are the rules in case of conflicting signals? Who is responsible for arranging maintenance and repairs? What is the policy with regard to spare monitors or other devices? What is the operator expected to do when there is a false alarm? Which supervisory measures and policy statements are in place to ensure sufficient contact between the operator and radiation protection officer (RPO) to detect the early failure of safety systems, unauthorised tampering of safety systems, or failure to report and/or record a safety event? [b].

**Table 3:** Accidents involving loss of source that caused deaths

Year	Place	Radionuclide	Source from	Estimated Dose	Number of deaths	Remarks
1962	Mexico City, Mexico	Co-60	Industrial radiography	9.9-52 Gy	4	
1963	China	Co-60	Industrial irradiator	0.2-80 Gy	2	Source taken home from a burial place (waste repository)
1984	Morocco	Ir-192	Industrial radiography	Unknown	8	loss of control of source; (failure to control retraction to shielding)
1987	Goiania, Brazil	Cs-137	Medical teletherapy	Up to 7 Gy ext and int	4	Radiation unit with source unsecured after decommissioning
1992	China	Co-60	Industrial irradiator	.25-10 Gy local	3	Source taken home from an irradiator during decommissioning
1994	Tammiku, Estonia	Cs-137	Waste repository	4 Gy whole body, 1800 local	1	loss of control of source; unsecured waste storage
1997	Georgia	Co-60	Medical teletherapy	Unknown	1	Source about to be returned; unsecured near a station

Source: [b].

As LL, a mobile radiography sources are the most important contributor to this type of accident; the typical scenario was a radiography source that dropped from the radiography device and was placed in a person's pocket; in many of these accidents, the source was dropped at the radiography site, and was picked up by a construction worker who was not associated with the use of the source and therefore not aware of the potential hazard; accidents have also occurred when sources have fallen out of unlocked exposure devices during transportation and resulted in the exposure of several members of the public.



**Table 4:** Accidents involving loss of source that caused several injuries

Year	Place	Radionuclide	Activity	Source from	Dose	Consequences
1968	La Plata, Argentina	Cs-137	Unknown	Industrial radiography	Local dose from	Amputation of both legs, permanent sterility
1971	Chiba, Japan	Ir-192	5.26 Ci	Industrial radiography	From 0.15 to 1.3 Gy	whole body Six persons (construction workers) exposed, three of them with acute syndrome
1978	Algeria	Ir-192	25 Ci	Industrial radiography	1 to 1.4 Gy	whole body, 25 Gy skin dose Irradiation of a family, including two children, amputation of fingers, grafting and flap at the buttock, injury in the mouth, four other patients suffered acute syndrome
1979	Los Angeles, USA	Ir-192	28 Ci	Industrial radiography	unknown	11 persons exposed, one of them needed skin drafting at the buttock
1983	Ciudad Juárez, Mexico	Co-60	15 TBq	Teletherapy	3.0 to 7.0 Gy(five persons) and from 0.25 to 3.0 Gy (75 persons)	Acute syndrome
1996	Iran	unknown	unknown	Industrial radiography	Local dose from	11 people with radiation injuries
1996	Lilo, Georgia	Cs-137	Four sources, 150	Sources for exercises by	Local dose	Injuries

			GBq (4 Ci) each	the army, were later abandoned	from	
1999	Yanango, Perú	Ir-192	unknown	Industrial radiography	Local dose from	Amputation of leg
1999	Istanbul, Turkey	Co-60	unknown	Teletherapy	Local dose from	10 persons with acute syndrome

Source: [b].

As LL, the simple knowledge of these facts should lead to straight forward regulatory actions to prevent major accidents arising from loss of control of sources; the first priority should be the verification that sources in industrial radiography, irradiators and medical teletherapy are under control; in developing countries, the small number of irradiators and medical teletherapy facilities should make this control relatively straight forward; the control of industrial radiography sources is, however, complicated by the fact that mobile sources may be lost any time during operation or transport; the majority of mobile radiography devices house sources of Ir-192, of the order of TBq (a few tens of Ci); since iridium-192 has a relatively short half-life, sources older than two years will not pose a significant threat and therefore priority should focus on iridium sources lost in recent months and on any Cs-137 and Co-60 sources.

### **A BRIEF HISTORY OF THE MAJOR ACCIDENTS INVOLVING RADIOACTIVE MATERIAL**

A total of 10 accidents involving radioactive materials were identified, listed in chronological order and the respective LL (with a briefly description and the corresponding LL) [15-20]:

**1) Kyshtym** (Ozyorsk - 1957) - The Mayak plant in the Soviet Union suffered a failure in the cooling system of the nuclear waste storage compartment, which caused an explosion in a tank containing 80 tons of radioactive material. The gas cloud contaminated the region within a radius of 800 km. The event was called "the Kyshtym disaster". About 10,000 people were evacuated, with no explanation from the government. At least 200 deaths were recorded because of exposure to radiation;

**2) Windscale** (1957) - During the Second World War, England also sought to develop nuclear weapons. The rush to make an atomic bomb in Windscale led to a fire in the reactor, leaking radioactive material into the atmosphere. It caused more than two hundred cases of cancer among neighboring communities;

**3) Yucca Flat** (1970) - This region of intense nuclear tests is located in Nevada, 65 km from Las Vegas. In December 1970, a high-powered device was detonated underground, but caused cracking, which resulted in radioactive debris in the atmosphere. About 86 workers were exposed to radiation. It is not known what happened to the employees. Currently deactivated, the region received its last test in 1992;

**4) Bohunice** (1977) - The accident at the Bohunice plant in Czechoslovakia (now divided into Czech Republic and Slovakia) occurred after a fuel change. The moisture absorbers that covered the fuel rods were not removed in the correct way. As a consequence, the fuel overheated, leading to corrosion of the reactor. According to the IAEA, there are no adequate estimates of injuries or deaths because, at the time, the accident would have been covered by the Soviet government. What is known is that the radioactive gases spread throughout the plant;

**5) Three Miles Island** (1979) - The North American nuclear plant at Three Miles Island in Pennsylvania was the scene of the worst nuclear accident up until the 80s. It was an accident caused by equipment failure and operational error in evaluating reactor conditions. The equipment failure caused a gradual loss of cooling water in the reactor core which resulted in a partial melting of the element-fuel rods, with release of radioactive material inside the building, including gases such as Xenon (Xe), Krypton (Kr) and also traces of iodine (I) released into the atmosphere;

**6) Chernobyl** (1986) - The Chernobyl accident is considered to be the largest nuclear disaster in history, resulting in the exposure of people in the regions known today as Belarus, Russia, Ukraine and the population of several European countries. The accident occurred because the on-call team wanted to do tests in Unit 4, requested by the then-Soviet State Atomic Energy Committee, to increase reactor safety. This procedure isolated the reactor, since, with the control rods raised, followed with little amount of water circulating in the nucleus, safety systems turned off and with the increase of the steam and the internal pressure, these conditions, made it impossible to control. Studies after the accident indicated that the reactor became highly unstable at low power, and this fault was unknown to the operators. For the test to happen, the staff on duty broke certain safety

rules. Among other errors, the officials involved in the episode interrupted the circulation of the hydraulic system that controlled the reactor temperatures. Thus, even when operating at a lower capacity, the reactor had entered a process of overheating that can not be reversed. In a few moments the formation of an immense ball of fire created an explosion of the reactor rich in Uranium-235, chemical element of great radioactive power. With this, the Chernobyl plant released a lethal amount of radioactive material that contaminated a large atmospheric region. In comparative terms, the radioactive material released at that time was four hundred times greater than the bombs used in the bombing of Hiroshima and Nagasaki at the end of World War II;

**7) Goiania (1987)** - The accident in Goiania, known as the "Césio-137" accident, is considered the largest radiological accident in the world, placing Brazil in the list of countries involved in a tragic radioactive accident. The accident occurred from the violation of a highly radioactive cesium 137 source (with activity of 50.9 (TBq or 1375 Ci), which was spread in the environment, causing the contamination of several locations. After 15 days, Brazilian Nuclear Energy Commission (CNEN) was informed of the accident, which in turn notified the IAEA. An emergency plan was then launched, with the participation of CNEN and various institutions, such as the Radiation Protection and Dosimetry Institute (IRD). The Goiania accident is considered by the IAEA as the worst event with radioactive sources, and is responsible for the IAEA publishing periodically details of the accident and the lessons identified, being available to the public. It is classified in the International Scale of Nuclear Accidents and Radiological (INES) level 5, being the only radiological accident outside such nuclear facilities. The accident occurred due to a series of errors, such as the abandonment of an irradiator used in the radiotherapy service of a local hospital that contained a Cs-137 chloride capsule, due to the lack of information of the local residents, exposing more than one thousand individuals and generating a trace of which affected 129 people. Of these, 49 were hospitalized with severe symptoms and, after intensive treatment, four did not resist and eventually died;

**8) Seversk (1993)** - The city of Seversk, in the Siberia region, houses nuclear reactors and chemical industries for the separation and processing of uranium and plutonium. The Soviet Union did not allow the city to appear on the map, a fact that changed in 1992, following a decree by Boris Yeltsin. Soon after, in 1993, the Tomsk-7 plant suffered an accident, in which a tank with

radioactive substances exploded. A radioactive cloud formed in the region, which today is closed and can only be visited by invitation. The number of victims is unknown;

**9) Tokaimura**(1999) - 100 km from Tokyo, the host city of the Japanese nuclear industry was the scene of an accident that exposed more than 600 people to high radiation in 1999. Employees of a uranium reprocessing company were exposed to an extreme dose of the radioactive metal in a reactor deactivated a year previous, which suffered an uncontrolled reaction, leaking radiation.

**10) Fukushima** (2011) - Located about 250 km north of Tokyo, the Daiichi nuclear power plant in Fukushima suffered damage in three of its six reactors after a level 9-magnitude earth quake hit the country. Japanese authorities have stated that the levels of released radiation were high, almost disturbing. The disaster was classified with grade 5 in the International Scale of Nuclear Accidents (INES). After that, Japanese scientists intend to create a nuclear mini-fusion reactor in order to better understand the 2011 accident and prepare properly in case of new disasters.

#### 4. CONCLUSION

It was noted that the problems identified from the accident analysis led to the adoption of a series of measures to make the installations safer and more prepared for such accidents. Thus, it was sought to evidence radioactive accidents as a learning tool in the field of nuclear energy science, opening space for discussions of a broader knowledge on KM.

It is understood that the analysis of the LL as a tool for NKM is of extreme relevance, not only for the prevention of accidents, but also knowing how to act. Therefore, the importance of inserting KM in radiation protection and emergency, in order to create means of sharing knowledge, preserving the existing knowledge and stimulating new knowledge produced from the progress of the sciences and the advances of new technologies.

This is because, generally, a radiological accident is seen in a very negative way because it brings damage to people and the environment. However, it is necessary to observe that even after a tragedy, one can so learn and draw lessons, which will serve as guiding tools so that events of this nature will not happen again, and in the unfortunate event that they do happen, there is a clear safe reaction for all parties involved.

In addition, since the discovery of radiation and the harm it can cause by its misuse, international organizations have been concerned with more effective protection. It is because radiation protection is a set of measures designed to protect humans, their offspring and the environment against possible undue effects caused by ionizing radiation from man-made sources and sources technologically altered, while an accident can be considered any unintentional event, including operating errors and equipment failures, whose actual or potential consequences are relevant.

From a radiological protection point of view, nuclear accidents are those occurring in facilities such as nuclear reactors and nuclear fuel cycle facilities. On the other hand, radiological accidents involve sources of ionizing radiation used in various practices and can occur anywhere.

In Brazil, the use of nuclear energy is for peaceful purposes, so it is known that the use of radiation in an erroneous way and in an unjustified way can bring about detriment rather than benefits.

However, a more democratic knowledge is necessary in this area, because it can be observed that in the science of ionizing radiation, the management of a knowledge becomes necessary, even for a complex subject and is still not very widespread in Brazil. CNEN also learned important lessons from the accident in Goiânia, teachings and techniques were boosted after the event, as well as greater controls of radioactive sources was introduced. Today in Brazil, there is an up-to-date, integrated register with strict usage and disposal rules. For example, Cesium-137 is a by product of uranium, that is, it can not be found in nature, it is normally produced in Germany or England, if a clinic or a Brazilian hospital wants to import a device with a cesium source, is possible to know exactly who is the importer, for what will be the use and address of the product.

CNEN also has an agreement for the return of radioactive sources to all nations, which means that after 10, 20, or 30 years of use, the source will be returned to the country of origin.

It should be noted that the accidents at Chernobyl and Three Miles Island also served to build the nuclear knowledge management. In the Chernobyl issue, due to the recklessness of professionals and a severe lack of a safety knowledge and training the accident occurred, another relevant factor is given because the design of the reactor did not have security systems that could identify and avoid an accident due to the combination of circumstances of this nature, that is, voluntary blocking of the technical protection system combined with violations of operational procedures.

The first cause of the accident was a rather unlikely combination of breaches of procedures and operating rules committed by the staff of the plant. With regard to Three Miles Island, lessons learned in this accident include the need to integrate emergency plans: conventional + nuclear; the need for a well-defined chain of command; the importance of communication with the media. The crash was mainly caused by a combination of human errors, design deficiencies, and mechanical and electronic component failures.

In addition to being the largest nuclear accident in United States history, it was responsible for permanently changing all regulations and oversight bodies of such facilities. The population's fear and distrust increased, and the measures of control and management of the facilities began to be analyzed with greater care. Thus, it is understood that the problems identified from the careful analysis of the events occurred in the accident end up leading to the adoption of a series of measures, in order to make the installations safer and prepared for this type of occurrence.

Regarding the term LL, although its approach is present in several IAEA publications, few of them use LL in its title (9.8% to Topic and 20.2% to Type), while to LLA is even smaller (0% to Topic and 7.8% to Topic). It is understood that, although references to LL are found in publications, the term seems to be better understood only in recent years.

However, compared to the total number of publications on LL, publications on LLA rise to 38.5% (in Type), which means that the LLA is relevant in relation to the total LL analysis.

In addition, for the researcher of the area, this papers is interesting because show that the IAEA periodically conducts studies and reports on various subjects related to practices with radioactive material. Thus, is possible find bibliographic references on nuclear activities, making understand that the IAEA is concerned with the elaboration of documents that serve as a reference, with the main objective of reporting LL, LLA and good practices, which strengthens the concept KM and NKM.

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