EPR-LESSONS
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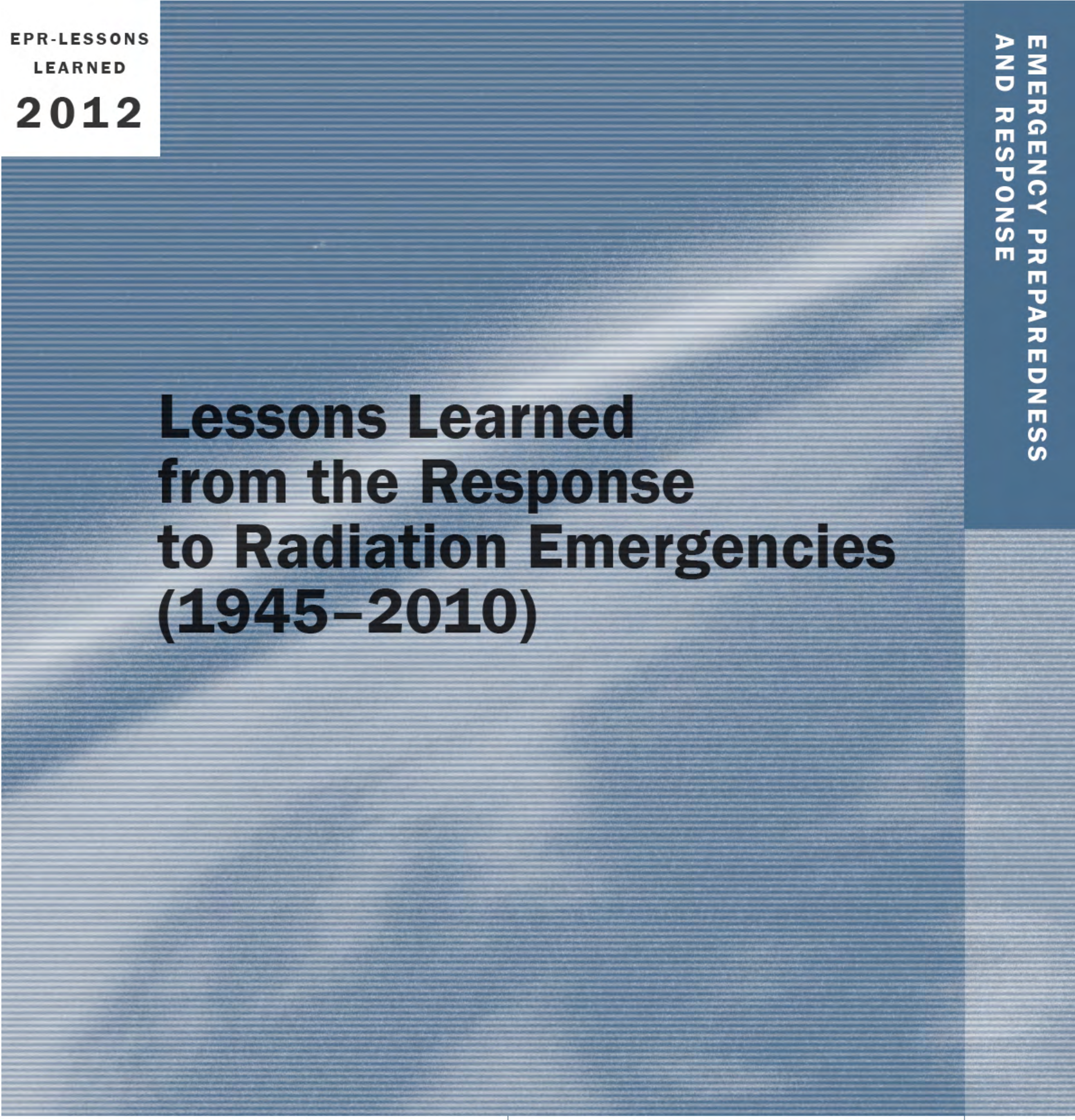
2012

EMERGENCY PREPAREDNESS
AND RESPONSE



# Lessons Learned from the Response to Radiation Emergencies (1945–2010)

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# IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

## IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

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Information on the IAEA's safety standards programme is available at the IAEA Internet site

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The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at PO Box 100, 1400 Vienna, Austria.

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# Lessons Learned from the Response to Radiation Emergencies (1945-2010)

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

EPR-LESSONS LEARNED

2012

EMERGENCY PREPAREDNESS AND RESPONSE

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# FOREWORD

The IAEA Statute authorizes the IAEA to establish safety standards to protect health and minimize danger to life and property. IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles, establishes the fundamental safety objectives, safety principles and concepts that provide the bases for these safety standards and the IAEA's safety related programme. Related requirements are established in the Safety Requirements publications, while guidance on meeting these requirements is provided in the related Safety Guides.

The Fundamental Safety Principles publication contains ten safety principles and briefly describes their intent and purpose. Principle 9 states that "arrangements must 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 State are given in IAEA Safety Standard Series No. GS-R-2, Preparedness and Response for a Nuclear or Radiological Emergency, which is jointly sponsored by seven international organizations.

Included in the safety principles stated in the Fundamental Safety Principles publication are principles for the effective management of safety. In particular, 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". 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.

The IAEA September 2011 General Conference, in resolution GC(55)/RES/9, emphasized for all Member States "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".

While the primary responsibility for safety must lie with the person or organization responsible for facilities and activities that give rise to radiation risks (Principle 1 of the Fundamental Safety Principles publication), the IAEA also has a responsibility to assist its Member States in improving safety. First, under its Statute, it is authorized to provide for the application of its standards. Second, one of the functions assigned to the IAEA under Article 5.a.(ii) of the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency is "to collect and disseminate to States Parties and Member States information concerning … methodologies, techniques and available results of research relating to response to nuclear accidents or radiological emergencies."

The present publication has been prepared in order to assist the IAEA's Member States in assimilating those lessons from past emergencies that reinforce the safety requirements given in the Safety Requirements publication GS-R-2.

This report was written prior to the March 2011 Japan earthquake and does not include consideration of the accident at TEPCO's Fukushima Daiichi nuclear power plant. Lessons learned from this accident will be discussed in future IAEA publications and will complement the findings reported here.

The officers responsible for this publication are T. McKenna and E. Buglova of the Department of Nuclear Safety and Security.

## CONTENTS

# 1. INTRODUCTION

## 1.1. BACKGROUND

An underlying concept in the safety standards of the International Atomic Energy Agency (IAEA) is that prevention is better than cure. This is achieved through the application of appropriate standards in design and operation. Nevertheless, radiation incidents and emergencies[1] do occur and safety standards are necessary that define the approaches to be used in mitigating the consequences.

The IAEA Safety Requirements publication, Preparedness and Response for a Nuclear or Radiological Emergency, GS-R-2 [1], establishes the requirements for an adequate level of preparedness and response for a nuclear or radiological emergency in any State. They take account of several other Safety Standards at the Safety Requirements level, namely: the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2]; Governmental, Legal and Regulatory Framework for Safety, GSR Part 1 [3]; Safety of Nuclear Power Plants: Design, NS-R-1 [4]; and Safety of Nuclear Power Plants: Operation, NS-R-2 [5]. Implementation of the requirements is intended to minimize the consequences for people, property and the environment of any nuclear or radiological emergency. Although developed before the publication of the Fundamental Safety Principles [6], they define the requirements that must be satisfied in order to achieve the overall objective and apply the principles that are presented in publications relating to emergencies.

An emergency is defined in the Agency's glossary [7] as 'a non-routine situation or event that necessitates prompt action, primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property or the environment. This includes nuclear and radiological emergencies and conventional emergencies such as fires, release of hazardous chemicals, storms or earthquakes. It includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard'.

Several nuclear emergencies have occurred, most notably, the Windscale fire in 1957 [8], the Three Mile Island accident in 1979 [9], the Chernobyl accident in 1986 [10], the Sarov accident in 1997 [11] and the Tokaimura accident in 1999 [12]. Radiological emergencies have occurred throughout the world, and when invited by the country concerned, the IAEA has undertaken comprehensive reviews of the events, the purpose of which is to compile information about the causes of the accidents, the subsequent emergency response including medical management, dose reconstruction, public communication, etc., so that any lessons can be shared with national authorities and regulatory organizations, emergency planners and a broad range of specialists, including physicists, technicians and medical specialists, and persons responsible for radiation protection [13-31]. It is appropriate to analyze the findings of these and other reports on the response to radiation emergencies in order to consolidate these lessons.

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[1] Throughout this document, the term 'radiation emergency' is used as a common term for a nuclear or radiological emergency.

## 1.2. OBJECTIVE

The objective of this publication is thus to provide a review of the lessons from the response to a number of radiation emergencies with the purpose of consolidating the lessons. A further objective is to demonstrate the necessity of establishing arrangements for emergency preparedness and response, for which the IAEA Safety Requirements publication, Preparedness and Response for a Nuclear or Radiological Emergency, GS-R-2 [1] provides a background.

## 1.3. SCOPE

This publication covers both nuclear and radiological emergencies (hereinafter referred to as radiation emergencies). It also takes account of the lessons obtained from other emergency situations, where these lessons are relevant. It is aimed at national authorities and regulatory organizations, emergency planners and a broad range of specialists, including physicists, technicians and medical specialists, and persons responsible for radiation protection. It is also relevant to any future review of the IAEA's Safety Standards relating to radiation emergencies.

The range of potential radiation emergencies of concern is enormous, extending from a major reactor emergency, to emergencies involving lost or stolen radioactive material. The document addresses the entire range of radiation emergencies.

This document does not address the lessons relating to the prevention of radiation events through the radiation safety measures that are incorporated into the design of facilities and their operation.

## 1.4. STRUCTURE

The document is structured around the structure of the Safety Requirements publication, Preparedness and Response for a Nuclear or Radiological Emergency [1]. Thus, Section 2 deals with the general requirements of emergency preparedness and response; Section 3 covers the functional requirements; and Section 4 covers the requirements for infrastructure. Each subsection starts with a list, in summary form, of the main requirements given in that document. This is followed by a short description of any relevant observations from the reviews of responses to various emergencies and, from these observations, conclusions have been drawn. Appendix I provides a review of some of the reported radiation and other emergencies that have occurred since 1945 and are most frequently referred to in the main text. Appendix 2 provides standardized summary description of different types of radiation emergencies and their statistics. Tables 4–12 are primarily adapted from Ref. [32].

The terms used in this document, unless otherwise indicated, are as defined in the IAEA's Safety Glossary [7].

# 2. GENERAL REQUIREMENTS

## 2.1. BASIC RESPONSIBILITIES

The principal requirements on basic responsibilities covered in the Safety Requirements publication [1] relate to:

- the establishment and maintenance of adequate preparations for response to deal with any consequences of a radiation emergency in the public domain;
- the provision of resources to the regulatory body and response organizations;
- the adoption of legislation that allocates clearly the responsibilities, including the identification of a national coordinating authority;
- the establishment of arrangements for preparedness and response for any practice or source that could necessitate an emergency intervention, and the integration of such arrangements with those of other response organizations;
- the testing of the arrangements at suitable intervals;
- the development of regulations and guides by the regulatory body;
- the reporting of emergencies;
- the role of the regulatory body as advisor to the government and response organizations;
- the coordination of arrangements for response to a radiation emergency with the arrangements for response to conventional emergencies;
- the adoption of appropriate management arrangements to meet the timescales for response throughout the emergency.

### 2.1.1. Observations

All of these requirements are repeated in the subsequent sections of the Safety Requirements publication. However, a number of general points can be made here based on the information provided in the Appendix.

Radiation emergencies can be conveniently divided into two groups[2], namely:

(a) Emergencies that can occur anywhere. These are generally radiological emergencies and cover:

  - exposures from dangerous[3] orphan[4] sources;

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[2] As noted in Section 1, radiation emergencies are of two types, namely radiological and nuclear. However, for the purpose of identifying the lessons for the response it is more convenient to categorize them in terms of the location at which they might occur.

[3] A dangerous source is a source that could, if not under control, give rise to sufficient exposure to cause severe deterministic effects (i.e. an injury that only occurs above a certain relatively high threshold of dose that is fatal or life threatening, or results in permanent injury that reduces the quality of life) 0.

- public exposures and contamination from unknown origins;
- radioactive satellite re-entry;
- terrorist threats/acts;
- transport accidents.

(b) Emergencies that occur in facilities where radioactive material is used or kept can be either nuclear or radiological. These facilities cover:

- nuclear reactors (research, ship and power);
- fuel cycle facilities (e.g. fuel processing plants);
- large irradiation facilities (e.g. industrial irradiators);
- storage facilities for large quantities of spent fuel or other radioactive material;
- industrial and medical uses of dangerous sources (e.g. teletherapy and radiography).

The first group of emergencies can occur in any country, whereas the second can only occur in those countries where such facilities exist. Even so, the second group of emergency can affect countries other than the one in which the facility exists if, for example, there is a release of radioactive material that is sufficient to traverse national boundaries, as was the case with the Chernobyl accident in 1986.

Many of the emergencies in the first group that resulted in the death, or serious injury to, members of the public involved dangerous orphan radioactive sources. A common scenario for such emergencies is that of a dangerous source obtained by someone who is unaware of the hazard. In a number of cases, the source is taken to a small scrap metal dealer who subsequently attempts to disassemble the container, resulting in the source becoming unshielded and high radiation exposure of those in the vicinity. When the persons exposed in high doses start exhibiting symptoms of acute radiation exposure (e.g. burns, vomiting), they seek medical treatment. It may, however, take the medical professionals some time before they suspect that the injuries have been caused as a result of radiation exposure and alert the appropriate officials. Once the possibility of a radiation emergency is recognized, the officials, using common survey instruments can, in most cases, quickly put the source under control, preventing further injuries. In some cases, the actions to make the situation safe may not be possible to complete immediately, due to the need to track down the location of the source(s) or the spread of contamination. However, the key is being able to recognise that an accident has taken place so that the emergency response plans can be activated. In all of these cases there has been considerable public and media interest and concern. The accidents in Goiânia in 1987 [13], Turkey in 1999 [21], and Thailand in 2000 [25] and the polonium-210 incident in London in 2006 [33] are examples of emergencies in this category.

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[4] An orphan source is defined in the IAEA's Safety Glossary 0 as 'a radioactive *source* which is not under regulatory control, either because it has never been under regulatory control, or because it has been abandoned, lost, misplaced, stolen or otherwise transferred without proper authorization'.

The major lessons from these emergencies are that:

- they can occur unexpectedly in any country;
- scrap dealers need to be informed on how to detect or otherwise identify a dangerous orphan source;
- the medical community need to be informed on the identification of the medical symptoms of radiation exposure;
- national and, as appropriate, local plans and procedures need to be established;
- predetermined generic and operational criteria are needed for decision making;
- the public and media concerns must be promptly addressed.

The accidents at Three Mile Island (TMI) in 1979 [9], Chernobyl in 1986 [10], Tokaimura in 1999 [12] and San Salvador [14] most notably exemplify the second group of emergencies.

The TMI accident involved severe damage to the core of a nuclear power plant, very high doses on site, and only minor releases of radioactive material off the site, but resulted in significant psychological impact for off-site population [9]. In the Chernobyl accident, there was an extremely large release of radioactive material from a nuclear power plant resulting in 28 radiation related deaths among the workers and emergency responders in 1986, several thousand radiation induced thyroid cancers among children, and enormous psychological and economic damage [10].

The major lessons from the TMI and Chernobyl emergencies were the need to:

- develop emergency response arrangements for very unlikely events;
- develop the capability to identify dangerous conditions in the facility and act immediately upon their detection;
- make arrangements to protect emergency workers on the site;
- have criteria and provisions to promptly assess facility conditions and off-site radiological conditions in order to make decisions on evacuation, relocation, restrictions on food and other countermeasures; and
- make provisions to promptly address public and media concerns.

The accident at Tokaimura was due to a criticality and resulted in the death of two workers, but no significant off-site release or exposure. Even though the off-site radiological impact was small, it nevertheless resulted in severe economic and psychological damage. The major lesson was the need to quickly address public concerns, even at facilities where emergencies cannot result in significant radiological consequences off-site.

The accident in San Salvador involved three untrained workers who were exposed to high levels of radiation in an industrial irradiator. The legs and feet of two of them were so seriously injured that amputation was required. One of the workers died six and a half months after the accident. The major lesson here was more concerned with prevention than response: the need to ensure that personnel working in facilities where high doses are possible (even if very unlikely), are adequately trained and equipped.

The first three examples in this second category were nuclear emergencies; the last was a radiological emergency. In addition, a number of radiological emergencies in this category have involved excessive exposure of patients undergoing radiotherapy [20, 24, 27]. This has resulted in, or contributed to, the death of patients or caused serious injury to them. Typically, these involved equipment failure, procedural errors, or use of unanticipated (and untested) configurations of computer or equipment systems.

The major response lessons from these emergencies are the need to:

- promptly alert users of similar treatment systems of the potential for accidental overexposures;
- provide specialized medical treatment to limit the suffering of patients and the extent of the permanent injuries.

### 2.1.2. Conclusions

These lessons demonstrate the importance of:

- all States establishing and maintaining arrangements (including exercising them) for dealing with radiation emergencies in the public domain according to the national circumstances;
- those responsible for facilities in which radiation sources are kept or used establishing their own arrangements for emergency response graded according to the level of risk;
- those responsible for facilities/locations where orphan sources might be encountered (e.g. scrap metal yards) establishing arrangements for emergency response;
- appropriate resources being available and responsibilities in an emergency being clearly defined in order for there to be an adequate response to radiation emergencies;
- medical personnel being trained to recognize radiation-induced injuries, since they are frequently the first to encounter such injuries in patients, and encouraged to inform the regulatory body in the event that they suspect the appearance of such an injury;
- giving clear information promptly to the media and the public in the event of a radiation emergency because of the considerable interest that such events attract, and in order to avoid undue disruption of the response.

## 2.2. ASSESSMENT OF THREAT[5]

For the purposes of defining the requirements for emergency preparedness and response given in Ref. [1], the radiological threats are grouped according to the threat categories[6] shown below in Table 1. Each of the categories in this grouping has common features in terms of the magnitude of the radiological consequences in the case of an emergency, and thus the arrangements for preparedness and response. Threat categories I, II and III represent decreasing levels of radiological threat at facilities and in the corresponding stringency of requirements for preparedness and response arrangements. Threat categories IV and V apply to activities[7]. Threat category IV applies to activities that can lead to emergencies occurring virtually anywhere; it is thus the minimum level of threat which is assumed to apply for all States and jurisdictions. Threat category V applies to the off-site areas where arrangements for preparedness and response are warranted to deal with contamination resulting from a release of radioactive material from a facility in threat category I or II. These threat categories are used to establish a graded approach to the preparation for, and response to, radiation emergencies. There is, however, no specific requirement to use these categories; they are simply defined for the purposes of the Safety Requirements publication.

Ref. [34] provides guidance on determining the threat category and examples of the threat category for different situations. Inherent in the assessment of threats is a clear understanding of what may potentially go wrong; and here knowledge and understanding of the causes and consequences of previous accidents is essential.

The principal requirements in the assessment of threats covered in the Safety Requirements publication [1] relate to:

- the use for a threat category I facility of probabilistic safety analysis to assess the adequacy of the operator’s emergency response arrangements;
- the use for a threat category I, II, or III facility of a comprehensive safety analysis to identify all sources of exposure for establishing emergency requirements;

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[5] In the future IAEA safety standards, guidance and manuals that are currently under development, the term “threat” as used in “threat assessment” is to be replaced with “hazard“ and “hazard assessment”.

[6] In the future IAEA safety standards, guidance and manuals that are currently under development, the term “threat category” is to be replaced with “hazard category”.

[7] Facilities and activities is a general term encompassing nuclear facilities, uses of all sources of ionizing radiation, all radioactive waste management activities, transport of radioactive material, and any other practice or circumstances in which people may be exposed to radiation naturally occurring or artificial sources. Facilities includes: nuclear facilities; irradiation installations; some mining and raw material processing facilities such as uranium mines; radioactive waste management facilities; and any other places where radioactive material is produced, processed, used, handled, stored or disposed of — or where radiation generators are installed — on such a scale that consideration of protection and safety is required. Activities includes: the production, use, import and export of radiation sources for industrial, research and medical purposes; the transport of radioactive material; the decommissioning of facilities; radioactive waste management activities such as the discharge of effluents; and some aspects of the remediation of sites affected by residues from past activities. See IAEA Safety Glossary [7].

- the need for the emergency arrangements to be commensurate with the potential magnitude and nature of the threat;
- the need to conduct a periodic review to ensure all practices and situations that could necessitate an emergency response are identified, and to ensure that an assessment of the threat is conducted for such practices and situations;
- the identification of facilities, sources, practices, on-site areas, off-site areas and locations for which protective actions are warranted;
- the identification of non-radiological threats;
- the identification of locations where there is a significant probability of encountering a dangerous source;
- the identification of large scrap metal processing facilities, national border crossings and facilities where large sources may have been used.

### 2.2.1. Observations

Numerous studies show that the worst possible fission product releases [35, 36, 37] from a large nuclear power plant[8] or from large spent fuel pools[9] could result in severe deterministic health effects off the site; therefore, these facilities would be included in threat category I. Research reactors and spent fuel processing facilities are examples of facilities that could result in releases warranting urgent protective action off the site and thus fall in threat category II.

It is generally recognized that facilities falling within threat categories I and II necessitate the preparation of comprehensive safety analyzes in order to determine the emergency arrangements. It is less generally recognized that serious emergencies can arise in facilities falling within threat category III. There have been major accidents involving threat category III facilities resulting in severe radiation injuries or deaths in several countries, including: Italy in 1975 [32, 39], Norway in 1982 [40, 41], San Salvador in 1989 [14], Israel in 1990 [15], China in 1990 and 1992 [32, 39], Belarus in 1991 [16] and France in 1991 [42, 43], amongst others. In view of the relatively small number of installations, the risk of such accidents was high. This prompted a major programme of work by the IAEA to promote improvements [29]. From the IAEA experience, the risk now is substantially lower due to improvements in design and practice, but should not be discounted.

The use of site industrial radiography falls within threat category IV. This has also resulted in serious injury or death. In the UK in 1992, an industrial radiographer died probably as a result of substantial radiation exposure (at least, 10 Gy) received over several years [39]. Accidents have also occurred in France in 1995 [39], in Iran in 1996 [26], in Peru in 1999 [22] and Bolivia in 2002 [28]. In addition, there have been many accidents or incidents involving exposures from orphan sources. Some early accidents in Mexico in 1962 [44], Algeria in 1978 [45] and Morocco in 1984 [46] demonstrated how

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[8] The Chernobyl accident resulted in doses that could have been fatal off-the site if the initial release had impacted an inhabited area [38].

[9] Containing spent fuel requiring active cooling.

industrial radiography sources could become orphan sources and result in multiple deaths. More recently, there have been examples involving the metal recycling industries [46] and these have led to the installation of systems to check incoming scrap metal for radioactive content. Orphan sources have also been responsible for injury to, or death of, members of the public. These have occurred in China in 1992 [39], Estonia in 1994 [18], Georgia in 1997 [23], Istanbul in 1998/9 [21], and Thailand in 2000 [25], amongst others.

### 2.2.2. Conclusions

These lessons demonstrate the importance of:

- establishing emergency arrangements, based on a safety analysis, for threat category III, as well as the threat categories I and II, a particular concern being industrial irradiators, which exist in many States throughout the world;
- establishing emergency arrangements for emergencies involving dangerous orphan sources that could occur virtually anywhere; proving the need to identify locations where such sources may be discovered, such as metal recycling industries.

TABLE 1. FIVE CATEGORIES OF NUCLEAR AND RADIATION RELATED THREATS FOR THE PURPOSES OF THE REQUIREMENTS [1]

| Threat category[6] | Description |
|---|---|
| I | Facilities, such as nuclear power plants, for which on-site events[10] (including very low probability events) are postulated that could give rise to severe deterministic health effects[11] off the site, or for which such events have occurred in similar facilities. |
| II | Facilities, such as some types of research reactors, for which on-site events[7] are postulated that could give rise to doses to people off the site that warrant urgent protective actions in accordance with international standards[12], or for which such events have occurred in similar facilities. Threat category II (as opposed to threat category I) does not include facilities for which on-site events (including very low probability events) are postulated that could give rise to severe deterministic health effects off the site, or for which such events have occurred in similar facilities. |
| III | Facilities, such as industrial irradiation facilities, for which on-site events are postulated that could give rise to doses that warrant, or contamination that warrants, urgent protective actions on the site, or for which such events have occurred in similar facilities. Threat category III (as opposed to threat category II) does not include facilities for which events are postulated that could warrant urgent protective actions off the site, or for which such events have occurred in similar facilities. |
| IV | Activities that can result in a nuclear or radiological emergency that could warrant urgent protective actions in an unforeseeable location. These include non-authorized activities such as activities relating to dangerous sources obtained illicitly. They also include transport and authorized activities involving dangerous mobile sources such as industrial radiography sources, nuclear powered satellites or radiothermal generators. Threat category IV represents the minimum level of threat assumed to apply for all States and jurisdictions. |
| V | Activities not normally involving sources of ionizing radiation, but which yield products with a significant likelihood[13] of becoming contaminated as a result of events at facilities in threat categories I or II, including such facilities in other States, to levels necessitating prompt restrictions on products in accordance with international standards. |

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[10] Involving an atmospheric or aquatic release of radioactive material or external exposure (such as due to a loss of shielding or a criticality event) that originates from a location on the site.

[11] Doses in excess of those for which intervention is expected to be undertaken under any circumstances; see Annex II of Ref. [2]. See Glossary under deterministic health effects [7].

[12] Annex III of Ref. [2].

[13] Contingent on the occurrence of a significant release of radioactive material from a facility in threat category I or II.

# 3. FUNCTIONAL REQUIREMENTS

## 3.1. GENERAL

The practical goals of emergency response, as defined in the Safety Requirements publication [1], are:

- to regain control of the situation;
- to prevent or mitigate consequences at the scene;
- to prevent the occurrence of deterministic health effects in workers and the public;
- to render first aid and to manage the treatment of radiation injuries;
- to prevent, to the extent practicable, the occurrence of stochastic effects in the population;
- to prevent, to the extent practicable, the occurrence of non-radiological effects on individuals and among the population;
- to protect, to the extent practicable, property and the environment;
- to prepare, to the extent practicable, for the resumption of normal social and economic activity.

In order to meet these goals, requirements for preparedness apply as part of the planning and preparation process.

### 3.1.1. Observations

There is nothing to observe here, except to note that these goals are eminently sensible.

## 3.2. ESTABLISHING EMERGENCY MANAGEMENT AND OPERATIONS

The principal requirements on establishing emergency management and operations covered in the Safety Requirements publication [1] relate to:

*Response*

- the execution of prompt on-site response without impairing the performance of the continuing operational safety functions;
- the effective management of the off-site response, coordinated with the on-site response;
- the coordination of the response between all responding organizations;
- the appraisal of the information necessary for decision making on the allocation of resources throughout the emergency.

*Preparedness*

- for facilities in threat category I, II or III, the clear definition of the transition from normal to emergency operations including the designation of responsibilities of those on site;
- for facilities in threat category I or II, the arrangements for coordinating the responses of all the off-site organizations with the on-site response;
- the arrangements for the integration of the response at the national and local level with those for response to conventional emergencies;
- the arrangements for a command and control system, including those for:
    - coordinating activities;
    - developing strategies;
    - resolving disputes;
    - arrangements for obtaining and assessing the information;
- for facilities in threat category I or II, the arrangements for coordinating the response between the response organizations and jurisdictions that fall within the Precautionary Action Zone (PAZ) or the Urgent Protective Action Planning Zone[14] (UPZ).

### 3.2.1. Observations

Many managers directing initial response were ineffective because they had not been trained under realistic emergency conditions and the response system was not designed for severe emergencies (e.g. TMI, Chernobyl). These managers were overwhelmed and confused by the stressful environment, performed their subordinates' tasks rather than their own managerial roles, had to move to new locations at crucial times, lacked telephone access because of jammed lines, and failed to develop an understanding of the true nature and severity of the emergencies [9, 10, 47].

During the response to emergencies [47, 48], senior officials/managers caused confusion by developing *ad hoc* plans because they were unaware of the plans and procedures that their organizations had established. Quite often, senior managers and decision makers failed to recognize the need for their participation in training and for identifying their roles in emergency situations.

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[14] The Precautionary Action Zone (PAZ) is an area around a facility for which arrangements have been made to take urgent protective actions in the event of a nuclear or radiological emergency to reduce the risk of severe deterministic health effects off the site. Protective actions within this area are to be taken before, or shortly after, a release of radioactive material or an exposure, on the basis of the prevailing conditions at the facility. The Urgent Protective Action Planning Zone (UPZ) is an area around a facility for which arrangements have been made to take urgent protective actions in the event of a nuclear or radiological emergency to avert doses off the site in accordance with international safety standards. Protective actions within this area are to be taken on the basis of environmental monitoring — or, as appropriate, prevailing conditions at the facility.

Immediately after the start of the TMI emergency, a large number of the plant staff reported to the control room, which greatly interfered with the efforts of the operators to understand and regain control of the emergency. The reason the staff went to the control room was because this was what they always did if there was a problem.

An example of the efficient operation under the established command and control arrangements in this regard was the response to the polonium-210 incident in London. This was an unprecedented scenario: however the UK's emergency response framework, which specified clear command and control arrangements for a multiagency response (regardless of the nature of the incident), together with the experience from many nuclear and counterterrorism exercises, provided a firm basis for an efficient and effective response [33].

### 3.2.2. Conclusions

These lessons demonstrate the importance of:

- establishing arrangements for emergency response, in advance and in accordance with the threat category;
- clarifying the roles and responsibilities of those who will be involved in dealing with the response to an emergency, including those involved in directing or managing the response;
- integration of the management of the response of the national authorities with that of the other response organizations as soon as possible, at a single location ideally close to the scene of the emergency;
- all involved in the response recognizing the arrangements that apply to normal situations do not necessarily apply in an emergency.

## 3.3. IDENTIFYING, NOTIFYING AND ACTIVATING

The principal requirements on identifying, notifying and activating covered in the Safety Requirements publication [1] relate to:

*Response*

- the prompt determination by operators of the appropriate class or level of response and the initiation of on-site actions; the notification and provision of updated information to the off-site notification point;
- the prompt notification by the off-site notification point of all appropriate off-site response organizations and the prompt initiation by the off-site response organizations of the appropriate pre-planned response;
- the prompt initiation of actions following receipt of a notification from another State;
- in the event of a transnational emergency, the prompt notification of those States that may be affected.

*Preparedness*

- the establishment of continuously available notification points for receiving emergency notifications;
- in jurisdictions in which there is a significant probability of a dangerous source being lost, or otherwise removed, the arrangements to ensure that the on-site managers and local officials are aware of the indicators of a potential emergency and the actions warranted if an emergency is suspected;
- the arrangements to ensure that first responders are aware of the trefoil symbol and dangerous goods labels and placards and their significance, the symptoms that would indicate a need to conduct an assessment to determine whether there may be an emergency, and the appropriate notification and other immediate actions warranted if an emergency is suspected;
- for operators of a facility or practice in threat category I, II, III, or IV, the arrangements for the prompt identification of an actual, or potential, radiation emergency and determination of the appropriate level of response. This requires a system of classification of all potential emergencies based on predefined emergency action levels;
- for facilities in threat category I or II, the designation of an off-site notification point, which is required to be continuously available;
- for facilities or practices in threat category I, II, II or IV, the designation of a person on site at all times with the authority and responsibilities: to classify the emergency, and upon classification promptly initiate an appropriate on-site response; to notify the appropriate off-site notification point; and to provide sufficient information for an effective off-site response. The person must be provided with a suitable means of alerting on-site response personnel and notifying the off-site notification point;
- the arrangements by operators of a facility or practice in threat category I, II, III or IV to ensure that adequate arrangements are made for the prompt generation of adequate information, and the communication of it to the responsible authorities;
- the prompt initiation of response upon declaration of a particular class of emergency at a facility or practice in threat category I, II, III or IV, and the definition of responsibilities and initial response actions of all response organizations;
- for facilities in threat category I or II, the demonstration by the threat assessment that identification, notification, activation and other initial response actions can be performed in time;
- the arrangements for response organizations to have sufficient personnel available to perform their assigned initial response actions;
- the arrangements for responding to an emergency for which details could not be formulated in advance;

- the making known of the point of contact to the IAEA and other States;
- the arrangements for notifying those States that may be affected by a transnational emergency;
- the arrangements for notifying any State in which urgent protective action should be taken.

### 3.3.1. Observations

The severity of nuclear emergencies at TMI and Chernobyl was not initially recognized by facility operators, even though there were indisputable indications [9, 37, 49]. These failures have been attributed to the fact that their training did not address severe accidents, and that their procedures lacked predetermined criteria on which to classify events and define the response. Severe emergencies were not addressed because staff considered their occurrence to be inconceivable, even though they were postulated by credible scientific analyzes.

Operator confusion of the TMI and Chernobyl accidents contributed to their severity because the operators did not take the appropriate action at an early stage. Thus, in the case of the TMI accident, the operators attempted to confirm they were taking the correct mitigatory actions by relying on a single instrument that proved to be misleading under emergency conditions, even with the indisputable indications of a melted core [9, 37].

Several radiological emergencies involving dangerous orphan sources were exacerbated when collectors of scrap metal did not understand the significance of the trefoil symbol. Strictly the symbol is intended to indicate the presence of radiation rather than of a serious hazard. Nevertheless, it has become widely recognized as indicating a radiation hazard, although the experience from these accidents clearly demonstrates that this recognition is not universal [21, 25, 50].

In a number of cases, these emergencies were identified by physicians diagnosing the injuries as being radiation-induced. However, these diagnoses were often delayed because the physicians were not familiar with the symptoms of radiation exposure [13].

In the polonium-210 incident in London the potential for the symptoms presented by a patient to be caused by radiation was recognised. However, the limitations of the actions taken to test this possible diagnosis were not recognised. In essence, the initial testing was based on carrying out dose rate and contamination measurements on the patient and the surroundings. Unfortunately, alpha emitters are not commonly encountered in hospitals and the instruments used were not capable of detecting the alpha radiation from $^{210}$Po [33].

In many accidents, particularly in threat categories III and IV, the lack of appropriate training, or failure to implement it efficiently, are both the cause of the accident itself and the reason why its occurrence is not quickly recognised. An example of this is the irradiator accident in San Salvador [14]. Here untrained staff were significantly exposed whilst freeing the movement of a jammed source rack, and even though the staff went to hospital with symptoms of acute radiation syndrome, the significance of the event went unrecognised. Indeed, a further accident occurred before it was recognised that there was a problem.

Once an emergency has been identified there has to be a well-known and accessible route for notifying and activating appropriate responses. Experience has shown that arrangements to deal with emergencies outside the nuclear sector that pose a threat to the public, although equally necessary, are often less robust. In the Goiânia accident [13] there was a lack of clarity of how to report the accident to the local authorities to initiate immediate local actions. Once achieved, there was action at the local level reporting to the national level and a subsequent national response. However, at each stage there was a need to improvise because clear emergency response plans to deal with such a situation had not been developed. It was possible to adapt elements of the response from the nuclear accident plans, but inevitably there were some delays in effectively deploying the necessary resources.

In the polonium-210 incident in London, in addition to UK residents, a large number of those potentially exposed to $^{210}$Po were overseas visitors who had stayed in, or visited, one of the hotels or other locations involved in the incident. These people had to be followed up. To address this, the Health Protection Agency (HPA) established an Overseas Advice Team (OAT) [33]. Such a team had not previously been part of the HPA emergency plan, but it is now clear that any emergency in a major city is likely to involve foreign visitors and plans need to accommodate this.

Working with the UK Foreign and Commonwealth Office (FCO) the OAT of HPA gave briefings to representatives from the embassies and missions in London. As individuals from overseas were identified as having the potential for intakes of $^{210}$Po, attempts were made to follow them up through diplomatic and public health channels. In total 664 people from 52 countries were identified, but there were a number of problems in the follow-up and feedback of results:

- It was clear early on that information through the diplomatic channels was not necessarily reaching the appropriate organization in the country.
- This prompted attempts to contact relevant national organizations either through radiological protection or public health contacts. Again, this was challenging and time consuming.
- Early in the incident the IAEA was formally notified of its occurrence as part of the requirements under the Convention on the Notification of Nuclear Accidents [51]. However, it was not until the above contacting problems were encountered that national use of IAEA’s emergency contact arrangements was made. In retrospect, earlier use of this IAEA capability would have been advantageous.

Even when contacts could be established and information passed on regarding the tests thought to be necessary, getting feedback on the results was patchy. In total, results were received for less than 25% of those originally identified. In some cases it was stated that reporting of the results was not possible due to data protection legislation or medical-in-confidence issues. The results that were reported fitted the profile of the risk assessment picture developed from UK individual and environmental monitoring. However, it is clear that lack of consistent reporting internationally could be an issue in future emergency response.

The number of patients who received severe overexposures while undergoing radiotherapy treatment could have been limited by early detection of the accidents. For instance, in the case of the Costa Rica accident, although the technologists questioned why the treatment times remained the same with a new radioactive source as with the old one, the matter was not followed up [20]. It was only identified after about a month when a physician considered that his patients were exhibiting a greater reaction than would normally be expected.

Under the Convention on Early Notification of a Nuclear Accident [51], States Party commit that, in the event of a nuclear accident that may have transboundary radiological consequences, they will notify countries that may be affected and the IAEA. The Safety Requirements document [1] however, goes further in that, in the event of a transboundary (or transnational) emergency[15], it requires States to notify directly, or through the IAEA, those States that may be affected. The response of States to warnings from the IAEA Incident and Emergency Centre of transnational emergencies has been delayed because the States had not identified a warning point, did not have access to an English speaker, or did not continuously monitor or assure the operability of the FAX machines used to receive these warnings.

### 3.3.2. Conclusions

These lessons demonstrate the importance of:

- the development of operating procedures for facilities within threat categories I, II and III to guide operators in recognizing all accident sequences identified in the safety analysis, including those of low probability;
- those involved in the metal recycling industry being familiar with the trefoil symbol and the devices containing dangerous sources, and the need to monitor the presence of radioactive material incoming as scrap metal and the various product streams;

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[15] A transboundary emergency is defined as a nuclear or radiological emergency of actual, potential or perceived radiological significance for more than one State and includes:
(1) A significant transboundary release of radioactive material;
(2) A general emergency at a facility or other event that could result in a significant transboundary release (atmospheric or aquatic) of radioactive material;
(3) Discovery of the loss or illicit removal of a dangerous source that has been transported across, or is suspected of having been transported across, a national border;
(4) An emergency resulting in significant disruption to international trade or travel;
(5) An emergency warranting the taking of protective actions for foreign nationals or embassies in the State in which it occurs;
(6) An emergency resulting in, or potentially resulting in, severe deterministic effects and involving a fault and/or problem (such as in equipment or software) that could have serious implications for safety internationally;
(7) An emergency resulting in, or potentially resulting in, great concern among the population of more than one State owing to the actual or perceived radiological hazard.

- the development of guidance for physicians on the recognition of radiation injuries;
- those involved in the treatment of patients using radiotherapy and in other situations where patients can receive high radiation doses such as interventional radiology being encouraged to adopt a questioning attitude, such that any unexpected occurrence is appropriately followed up;
- States establishing and maintaining arrangements to promptly notify the IAEA and any potentially affected States in the event of a radiation emergency having transboundary consequences, and to be ready to respond to such a notification from another State, consistent with IAEA procedures [52].

## 3.4. TAKING MITIGATORY ACTION

The principal requirements on taking mitigatory action covered in the Safety Requirements publication [1] relate to:

*Response*

- the minimization by first responders of the consequences of an emergency in threat category IV;
- the minimization by the operator of a facility or practice in threat category I, II, III or IV of the consequences of an emergency;
- the provision of support by the emergency services to the response at facilities in threat category I, II, or III.

*Preparedness*

- the arrangements for the provision of expertise and services in radiation protection to local officials and first responders to an emergency in threat category IV, and for the provision of guidance to first responders on response to transport related emergencies and suspected illicit trafficking;
- for the operator of a practice in threat category IV, the provision of basic instruction in the means of mitigating the potential consequences of emergencies and protecting workers and the public;
- for the operator of a practice using a dangerous source, the arrangements to respond to an emergency involving the source, including prompt access to a radiological assessor or radiation protection officer;
- the arrangements for initiating a prompt search and to issue a warning in the event of a lost dangerous source;
- for operators of threat category I, II or III, the arrangements for mitigatory action to prevent escalation of the threat, to return to a safe and stable state, to reduce the potential for releases of radioactive material or exposures, and to mitigate the consequences of any actual releases or exposure;

- also for these same threat categories: the arrangements for the provision of technical assistance to the operational staff, for the availability of teams for mitigating the consequences, for the location of equipment, for the personnel directing mitigatory actions, for obtaining support promptly from police, medical and fire fighting services off-site, and for access to the facility by, and the provision of information to, the off-site support personnel.

### 3.4.1. Observations

Emergencies by their very nature call for prompt response. Early recognition that an event has occurred is therefore essential, and this is covered in the previous subsection. However, many of the emergencies that have been reviewed reveal that action was not taken as rapidly as necessary, even though it was realized that they were taking place. In some cases, staff within the facility were not prepared to perform their assigned emergency functions due to the hazardous conditions that were present (e.g. high radiation levels or temperature). In others, the procedures and training were ineffective because they did not address all plausible emergencies, could only be used after the underlying causes of the events had been diagnosed [37, 49, 53, 54], or did not consider the response of systems or instrumentation under emergency conditions [30, 55]. These procedural and training deficiencies occurred even though the high hazard conditions were a logical implication of postulated emergencies [49, 54].

In some emergencies within facilities, assistance by off-site organizations was delayed because there were no provisions for giving them prompt access, the information on what to expect upon arrival, or appropriate radiological precautions to take. For example, many local firemen responded to the Chernobyl accident within the first few hours. However, they did not have sufficient training and adequate personal protection, which contributed to the formation of high doses for them.

### 3.4.2. Conclusions

These lessons demonstrate the importance of:

- undertaking mitigatory action following the identification of an event situation as rapidly as possible, as delay can exacerbate the consequences;
- arrangements being in place whereby facility operators and those undertaking activities with dangerous mobile sources (threat category IV) can undertake mitigatory action promptly;
- account being taken in emergency arrangements of the actual conditions — for example, areas of high radiation levels — which may affect the functionality of the emergency arrangements and the performance of the emergency procedures;
- account being taken in emergency arrangements of the information and resource requirements of any off-site agencies providing on-site emergency assistance, and of their need to be contacted rapidly and obtain immediate access to the site.

## 3.5. TAKING URGENT PROTECTIVE ACTION

The principal requirements on taking urgent protective action covered in the Safety Requirements publication [1] relate to:

*Response*

- the need to save lives;
- the need to prevent serious deterministic effects and avert doses;
- the need to modify protective actions as information becomes available;
- the discontinuance of a protective action when it is no longer justified.

*Preparedness*

- the establishment of optimized national intervention levels;
- the adoption of national guidelines for the termination of urgent protective actions;
- the provision of information to first responders about the urgency of saving lives and preventing serious injury;
- for facilities in threat category I or II, the arrangements for making and implementing decisions on actions to be taken off-site;
- the arrangements for the off-site officials to make protective action decisions promptly;
- the arrangements for the jurisdictions within the PAZ and/or UPZ to take urgent action promptly;
- for the operator of a facility in threat category I, II or III, the arrangements to ensure the safety of persons on site;
- for the operator of a facility in threat category I, II or III, the need to ensure the necessary means of communication is available.

### 3.5.1. Observations

By definition, facilities within threat categories I and II are such where on-site events are postulated that could give rise to doses to people off the site that warrant urgent protective actions. Urgent protective actions include: evacuation, substantial shelter, iodine thyroid blocking and restricting consumption of food and water that could be contaminated. The Chernobyl accident, in particular, necessitated urgent actions off-site [10]. The TMI accident could have led to significant doses off-site if the containment had not retained the radioactive material that had been released due to the melting of the core. In the event, precautionary evacuation of some people was undertaken [9]. Precautionary evacuation of the local population was also undertaken during the Tokaimura accident [12].

Some local officials have been reluctant to order an evacuation because they believed incorrectly that it would cause panic and numerous traffic fatalities. However, nearly fifty years of research [56, 57, 58] on major evacuations (including those in response to serious radiation emergencies, release of a toxic chemical, the discovery of an unexploded World War II bomb, hurricanes) has shown that evacuations are relatively common and can be undertaken without panic and increased risk of traffic fatalities [57, 59-61]. The experience from the evacuations that took place in response to hurricanes Katrina and Rita, which involved large populations, demonstrated the importance of careful management of the ensuing traffic flow and the provision of the necessary vehicles [62].

At TMI, two days after the core had melted, pregnant women and preschool aged children were advised to leave the area within a 5-mile radius [63]. Approximately ten times as many people evacuated as were specifically advised to do so [56, 64, 65, 66]. Much of this was due to confusing and conflicting information about the seriousness of the accident, as well as to expectations that there would be further evacuations later. At TMI, the protective action was aimed at a subgroup of the population (i.e. pregnant women and pre-school children). The authorities, however, failed to explain that the purpose of evacuating pregnant women was in order to protect the foetus. As a consequence, women of child-bearing age and families with infants also tended to evacuate [67].

The precautionary actions in the TMI accident were by no means complete. If the containment had failed, then substantial exposure of members of the public would have occurred. The high radiation levels within the containment should have indicated the need for more substantial precautionary actions. The Nuclear Regulatory Commission (NRC) inquiry found it would have been prudent to recommend precautionary evacuation at about the time the core was being damaged because ‘the containment building was … filling with intensely radioactive gas and vapours, leaving the nearby public protected by only one remaining barrier, the containment, a barrier with a known leak rate that needed only internal pressure to drive the leakage’ [66]. The authorities had not, however, adequately identified the off-site risk areas before the accident occurred. Consequently, they had difficulty determining the distance from the plant within which evacuation should be carried out. This uncertainty on the part of the authorities became evident to the public and it was this that undermined public confidence in the authorities’ competence, and thus made local residents less inclined to trust the authorities’ protective action recommendations.

Studies and experience also show that releases into the atmosphere during severe emergencies at threat category I and II facilities are unpredictable [68]. They can occur via an unmonitored release route and can begin within minutes after core damage. Consequently, facility operators cannot predict with certainty the occurrence of a major radioactive material release, the magnitude and duration of any such release, or its radiological consequences [68]. However, studies also show that taking precautionary protective actions (such as evacuation, substantial shelter, iodine thyroid blocking and restricting consumption of food and water that may be contaminated) promptly upon the detection of conditions in the facility that might lead to fuel being damaged (uncovered) will greatly reduce the off-site consequences [35, 68]. These precautionary protective actions should be followed by prompt monitoring after a release and further implementation of urgent protective actions based on the results of the monitoring. Evacuation has been shown to be the most effective protective action for protection of those near by the facility if it can be implemented relatively quickly.

Sheltering within buildings is an appealing protective action because it can reduce the risk to people and avoids the disruption caused by evacuation. However, the effectiveness of sheltering to protect against an airborne release of radioactive material varies and depends on the structure of the buildings. In general, only large masonry buildings and specially prepared shelters provide significant protection. Its effectiveness also requires the occupants to seal the structure and shut off any ventilation systems before the plume arrives and to ventilate the structure as soon as possible after the plume has passed. There is, however, some evidence that people do not believe sheltering would be effective [59, 69]. Other research indicates that at least 50% of those advised to shelter in-place during a toxic chemical release evacuated instead [70].

The use of stable iodine can substantially reduce the thyroid dose from radioiodine if taken before or shortly after intake [71]. During the Chernobyl accident, the Polish authorities distributed 17.5 million doses of stable iodine that caused serious short duration side effects in only two adults with known iodine sensitivity [72]. A joint IAEA/WHO Technical Meeting held in September 2001 agreed that ‘the administration of stable iodine to the public is an effective early measure for the protection of the thyroid to prevent deterministic effects and to minimize stochastic effects for persons of any age. However, it is primarily intended for the protection of children and the embryo or foetus’ [1, Addendum to Annex III].

The cases of radiation induced thyroid cancer that occurred subsequent to the Chernobyl accident were due to the doses of internal exposure from consumption of milk and leafy vegetables contaminated with I-131. The vast majority of these radiation-induced cancers occurred among people residing at the time of the accident at distances more than 50 km from the plant; excess cancers were detected also among those residing at distances more than 300 km away [73]. These radiation-induced cancers could have been prevented if the authorities had instructed people not to drink milk until the supplies had been shown to be free of I-131 contamination. Alternatively, people could have been given stable iodine prior to drinking the contaminated milk. However, this approach would have required the authorities to have available millions of doses of stable iodine and distribute them rapidly to those in the contaminated area. In addition, authorities would have had to convince the affected population of safety of stable iodine.

It is very difficult, if not impossible, to provide real time predictions of the off-site impact of a severe atmospheric release as a basis for undertaking urgent protective action, following an accident in a facility in threat category I or II [9, 19, 49]. This is not only because of the limited data available, but also because tests [74] and experience [9, 37, 55] have shown that computer dose projections are not capable of providing a sufficiently timely or accurate basis for taking protective action at an early stage for areas near the facility. Nevertheless, the instrumentation used in facilities in threat categories I and II can, in most cases, detect the onset of severe accident conditions in the facility in time for the operators to provide a warning to initiate protective action before or shortly after a release [37, 49, 54, 75]. However, protective actions may not be undertaken quickly if the emergency plans lacked systems for taking decisions rapidly that coordinate with the off-site organizations [76].

When an emergency occurs within a facility, prompt detection of high radiation levels (e.g. with radiation/criticality alarms) and immediate evacuation, in accordance with prior training, has saved lives [77]. Immediate search and rescue operations are sometimes required on site. Such operations have been performed under very hazardous conditions while the rest of the facility staff conducted other emergency operations. Rescue efforts are typically conducted by those nearby [58] and may divert attention and effort from other emergency response tasks if they have not been integrated into the response plan [56].

### 3.5.2. Conclusions

These lessons demonstrate the importance of:

- prompt action being taken at the time of an emergency to prevent people from receiving high doses, which in turn, avoids the expensive medical treatment (e.g. for radiation-induced injuries or thyroid cancers) that may otherwise be necessary;
- for facilities within threat categories I and II, taking action based on plant conditions, rather than on dose projections derived from atmospheric release data or environmental monitoring;
- establishing, in advance, criteria for action to protect the public for facilities within threat categories I and II and for activities within threat category IV, thereby avoiding *ad hoc* decisions;
- the emergency plans containing these criteria for urgent protective action to be coordinated with all the authorities involved in responding to the emergency.

The lessons also indicate that:

- concerns about possible panic and traffic risks should not prevent the institution from undertaking evacuation to protect the public;
- administration of stable iodine needs to be done rapidly if it is to be effective in preventing the uptake of radioiodine by the thyroid, but that this may pose difficult logistical problems if the affected population is large;
- the preferred protective action upon the detection of a severe emergency (general emergency), in threat category I or II, is timely evacuation, iodine thyroid blocking and restricting consumption of food and water that may be contaminated, shortly followed by prompt monitoring and further urgent protective actions after a release. These actions will greatly reduce the off-site consequences [35, 68]. However, if evacuation cannot be implemented promptly, sheltering is also a possible countermeasure, but should be used with caution, depending on the nature of the emergency and the construction of buildings. Sheltering, if instituted, can only be a temporary measure;

- the protective action strategy to be implemented in the event of an emergency must be decided in advance after consideration of the site and facility characteristics, and insights on the effectiveness of various protective actions. For threat category I facilities, such as large nuclear reactors, or facilities with large amounts of spent fuel, an effective response strategy for an emergency involving damage to the core or fuel in the spent fuel pool would include:

    - taking precautionary protective action nearby (3–5 km)[16], immediately upon detection of conditions within the facility that are likely leading to core or spent fuel damage, without waiting for dose projections (too slow and uncertain);
    - promptly (within hours) conducting monitoring and initiate appropriate urgent protective action (e.g. evacuation) for the area within about 30 km[17] of a large reactor;
    - promptly stopping consumption of local produce[18], milk from animals grazing on contaminated pasture or rainwater up to a distance of 300 km[19] until sampled and analysed;
    - within days, conducting monitoring of ground deposition and initiate early protective actions (e.g. relocation) for the area within about 250–300 km;

- provision for promptly (within an hour of the predefined criteria being exceeded) making decisions concerning precautionary and urgent protective actions and subsequently notifying the public, is essential to reducing the probability of radiation health effects among the public in the event of a severe emergency [35, 68];
- although the focus during an emergency will be on the actions to be taken to mitigate the consequences, criteria are also necessary for determining when protective actions can be lifted. People who have been evacuated will naturally wish to return to their homes and re-establish their normal activities. Thus, if precautionary countermeasures have been used, action will be necessary to assess the affected areas against the pre-established criteria so that they can be progressively lifted.

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[16] Area called the Precautionary Action Zone (PAZ).

[17] Area called the Urgent Protective Action Planning Zone (UPZ).

[18] Local produce is food that is grown in open spaces that may be directly contaminated by the release and that is consumed within weeks (e.g. leafy vegetables).

[19] Area called the food restriction planning radius.

## 3.6. PROVIDING INFORMATION AND ISSUING INSTRUCTIONS AND WARNINGS TO THE PUBLIC

The principal requirements on providing information and issuing instructions and warnings to the public covered in the Safety Requirements publication [1] relate to:

*Response*

- the prompt warning and provision of information to the public;

*Preparedness*

- for facilities in threat category I or II, the arrangements for the provision of promptly warning and instructing on the response to the off-site population and entities (e.g. farms, food distribution centres) and for those in the PAZ, UPZ and food restriction planning radius.

### 3.6.1. Observations

During the first few days of the TMI emergency, assessments of the situation were being issued simultaneously to the media and public, by a number of different official sources — the site of the emergency, the local state capitol, and the regional and national headquarters of the regulatory body. These assessments were often wrong, inconsistent, misleading, not current, or did not address the immediate concerns of the local population. This resulted in public confusion, concern and loss of trust in the officials. This problem was later rectified when the President of the USA ordered that all official assessments must come from a single source of official information located in a facility close to the location of the accident. [78].

The Safety Requirements document [1] specifically refers to the need for facilities in threat categories I and II to make arrangements, before and during operations, to provide information to permanent, transient and special populations groups. There have, however, been emergencies at threat category III facilities that posed no significant risk to the off-site population but the public became concerned about the possible radiological risk following inaccurate reports and speculation by the media [79, 80]. Since no efforts had been made in advance to inform the population of the facility’s risks, local residents had no basis on which to assess the media reports. Consequently, they lost confidence in both the authorities and the facility operator.

The Goiânia accident (an accident with a source within threat category IV) also demonstrated the need to consider the demand for public information in radiological emergencies. From the day of the discovery of the radioactive contamination there was intense public concern and media interest. In the absence of clear information from the authorities, rumours abounded. During the first week or so, there was no dedicated press officer with support staff. This meant that the media and the public flocked around the staff trying to deal with the emergency, side-tracking them from their key tasks. It took several days for the authorities to gain control of the accident, and it was subsequently recognised that failure to deal with the press and public at an early stage had been a major factor in the time taken. When resources were later committed to dealing with the media and public, it took some time to re-establish public trust in the actions being taken by the authorities [13].

Such problems of communication are not confined to radiation emergencies. In the Bhopal accident [81] which involved a release of methyl isocyanate, a warning siren was sounded, which instead of causing the local population to move away from the site and take precautions, attracted them to the site to see what had gone wrong.

In general, it would appear that operators of facilities in the event of an emergency that could present a hazard to those in the surrounding community avoid disseminating information in advance on the actions to be taken in an emergency. The reason is that they do not want to alarm local residents.

Before the TMI accident, the plant operator had used public information programmes to persuade the local people that nuclear power was reliable and safe. Discussions of plant risks addressed only routine exposures and people were told that a major accident was impossible. Consequently, local residents had no knowledge of what to do when the accident occurred.

All serious emergencies, and many much less serious emergencies, attract considerable public and media interest. In fact, it is now common for the media to arrive in the vicinity of an emergency within a very short space of time. This can add to the pressure on those concerned with the management of the response. However, it can also be used to an advantage, if clear information is provided to the media. In the case of the Katrina and Rita hurricanes, the public relied heavily on the media for information [62]. By the time a protective action recommendation was issued two days into the TMI accident, local residents were actively monitoring the news media. Similar behaviour has been observed in other emergencies [82].

In the polonium-210 incident in London [33] there was intense media and public interest in the incident. The lessons from previous emergencies were heeded and significant effort put into providing early information to the public on the nature and scale of the hazards, and to ensure authoritative updates were provided throughout this protracted incident. Key early actions were to provide Question and Answer documents on a website (with links to it from relevant internet sites) and hold a press conference to provide information available on what has happened (to the extent known), the response actions planned and putting the hazards in perspective. Crucial to the last of these was getting the message to the public that $^{210}$Po was not an external radiation hazard and was only hazardous if taken into the body.

It was important to recognise the needs of the media and their deadlines, by making staff available for interviews and being amenable to providing visual backdrops for television, e.g. laboratories involved in urine analysis. This was challenging both logistically and in terms of staff resources, but was seen as both necessary and effective in ‘keeping ahead of the game’ in establishing and maintaining public confidence and understanding.

There were mechanisms to ensure that the daily press releases were coordinated across the various agencies involved, so that a unified view of the situation was presented. In parallel to the public health response, there was also a criminal investigation being undertaken by the police and it was necessary to balance the confidential nature of information stemming from the police investigation, with the need to keep the public informed. Where there was any threat to the safety of the public, this took precedence.

One of the key aspects of interacting with the public was the use of NHS Direct (a 24 hour National Health Service helpline). As part of emergency response arrangements involving any kind of public health issue, NHS Direct provided a focus for concerned members of the public to telephone for information. Emergency Question and Answer algorithmic scripts were available for nuclear and radiological incidents, but the unique nature of the polonium incident required these to be quickly adapted. Also, the police investigation and incident response quickly identified locations which, if visited by individuals on specified dates, provided the potential for them to have had intakes of $^{210}$Po. As part of the process to identify those who might need intake and dose assessment, a media appeal was put out for these people to contact NHS Direct.

### 3.6.2. Conclusions

These lessons demonstrate the importance of:

- including consideration of the provision of public information and warnings in the emergency response plans for facilities in threat categories I and II;
- providing information on the protective actions to be taken in the event of an emergency to be made available to the public in potentially affected areas in advance of any emergency in the case of facilities in threat categories I and II. This will engender confidence — the knowledge that the officials have their interest at heart — and, by doing so, improve compliance with protective action recommendations in the event of a real emergency. In addition, there will be a better understanding of the systems used to warn them of an emergency;
- a coordinated approach to the provision of information to the media, and this should be addressed in the emergency plans.

The lessons also indicate that:

- consideration needs to be given to the demand from the public for information of events in facilities in threat category III, if only to ensure that correct information is given and unnecessary fears are allayed;
- prior thought needs to be given to the means to be used to provide information to the public in the event of an emergency involving an activity within threat category IV;
- the quality of the information disseminated to those at risk substantially determines their ability to protect themselves. Implementation of a protective action by the public after hearing a warning signal (e.g. a siren) is significantly higher when followed by a warning message (e.g. over a loudspeaker or radio) describing the threat, which areas are at risk (thus requiring protective action) and which areas are not at risk (thus requiring no protective action). The messages should identify the location of the event, the nature of the radiological hazard, and the severity and immediacy of the threat. It is critically important that the message describes the areas at risk in terms of political and geographical boundaries that

will be readily recognized by local residents, gives specific recommendations for the actions that they should take to protect themselves, and identifies the legitimate authority making the recommendation. It is also important that the messages are clear, consistent and repeated;

- those transiting through the areas affected by an emergency cannot be expected to understand the warning signals and to know the local landmarks, so specific mechanisms will be needed to contact them and provide them with guidance;
- the media (e.g. local radio stations) can be used effectively as the primary warning method for emergencies at unforeseen locations — threat category IV — and as a supplement to other warning systems.

## 3.7. PROTECTING EMERGENCY WORKERS

The principal requirements on protecting emergency workers covered in the Safety Requirements publication [1] relate to:

*Response*

- the arrangements to protect emergency workers.

*Preparedness*

- the arrangements to designate as emergency workers those who may undertake an intervention to save lives, prevent large collective dose or prevent the development of catastrophic conditions;
- the designation of those responding at a facility in threat category I, II, or III or within the PAZ or UPZ as emergency workers;
- the provision of information to first responders on the risks of radiation exposure and the meanings of signs and placards;
- the adoption of national guidance for managing, controlling and recording doses received by emergency workers;
- for facilities in threat category I, II or III, the identification of the anticipated hazardous conditions in which emergency workers may be required to operate;
- the arrangements to protect emergency workers;
- the application of the full system of occupational protection once the emergency phase has ended;
- the communication of the doses and risks to the workers involved after the intervention has ended;
- the specification of the person responsible for ensuring compliance with the requirements for occupational protection in the emergency plans.

### 3.7.1. Observations

The severity of the Chernobyl accident called for heroic measures. Workers entered the damaged building to rescue injured colleagues. In addition, there was both a need to assess the amount and type of radiation being emitted to the atmosphere. This was done by having aircraft fly through the plume in and around the site. An attempt was also made to quench the fire and reduce radioactivity levels by dropping materials from helicopters directly through the hole in the roof. These essential activities could not have been done within the annual occupational dose limits.

During the accident, many emergency workers, including members of the off-site fire brigade, received very high levels of radiation exposures, some of which proved to be fatal. This occurred, in part, because monitoring instruments went off scale, no means were provided to measure doses to individuals on an on-going basis, and protective clothing and training were inadequate. Standard fire fighting clothing did not provide adequate protection from beta radiation, which resulted in severe radiation burns and, in some cases, contributed to the fatalities.

At TMI, the need to perform response operations and the hazardous conditions could have been anticipated from accident studies. Nevertheless, there were shortages of high range survey instruments, self-reading high range dosimeters, and respiratory protection equipment.

The response to the Goiânia accident lasted several months and emergency workers were involved in many very stressful activities. Some had to perform radiation protection activities in hospitals in close contact with the accident victims and, in some cases, to undertake radiation monitoring during the post mortem examinations of the four persons who died. For years after the event, the responders still felt the psychological effects [83].

After the emergency phase of the Chernobyl and Goiânia accidents, several months were required to implement a system of radiation protection for the large number of workers involved in the post-emergency phase. In the case of Chernobyl, the lack of detailed dose records for the individuals involved in emergency and post-emergency operations caused problems affecting their medical follow-up.

The dose received by emergency workers involved in the recovery of uncontrolled sources can be minimized by establishing a system of radiation protection to be implemented from the beginning of recovery operations. This includes careful identification of the source location, procurement of necessary resources such as shielding, dosimeters and shielded container, identification of means of minimizing doses during recovery, and rehearsal of the recovery actions [21, 25].

### 3.7.2. Conclusions

These lessons demonstrate the importance of:

- emergency workers being clearly and comprehensively informed in advance of the risks, and to the extent possible, to be trained in the actions that may be required;

- emergency workers being provided with suitable protective and monitoring equipment, and for this equipment to be readily accessible and in sufficient quantity for the postulated emergency;
- the emergency plan reflecting the needs of emergency workers;
- the doses to emergency workers being appropriately assessed and recorded for the purpose of subsequent medical care.

The lessons also indicate that a release of radioactive material can lead to both internal and external radiation exposure. Therefore, direct reading individual dosimeters, which, very often, only measure exposure from external penetrating radiation may not provide a sufficient measure of the hazard and hence, additional criteria may be necessary to manage the exposure of emergency workers.

## 3.8. ASSESSING THE INITIAL PHASE

The principal requirements on assessing the initial phase covered in the Safety Requirements publication [1] relate to:

*Response*

- the appraisal of the magnitude and likely development of hazardous conditions throughout the emergency;
- the monitoring and environmental sampling and assessment;
- the information to be made available to all response organizations.

*Preparedness*

- for operators of practices or sources in threat category IV, the arrangements to characterize the situation, to initiate action, to identify those who are potentially exposed and to communicate with the off-site response organizations;
- for operators of facilities in threat category I, II or III, the arrangements to assess the conditions and exposures, and the use of this information for protective actions;
- for the PAZ and UPZ, the arrangements to promptly assess the radiological conditions for the purpose of determining the urgent protective actions to be taken;
- for the team of radiation specialists who support the first responders, the arrangements for identifying the radionuclides and for delineating the areas in which protective action is warranted;
- the arrangements to ensure that information is recorded and retained.

### 3.8.1. Observations

For some emergencies, facts about what happened and the possible consequences are available early on in the response, however in many situations the relevant data only emerges over a period of time and through a variety of sources and actions. It is therefore important to know the critical data needed and to have clear mechanisms to bring together these data streams to form an overall picture. For example, in the polonium-210 incident in London the initial data available was the intake of the poisoned individual and details of a few places he had been over the preceding weeks. The initial risk assessment identified that there was a significant public health risk from the potential spread of contamination from the events leading to the poisoning, any residue and from the victim's body fluids. Also at this stage it could not be assumed that this was an isolated event, or had a single victim. A strategy for the public health response was quickly developed [33]. Within this, priority was placed on checking with other hospitals in the area to ensure no other victims were suffering, or had suffered the same symptoms; and on monitoring the environments most likely to be contaminated, e.g. the victim's home, hospitals where he was treated, and known locations he had been to.

The early contamination monitoring at the identified locations found levels that confirmed the potential for a public health threat, but also identified that the contamination was patchy and largely fixed to the surfaces it was found on, and not widely dispersed. This helped refine the overall risk assessment and to then focus attention on assessing the various mechanisms for transfer and spread of the contamination, and for intakes of the radioactive material. From this, triage questionnaires were developed to identify groups of staff, guests and visitors at hotels, restaurants and offices that may have been at most risk of exposure and who should be offered personal monitoring using a urine analysis technique. As the police investigation continued, more locations were identified that required monitoring. As these data streams were brought together within the lead public health response organization, patterns of contamination transfer emerged which helped refine the risk assessments and also fed back into the police investigation.

Many organizations were involved in the response to the incident and it was important that there was a coherent view of the situation and a coordinated response. At the top level this was achieved through the government led Civil Contingencies Committee (CCC) at which the various agencies responding were represented. A key input to the CCC was the Common Recognised Information Picture (CRIP). Two hours before meeting, each agency had to submit their Situation Report, from which the CRIP was produced. This allowed time for any differences in data to be reconciled, and allowed the CCC to concentrate on the strategy of the response. Any 'breaking news' or important updates could be provided at the meeting.

### 3.8.2. Conclusions

These lessons demonstrate the importance of:

- assessing the magnitude and scope of a problem is an evolving process, so emergency responders should continue to assess the problem to test the validity of the initial assessment and monitor changing conditions.

## 3.9. MANAGING THE MEDICAL RESPONSE

The principal requirements on managing the medical response covered in the Safety Requirements publication [1] relate to:

*Response*

- the notification by the medical practitioner or other party of the identification of medical symptoms of radiation exposure;
- the provision of specialized treatment to any person who receives doses that could result in severe deterministic health effects;
- the detection of increased incidence of cancer among emergency workers and the public.

*Preparedness*

- the arrangements for medical personnel to be made aware of the medical symptoms and the appropriate notification procedures and other actions;
- for facilities in threat category I, II or III, the arrangements to treat contaminated or overexposed workers;
- for jurisdictions within the emergency zones of a facility in threat category I, the medical management plan for triage;
- the arrangements at the national level to treat people who have been exposed or contaminated;
- the arrangements for the identification, long term health monitoring and treatment of people in those groups that are at risk of sustaining detectable increases in incidence of cancers.

### 3.9.1. Observations

A number of the emergencies in threat categories III and IV were first discovered by physicians treating the victims. Examples of the first are the accident involving radiotherapy patients in Costa Rica [20], and that involving workers in the irradiation facility in San Salvador [14]. Examples of the second are the accidents in Goiânia [13], Thailand [25] and Turkey [21]. As local physicians are inexperienced in the diagnosis of radiation injuries, it has often taken some time before radiation exposure was suspected. Early diagnosis of the cause of the injuries may have prevented further injuries or deaths.

In addition, failure to diagnose correctly the cause of the injuries has led to inadequate treatment. For instance, the physician undertaking the annual medical examination of the individual who had previously received high exposure to his hands, failed to correctly diagnose the symptom of radiation exposure, even though the victim told the doctor that he may have been exposed to radiation [17]. It took another 14 days before the acute radiation exposure was diagnosed.

It is well known that radiation injuries evolve with time and affect deep tissues. As a consequence, information on the profile of the dose received by a patient is essential. Some physicians, however, not realizing this, have incorrectly assumed that radiation injuries require only conventional treatment which could be provided locally, and did not consider the dose related prognosis for the exposed tissue [17]. This led to inadequate treatment (e.g. to save tissue) and a delay in the required treatment. Following the irradiator accidents in Italy in 1975 [29] and in San Salvador in 1989 [14], physicians treating the radiation-induced injuries were not provided with a description of the initial symptoms, or with sufficient information to be able to reconstruct the dose. In the San Salvador accident, the patients were subsequently sent to another country with more experienced medical staff and better facilities.

The treatment of a severe overexposure can involve specialized drugs that are not commonly available, replacement therapy, and surgery prompted by both clinical symptoms and prognosis based on dose reconstruction. There are only a few medical centres worldwide that have significant experience in the specialized treatment of radiation-induced injuries. However, depending on the severity of the injury, with appropriate diagnosis and expert consultation, some radiation-induced injuries could also be effectively treated in local hospitals. This would have the advantage of reducing the psychological stress on the patient that might otherwise occur, if the patient is sent to another country for treatment.

Cooperation between several governments and international organizations in rendering expert experience to San Salvador on medical treatment and dosimetry, was delayed because normal administrative procedures were used to request the assistance [14].

In any case, the international cooperation and assistance in addressing challenges of medical management of overexposed patients is essential.

In the event of a large radiation emergency such as the Chernobyl or Goiânia accidents, triage of patients would appear necessary. In the response to the Goiânia accident, authorities provided a three-tiered system of medical treatment facilities — one focused on decontamination, one on patients who had received doses between 1–2 Gy, and one on patients who had received doses above 2 Gy, or with local radiation injuries requiring isolation and replacement therapy. However, this strategy entailed separating families and establishing multiple medical facilities staffed by physicians and health physicists experienced in treating contamination. Experienced staff were sometimes in very limited supply, facilities had problems controlling contamination and contaminated waste, and some medical staff were fearful of radiation exposure and contamination from the patients [13].

There are radiation-induced thyroid cancers amongst those who were exposed as children to radioiodine as a consequence of the Chernobyl accident. Early identification of those with this cancer is necessary and requires the long term follow-up of the exposed population. Thus, Belarus, for example, has a programme for medical monitoring of the individuals who have an increased risk of thyroid cancer. The mortality rate of those detected by this programme is significantly lower than the international mortality rate for those diagnosed with thyroid cancer [84].

Following the recognition of the polonium-210 incident in London, one of the early concerns was there may be other victims with acute symptoms that had yet to be identified. To address this possibility the response included the following three elements: (1) hospitals in the London area were contacted directly to check if any of their patients were presenting, or had presented with relevant symptoms; (2) the Government’s Chief Medical Officer issued an Alert Letter to be cascaded to all health professionals; and

(3) triage questionnaires, used by NHS Direct and public health teams assigned to affected locations, included questions to identify those who may have relevant symptoms. This produced 186 persons that warranted further review, of which 29 were referred to a dedicated clinic for assessment.

Fortunately, no one was found to be suffering from any acute radiation effects. Nevertheless, the above actions were necessary to eliminate this possibility.

Both, the Goiânia and London polonium-210 events, involved large numbers of members of the public with potential intakes of radioactive material due to the spread of contamination. For these events it was necessary to develop triage and personal monitoring programmes for health monitoring of individuals, and overall public reassurance as part of the input, along with environmental monitoring, to the on-going risk assessment during the response, i.e. what had happened and the consequences. The radionuclides in the two events, $^{137}$Cs (a beta/ gamma emitter) and $^{210}$Po (an alpha emitter) posed different triage, monitoring and patient management challenges. These experiences showed that it is important to have plans to address these challenges and the underlying capabilities to implement them across diverse situations.

In the Goiânia accident 112,000 people either needed, or wanted (for reassurance), to be monitored. The gamma emissions from $^{137}$Cs made triaging with handheld monitors technically easy, albeit that the logistics and resources needed were significant. For those identified as potentially contaminated, a bioassay of urine and/or faecal samples was carried out to assess doses. This was done by transporting the active samples for bioassay to well-established laboratories that were over 1000 km away, with consequent delays in getting results and logistical issues. Ref. [13] concluded that having transportable equipment for bioassay and whole body monitoring, together with specialists trained to adapt normal procedures to abnormal situations, should be considered for emergency preparedness plans. Since then, many countries have improved their capabilities in this area.

In the polonium-210 incident in London, the nature of $^{210}$Po as an almost pure alpha emitter, posed different challenges. External monitoring for triage purposes was not possible. It was necessary to triage on the basis of where people had been and what they had been doing. Environmental monitoring was able to narrow down the tens of locations to 11 with the greatest potential for intakes, some of these, the hotels and restaurants, involved thousands of individuals. A public health team was assigned to each of these locations and together with radiation protection specialists, they developed site specific questionnaires to identify those most at risk of having had an intake of $^{210}$Po and to offer individual monitoring involving 24 hour assessment of urine samples. The public health teams were responsible for the logistics of getting the urine sample to the radiation laboratories for testing and for reporting back the results to individuals, together with providing reassurance to the staff at these locations. These interactions were made more difficult by the fact that, for many staff in the hotels, English was not their first language. The lesson here is about using non-radiation protection specialist resources to provide the interface with the public. The public health teams' backgrounds were in communicable disease control and chemical incidents, and as such, had significant experience in dealing with concerned members of the public. With input from the radiation protection specialists they were able to deal with a resource intensive part of the response that would otherwise have used valuable radiation protection resources, in what was an incident with a long response period.

During the incident, people were offered the opportunity to have their name and details held by the agency on a secure Long Term Register (LTR) in the event that it was necessary or useful to contact them in the future**.** The LTR was ultimately regarded as something that was not necessary, as the levels of exposure did not require long term follow up. However, this judgement could not be made in the early phase of the response due to a lack of information. Experience from previous non-radiological incidents has shown that if collection of data on persons involved is not initiated at an early stage, it is difficult to capture such information at a later stage. Hence, resources were committed to the data capture as a precautionary measure.

In both the Goiânia and London polonium-210 events the patients presented a hazard to those caring for and treating them. In both cases radioactivity was present in body fluids: urine, faeces, vomit and sweat; whilst in the Goiânia incident the patients also provided an external exposure hazard. In the Goiânia accident, medical and nursing staff had concerns over their own safety, which took time to overcome, and there were limited numbers with relevant expertise. This experience is pertinent to the training programmes of medical staff, the availability of relevant information for medical professionals and planning for emergencies.

In the polonium-210 incident in London the care and treatment of the patient largely took place before the presence of $^{210}$Po in the patient was known. Although significant activity was present in the body fluids it is interesting to note that: the contamination levels found in the hospitals were relatively low, which is ascribed to the thorough cleaning regimes in place to prevent the spread of infection; similarly, the intakes of hospital staff treating the patient were low (this is ascribed to the routine use of personal protective equipment and procedures to maintain infection control. The highest assessed dose, apart from the patient, was to his wife who cared for him at home in the first few days.).

Both the Goiânia and London polonium-210 events involved post mortem autopsies on corpses that were highly radioactive. Appropriate safety procedures were developed and facilities temporarily adapted to enable the autopsies to proceed successfully and safely. This demonstrates the need for emergency arrangements to cover such eventualities.

### 3.9.2. Conclusions

These lessons demonstrate the importance of:

- medical professionals being trained to recognize radiation-induced injuries and to understand the difficulties in treatment;
- the physicians involved in treating patients who have received exposures that may result in tissue damage, or life-threatening doses, to promptly consult with other physicians with experience in dealing with severe radiation exposures, and transferring the patient to an appropriate hospital if warranted;
- those involved in emergency response gathering sufficient information to allow the dose profile of the highly exposed individuals to be reconstructed, in order to

determine the evolution of the damage and the treatment that is necessary. This information includes:

(a) estimates of the dose received to the whole body or tissues,

(b) photograph/diagrams of the facility/practice involved,

(c) a description of the source of exposure (e.g. activity, radionuclide, dose rate at 1 m),

(d) a detailed description of circumstances of the exposure (e.g. location of person as a function of time,

(e) readings of all individual dosimeters (all staff members) or other monitoring devices,

(f) samples of items worn by the overexposed person,

(g) a full description and time of onset of any early clinical symptoms,

(h) results of a general medical examination of all systems and organs to include the skin for visible muscosa,

(i) total blood counts in order to detect the first wave of symptoms related to exposure;

- the authorities establishing plans and procedures: for triage of the victims and transporting them to the appropriate medical facilities, for ensuring that there will be a sufficient number of medical staff available to deal with the postulated number of victims, for collecting individual dosimetry data and providing those data to physicians, for obtaining expert assistance in the diagnosis and treatment of radiation injuries, and for transferring patients who suffered a severe exposure to facilities with experience in treating radiation injuries;
- the national emergency plan having provisions for promptly requesting emergency assistance for dealing with victims from international organizations under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency [51];
- establishing criteria for determining the groups which have been highly exposed and should be subject to long term medical follow-up to detect the early appearance of cancer.

The lessons also indicate that the psychological impact of the treatment of radiation-induced injuries must be minimized and therefore the treatment should be provided as close to the individual’s home as possible, or in a region with the same language and culture. Provision should be made for family members to accompany the patient when treated in another country.

## 3.10. KEEPING THE PUBLIC INFORMED

The principal requirements on keeping the public informed covered in the Safety Requirements publication [1] relate to:

*Response*

- the provision of information to the public.

*Preparedness*

- the arrangements for providing information to the public;
- the arrangements for coordinating the provision of information to the public.

### 3.10.1. Observations

Experience has shown that during an emergency of whatever type, there is intense pressure from the public and media for information. The advent of 24 hours a day news broadcasts have further intensified this pressure. It is not uncommon for members of the media to arrive at the site of an emergency shortly after it has become known, and to observe it directly as it unfolds. In addition, those who think they may have been directly affected will pursue their own investigations, with this creating further pressure. Thus, in the event of an airplane crash, for example, it is normal for the airlines to rapidly establish a telephone number to deal with inquiries from members of the public who believe that a member of their family or friend may have been involved.

There are many examples of radiation emergencies where the demand for information has been underestimated and because no detailed arrangements had been made to deal with the demand, those dealing with the management of the response had been overwhelmed, and thus limiting their effectiveness in responding to the actual emergency. This was the situation, for example, during the TMI accident (threat category I) and the Goiânia accident (threat category IV).

Experience has also shown that the demand for information is not necessarily related to the severity of the emergency, as judged by those responsible for managing it, at least in the short term. This was the case with the accident in USA in January 1986 when a cylinder ruptured releasing $UF_6$ (threat category III). One worker died but the uranium contamination off the site presented no significant radiological hazard to the public. Nevertheless, this event received extensive media attention. Those concerned were not prepared for this, and were therefore unable to respond promptly to misleading reports. The failure to inform and correct the media with accurate and consistent official assessments caused unwarranted fear of contamination among nearby residents. This resulted in extensive monitoring simply to reassure the public and local officials [80].

This example also shows that if the provision of information is not carefully managed, the authorities may be required to undertake action that may not be necessary to mitigate the radiological consequences of an emergency. In the response to the accident in Thailand involving an orphan source, those involved in the recovery of the source wore lead aprons to give the appearance to the media that they were being appropriately protected. These aprons, however, are not effective in reducing the dose rate from cobalt-60 gamma rays and undoubtedly slowed down the progress of the workers [25]. During the response to a lost source in Turkey [21], there was severe pressure, mainly from the media, to mitigate the hazard by pouring concrete over the area where the source was located. In this case, the pressure was resisted since it would have made the recovery operation more difficult and precluded locating other sources.

If the information is not carefully managed, the media are very likely to seek the views of ‘self-appointed experts’, local doctors and others respected within the community. Confusing, conflicting and misleading information can then lead to unwarranted and sometimes harmful actions by the public. In the TMI accident, many more people than recommended decided to go for evacuation; in the Goiânia accident, 100,000 people asked to be monitored, many of whom did not even come from the impacted area; in the Chernobyl accident, unwarranted abortions were undertaken; in both the Goiânia and Thailand accidents, there were protests against the funerals of the victims.

The pressures during an emergency can result in those responsible for giving information to the public and the media not thinking through sufficiently whether they are communicating in language that will readily be understood. During some emergencies, official spokespersons have used technical terms. This can give the impression that information is being withheld and lead to speculation. In some cases, responsibility for giving media briefings was sometimes assigned to individuals because of their technical or managerial role rather than their communication skills. This contributed to errors in reporting the technical aspects of the emergency and reduced public confidence in the credibility of authorities [82].

Keeping the public well informed during response to uncontrolled source emergencies appears to increase their trust and cooperation [13, 21, 25] and helps to limit pressure for a quick solution when a more considered solution is required. This includes holding regular press briefings to provide timely and accurate descriptions of current operations, correcting inaccurate information and maintaining a close and mutually supportive relationship with the news media. It also includes long term efforts such as participation in debates, the production of simple language information and a 24 hour rumour control/information telephone service.

In the Goiânia accident, as the need to address the media and public information became more apparent, even overwhelming, more resources were deployed. However, no previously prepared material was available and the responders had no media training. Even so, they briefed journalists who were then able on television and radio to describe the situation in basic terms. The journalists were known to the public and brought with them a degree of credibility. In addition, a pamphlet ‘What you should know about radioactivity and radiation’ was produced and 250,000 copies distributed. Also, a 24 hour telephone hotline was created to answer calls.

### 3.10.2. Conclusions

The major objectives of emergency public information are:

- to ensure that those who are not at risk understand that their safety is being actively monitored and that, unless otherwise instructed, there is no need to take protective actions. This contrasts with the goal of the emergency warning, which is to ensure that all of those at risk comply in a timely manner with authorities’ protective action recommendations;

- to ensure that the demand for public information does not detract from the management of the response to the emergency.

These lessons demonstrate the importance of:

- giving careful attention to the provision of timely and accurate public information, both immediately and on an on-going basis, irrespective of whether or not public concern seems misplaced;
- defining the arrangements for providing appropriate information to the public and media in the emergency plan for all facilities in threat categories I, II and III and for activities within threat category IV;
- coordinating the provision of information between the public authorities and operators;
- the staff manning the information centres being trained in providing information to the public and media in a clear and straightforward fashion.

## 3.11. TAKING AGRICULTURAL COUNTERMEASURES, COUNTERMEASURES AGAINST INGESTION AND LONGER TERM PROTECTIVE ACTIONS

The principal requirements on taking agricultural countermeasures, countermeasures against ingestion and longer term protective actions covered in the Safety Requirements publication [1] relate to:

*Response*

- the taking of agricultural countermeasures and longer term protective actions;
- the appropriate management of radioactive waste and contamination;
- the discontinuance of a protective action.

*Preparedness*

- the establishment of optimized intervention levels and actions levels;

- for areas with activities in threat category V, the arrangements for taking agricultural countermeasures;
- for a major release of radioactive material from a facility in threat category I or II, the arrangements for temporary relocation;
- for the emergency zones, the arrangements for monitoring vehicles to control the spread of contamination;
- the arrangements for the management of radioactive waste;
- the arrangements to assess the exposures of the public and to make the information publicly available.

### 3.11.1. Observations

Following an accidental release of radioactive material into the atmosphere from a facility in threat category I or II, protective actions relating to the consumption of foodstuffs produced in the path of the plume may be necessary. The prevention of the consumption of contaminated milk is usually the most urgent, but other foodstuffs also need to be considered in the relatively short term, particularly leafy vegetables. Protective actions regarding the consumption of food that may be contaminated within months, such as meat, should also be instituted on a somewhat longer timescale. As the Chernobyl accident has demonstrated, such countermeasures may need to be extended out to considerable distances from the site of the accident, covering very large areas, which require extensive environmental monitoring. The Safety Requirements document [1] requires arrangements to be made for taking effective agricultural countermeasures and for these arrangements to include default Operational Intervention Levels (OILs), including means to revise them. Clearly, such OILs should be established in advance and be incorporated into the emergency arrangements for facilities in threat categories I and II and for activities within threat category V.

Following the Chernobyl accident, many States implemented controls on contaminated foodstuffs. The activity concentrations used varied considerably as a result of the use of different dose criteria and modelling assumptions, often more as a consequence of political pressure than for scientific reasons. However, this created considerable confusion. As a result, the Codex Alimentarius Commission developed activity concentrations for use in the international trade of foodstuffs [85, 86].

The activity concentrations in most foodstuffs decrease rapidly with time. Nevertheless, several countries that set up programmes to monitor foodstuffs during that period still continue to monitor routinely imported foodstuffs without necessarily reviewing the need to do so.

The values of the Codex Alimentarius Commission only apply to international trade and do not regulate the internal use of possibly higher levels within the country affected by the accident. However, it is unclear whether this would be understood by the public and they would be willing to accept higher levels in the event of an event within their own country.

Following the Chernobyl accident, the Ministry of Health of the former USSR adopted the following permissible limits of annual dose for the public from the accidental exposure: 100 mSv in 1986, 30 mSv in 1987, and 25 mSv in 1988 and 1989. As for the emergency workers the permissible limits were as follows: 250 mSv in 1986 (for the military personnel - 500 mSv until 21.05.1986), 100 mSv in 1987, and 50 mSv in 1988 and 1989. The government of the former USSR initially adopted a criterion for resettlement at a lifetime dose since 1990 of 350 mSv. This value was strongly criticized as being too high and was not applied. In 1991 a lower criterion was adopted in law, which applied a lifetime dose of approximately 70 mSv. This resulted in a much larger number of people leaving at contaminated territory being subject to relocation. The adoption of such a low criteria can, in part, be attributed to the fact that the criteria had not been established before the emergency, and thus were developed during a period of heightened emotions and mistrust following the accident [88, 87].

During the Goiânia accident, it also was very difficult to set OILs for relocation during the emergency because of time constraints, political pressure and lack of international guidance. The result was the use of excessively cautious assumptions in developing OILs, which in turn resulted in unnecessary protective action, the generation of unnecessary amounts of radioactive waste and unnecessary decontamination and disposal costs. In addition, rather than convincing the public that the action being taken was in their interest, it gave them a feeling that the risk was far greater than actually was the case.

Immediately after the emergency response phase of the Chernobyl, Goiânia and other emergencies had been completed, there was immense pressure from the public, public officials and the media to act and return to normal activities. In the case of the Chernobyl accident, many unjustified efforts were carried out because of this pressure, such as the decontamination of areas that had been evacuated, that would not be resettled in the foreseeable future (e.g. Pripyat) [89].

Many of the attempts to decontaminate villages after the Chernobyl accident were ineffective due to a lack of proper pre-emergency planning. These results produced the general impression that urban decontamination was not worthwhile. Since then, however, it has been demonstrated in the Novozybkov area that simple countermeasures, such as topsoil removal, special digging measures and roof cleaning, can, even 10 to15 years after the Chernobyl accident, significantly reduce the external dose rate [90].

During the Goiânia response, additional decontamination was carried out after the official announcement that all decontamination had been completed. This added to public concern and mistrust of officials.

### 3.11.2. Conclusions

These lessons demonstrate the importance of:

- developing OILs for various protective actions in advance and incorporating them into the emergency arrangements;
- using internationally harmonized generic OILs and protective actions;
- providing clear explanations to the public in the case of when and why values need to be changed during an emergency;
- establishing beforehand methods and criteria for decontamination of areas (streets, roofs, surface soil, subsoil, etc.) to reduce dose rates;
- refraining from declaring decontamination operations as completed until a final assessment confirms that dose reduction goals have been achieved.

## 3.12. MITIGATING THE NON-RADIOLOGICAL CONSEQUENCES OF THE EMERGENCY AND THE RESPONSE

The principal requirements on mitigating the non-radiological consequences[20] of the emergency and the response covered in the Safety Requirements publication [1] relate to:

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[20] Non-radiological consequences refers to psychological, economic and other consequences.

*Response*

- the consideration of the non-radiological consequences to ensure that actions do more good than harm.

*Preparedness*

- for jurisdictions within the emergency zones, the arrangements for justifying, optimizing and authorizing different intervention levels or action levels, for agricultural countermeasures or longer term protective action;
- the arrangements for responding to public concern.

### 3.12.1. Observations

All serious nuclear (e.g. Chernobyl) and radiological (e.g. Goiânia) accidents resulted in significant adverse psychological effects. People’s fear of radiation, together with conflicting and confusing information about the event, or lack of adequate explanatory information, created mistrust of authorities and official experts, and feelings of loss of control over their lives. Consequently, some people took inappropriate, and occasionally harmful, actions due to misconceptions concerning the risks and how to reduce them[21]. Some of those in the vicinity of the event were subject to stigmatization and social segregation.

Within the former Soviet Union, a system of compensation was instituted that was intended to reduce public stress and to promote recovery. The compensation was determined primarily on the basis of the location where people lived during or after the accident, rather than on the basis of the risk of health effects, or as compensation for tangible impacts (e.g. the cost of resettlement, loss of property or jobs). This system produced misconceptions about health risks because receiving financial compensation implied recognition of possibility for the future adverse health effects.

The compensation system also placed a large burden on the affected countries. The number of people claiming Chernobyl-related benefits was increasing over time. Chernobyl benefits drained resources away from other areas of public spending [91]. Compensation policies implemented after the Goiânia accident also created problems: when people discovered they were to be compensated for contaminated items, they demanded more restrictive criteria for defining contamination.

### 3.12.2. Conclusions

These lessons demonstrate the importance of:

- considering and taking account of the psychological impact that actions undertaken during and subsequent to a serious emergency might have on members of the public;

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[21] Interference in funerals of victims, shunning victims or people from the affected area, refusing to buy products from the area, refusing to sell airline tickets to people from the area, having abortions due to a fear of genetic effects, refusing to provide medical treatment to victims, spontaneous evacuations, and taking inappropriate drugs.

- basing any system of compensation on pre-established criteria that are clearly linked to health risks and tangible economic impacts.

## 3.13. CONDUCTING RECOVERY OPERATIONS

The principal requirements on conducting recovery operations covered in the Safety Requirements publication [1] relate to:

*Response*

- the planning of the transition from emergency phase to long term recovery operations and the resumption of normal social and economic activity;
- the application of the full system of occupational protection to workers once the emergency phase has ended.

*Preparedness*

- the establishment of arrangements for transition from the emergency phase to routine long term operations;
- the establishment of a formal process for cancelling restrictions and other arrangements.

### 3.13.1. Observations

As soon as the media and the public believe that the emergency response phase has been terminated, there is intense pressure to return the community to normal living conditions. At this point, public officials are likely to take highly visible actions even if these are only minimally effective or are even counterproductive[22] .

During the Goiânia accident, the basic recovery strategy for contaminated areas was to identify, relocate, isolate, decontaminate and rapidly release them for unrestricted use. Areas that could not be decontaminated to levels allowing unrestricted use were converted to uses controlled by authorities, such as paved public squares. These strategies were effective in reducing public disruption and stress.

Accidents involving significant contamination will inevitably produce large amounts of radioactive waste [13, 92]. In Goiânia [13] and Juarez [93], decisions on where to store the waste (both temporary and final) were protracted and politically sensitive; and this delay had an adverse effect on the speed of the whole recovery process. Each accident situation will be different but ‘What to do with the waste?’ will be a time critical issue. It therefore follows that generic preparedness planning should provide a framework to deal with this.

The polonium-210 incident in London was protracted with the response phase covering some six weeks, overlapping with the recovery phase that lasted several months. The UK generic advice ‘Emergency Response and Recovery’ [94] recommends that multiagency recovery operations should start as soon as possible after the onset of an emergency and

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[22] After the Chernobyl accident decontamination efforts made in Pripyat and other areas where people were not to return resulted in unnecessary doses to workers.

that ideally this should be taken forward in tandem with the response itself. The objectives are to ensure that: longer term recovery priorities are reflected in the planning and execution of the response; relevant organizations in the public, private and voluntary sectors are engaged in the recovery effort from the earliest opportunity; and there is continuity of the management of the emergency once the response phase has been concluded.

The above approach was taken in the polonium-210 incident in London with the Strategic Coordinating Group, chaired by the police, taking an early decision to establish a subgroup, the Recovery Working Group (RWG) chaired by Westminster City Council (WCC), who acted on behalf of the various London Local Authorities in which the contaminated locations were situated. During the early response phases, the RWG developed a framework strategy and processes for remediation and clearance of locations [95]. The Framework Strategy was intended to apply from the time the police or other appropriate agency first became interested in a location as potentially contaminated, to the time when the location was cleared as safe for public use. The aim was to ensure that each of the locations potentially contaminated by radioactive material was declared safe, or returned to a condition that was safe for public use, taking into account the intended usage of the venues and the results of specific risk assessments. The objectives of the framework were to clarify lines of communication and responsibilities, provide guidance on the extent of monitoring required to characterise the relevant contamination and remediation requirements including waste management considerations, prioritise potentially contaminated venues notified to WCC, provide guidance addressed to owners/occupiers of venues, and provide a framework for a consistent approach to returning premises to a condition which is safe for public use.

As part of its preparations to deal with possible Chemical, Biological, Radiological or Nuclear (CBRN) or hazardous material incidents, the UK government had previously established the Government Decontamination Service (GDS). This has a coordination and facilitation role, providing advice and guidance to those responsible for decontamination, as well as assessing the ability of specialist companies in the private sector to carry out decontamination operations and ensuring ready-access to their services. Thus, remediation resources were quickly available. However, most of the contaminated locations were business premises, e.g. hotels offices and restaurants, and the legal onus for the costs rested with the owners who had to claim against their insurance. This caused some delays and raised issues requiring resolution by the government.

There were ten locations that required remediation, and until the work was completed, they were closed for normal access. This produced significant problems for some of the occupants in terms of being able to continue running their business. In a few cases, following risk assessments, a controlled re-entry was undertaken to recover items that would alleviate some of the problems.

### 3.12.2. Conclusions

These lessons demonstrate the importance of:

- anticipating the intense pressure from the media and the public to return to normal living conditions, which can result in the temptation to engage in actions that have no meaningful impact on public safety;
- the authorities maintaining a high level of credibility in order to facilitate the process of recovery.

# 4. REQUIREMENTS FOR INFRASTRUCTURE

## 4.1. GENERAL

It is now widely recognized that the achievement and maintenance of a high level of safety depends on there being a sound legal and governmental infrastructure, including a national regulatory body with well-defined responsibilities and functions. Many emergencies would have been more appropriately mitigated if there had been an adequate infrastructure to deal with such emergencies. The emergency functions cannot be expected to be performed appropriately unless an adequate infrastructure for emergency preparedness and response is in place.

## 4.2. AUTHORITY

The principal requirements on authority covered in the Safety Requirements publication [1] relate to:

- the establishment by acts, legal codes or statutes, of the authority for the arrangements for preparedness and response;
- the documentation of the roles, functions, authorities and responsibilities of all those involved;
- the allocation of responsibilities, authorities and arrangements for coordination;
- the specification in the emergency plans of the arrangements for delegation and/or transfer of authority.

### 4.2.1. Observations

The Safety Requirements publication [1] explicitly states that the prime responsibility for safety shall be assigned to the operator. In the event of an emergency, the operator is therefore responsible for providing the first warning and information concerning the hazards. There have, however, been cases where the operator delayed notifying off-site authorities while conferring with the management or attempting to solve the problem. This has occurred when the operator is not explicitly required to promptly notify and advise off-site authorities. A number of countries have established a legal requirement for prompt notification, and the regulatory body undertakes inquiries after emergencies to ensure that these legal requirements have been met.

The requirement in the Safety Requirements publication [1] is primarily aimed at organizations or persons applying for authorization or authorized to undertake a practice (i.e. the person who is legally responsible for radioactive material). However, a particular issue arises with activities in threat category IV. Metal recycling plants, for example, may not have been made formally responsible for detecting and responding to the presence of an orphan source in scrap metal. Furthermore, if they do declare it, they may be made responsible for its subsequent waste management. Unscrupulous managers therefore may be tempted to conceal the presence of such a source and not report it to the national authorities.

Responsibilities for response to a declared radiation emergency are likely to be distributed among many local and national agencies and may change depending on the nature of the emergency (e.g. accidental or intentional/criminal), of the material or practice involved, of the institution responsible for the practice (e.g. civil government, military, or private organizations), or of the nature of the response activity (e.g. protection of food, public health, regaining control over the practice). Since it has been often impossible to make these distinctions promptly at the early stage of an emergency, governmental response has been delayed and confused resulting in mistrust of the government by the public and media. These competing bases of authority characterized the TMI emergency, which resulted in several organizations inefficiently attempting to perform the same role. Inadequate identification and communication of information to other response organizations meant that critical emergency response functions were neglected [47, 48]. Following the TMI accident, these difficulties were overcome, by establishing a comprehensive process [96] through which all organizations vested with a role in an emergency (e.g. technical, humanitarian and law enforcement) operate under clearly defined and allocated local and national responsibilities.

Local authorities are best suited to take immediate action to protect the public, but they often lack the specialized knowledge, equipment and means to respond to a radiation accident. This problem may be exacerbated with an emergency involving an activity in threat category IV if the local authorities are unaware of the possibility of such an emergency and therefore unprepared for it.

During the Chernobyl and TMI accidents, national authorities took responsibility for deciding protective actions but failed to coordinate effectively with the local authorities. Consequently, the implementation of protective action was delayed for days and, in the case of Chernobyl, resulted in avoidable radiation-induced thyroid cancers among children [87].

During the TMI emergency, national response decisions were unnecessarily delayed because, by law, they had to be approved by a majority vote of the five-member Nuclear Regulatory Commission. Introducing legal changes that called for the appointment of a single decision maker during an emergency solved this problem.

In the UK the primary legislation in this area, is the Civil Contingencies Act 2004, together with the maintenance of the supporting guidance and infrastructures [97]. These documents set out a single framework for civil protection in the UK, capable of meeting the full range of emergency response challenges. They establish a clear set of roles and responsibilities for those involved in emergency preparation, and response at the local level which then fits into a national framework. The Act divides local responders into two categories, imposing different duties on each.

Category 1 responders are those organizations at the core of the response to most emergencies (e.g. emergency services, local authorities, Health Protection Agency). They are subject to the full set of civil protection duties.

Category 2 responders (e.g. regulatory bodies, transport and utility companies) have a lesser set of duties: cooperating and sharing relevant information with other category 1 and 2 responders. Category 1 and 2 organizations come together to form Local Resilience Foras (LRFs), which help coordination and cooperation between responders at the local level. The LRFs are based on police force areas, as in the UK the police take the lead role in matters of public safety.

Research on natural and technological hazards shows that emergency planning is a low priority for organizations in both the public and private sectors [56, 59, 60], which makes it difficult for national and regional emergency planners to obtain a commitment from jurisdictions to engage in it. Similarly, local emergency planners have difficulty getting other local agencies such as police, fire, and emergency medical services to commit staff time to developing emergency plans and procedures and to participating in training, drills and exercises.

Following emergencies, there have been cases where response management has been criminally investigated or prosecuted. This obviously puts considerable stress upon management and could delay response action even when acting within assigned authority and in accordance with accepted international practice.

#### 4.2.2. Conclusions

These lessons demonstrate the importance of:

- clearly defining the responsibilities and authorities of each of the parties, local and national authorities and the operator, involved in emergency response in legislation in order that decisions can be taken rapidly.

### 4.3. ORGANIZATION

The principal requirements on organization covered in the Safety Requirements publication [1] relate to:

- the establishment of the organizational relationships and interfaces between all the major response organizations;
- the assignation in the emergency plans of the positions responsible within each organization for the performance of the response functions;
- the assignation of personnel to appropriate positions in order to perform the necessary functions;
- the availability of a sufficient number of qualified personnel at all times.

### 4.3.1. Observations

The tasks and work conditions in an emergency situation are different from those in a normal situation, and consequently so are the abilities of the staff needed to provide an effective emergency response. However, sometimes staff are assigned emergency response duties according to their status in the organization, even though they are aware they might not be suited for these duties.

During the response to the Goiânia emergency, local volunteers were trained and used to perform tasks that required interaction with the local population (e.g. obtain information or locally available materials). Local fire brigade members (following training) were included in the radiological protection and decontamination teams. The use of local people reduced the feeling among the public of being submitted to external intrusion and enhanced public confidence in the emergency response efforts [92].

Assistance through the IAEA has been requested on many occasions [13-28]. This assistance has included monitoring, dose reconstruction, source recovery and medical expertise on the treatment of radiation induced injuries. However, from IAEA experience, some countries have had problems promptly requesting and receiving this assistance because their routine systems used for requesting international assistance are extremely time consuming.

There are many recurrent problems with responses to rare emergencies (e.g. severe wild fires, earthquakes) requiring prompt response by many different organizations and jurisdictions that are using different command structures, terminology, communications and facilities. Consequently some countries (e.g. Canada, Mexico, USA) have implemented an Incident Command System (ICS) which provides standardized terminology and concepts of operation and process for response at all levels of an emergency (local to national). One major feature of the ICS is a clear chain of command led by the Incident Commander. This appears to have enhanced the effectiveness of multiagency responses by allowing an element from any response organization to be promptly integrated into the overall emergency organization. The application of the ICS in meeting international requirements [1] is described in Ref. [34].

### 4.3.2. Conclusions

These lessons demonstrate the importance of:

- consideration being given in advance, by the organizations concerned, to the organizational arrangements for emergency response in spite of the fact that they might consider emergencies to be of low probability, and for these organizational arrangements to be reflected in the emergency plans;
- assigning responsibilities for response to organizations that are as compatible as possible with their normal functions; consequently the non-radiological aspects of a response should remain with those who routinely perform these activities;
- integrating within the plans for emergency response a standard framework for the use of local agencies and volunteers, while ensuring that the people concerned are

aware of the hazards and methods of safe operation and are carefully monitored and their activities are appropriately coordinated;

- establishing simplified and time-efficient procedures for requesting international assistance.

## 4.4. COORDINATION OF EMERGENCY RESPONSE

The principal requirements on coordination of emergency response covered in the Safety Requirements publication [1] relate to:

- the development of arrangements for the coordination of response;
- the coordination arrangements for assessments of doses and health effects between different organizations or States;
- the arrangements to ensure that all States within defined emergency zones are provided with information for developing their own preparedness in response to an emergency, and to ensure transboundary coordination.

### 4.4.1. Observations

During some emergencies, a departing shift failed to brief the new shift adequately which impaired the response [9]. During the Goiânia event, adequate transfers of information from one team to another were ensured by scheduling a briefing with the replacement staff and staggering replacement.

There have been radiation emergencies in countries during which different responding national organizations were unaware of, and did not recognize, the responsibility of the other response organizations. This resulted in delays and confusion. There also have been agencies or ministries that incorrectly believed they had a role simply because the public or senior officials thought so; this too had a negative impact on emergency response [63, 66].

Some countries have established local coordinating committees that include all organizations vested with a role in hazardous materials emergency response [56]. Experience shows that these committees build up not only coordination, but also mutual trust and awareness; to do this, they need to meet regularly. Such committees are more effective when they have a full-time coordinator responsible for administrative/logistical activities and have access to training materials and information on the threat and the resources that are available in their own and neighbouring communities.

Communities respond more effectively to disasters when emergency response organizations have collaborated in the development of plans and procedures and have held joint training, drills, exercises, and critiques [56, 59, 98].

The coordination of information and advice to the public has been discussed earlier. Nevertheless, this is an important matter and should be stressed. During the TMI accident, the regulatory body was almost immediately asked for their assessment of the situation. The regulatory body, however, did not have a clearly designated role in the emergency plan and was therefore unable to react on an appropriate timescale, or with an appropriate understanding of the situation to any requests that it received. The effectiveness of the response to this accident was greatly improved when a single emergency operation centre for coordinating the national response and for providing information to the media was established close to the scene of the emergency. Following the TMI accident, the regulatory body made arrangements to clarify its role in the event of an emergency, to streamline its decision making process, and to make provisions to activate technical and other teams that were specifically trained and prepared to assess emergency conditions and to perform other response activities [99].

Also during the TMI accident, all counties within 20 miles of the plant were told to develop evacuation plans [100]. In the course of independently developing their evacuation plans, two counties west of the plant decided to reverse the flow on a freeway. Unfortunately, the more northerly county chose to direct all traffic southbound and the more southerly county decided to direct all of their traffic northbound. Later, planners at the state emergency management agency discovered the conflict between these two plans. A major traffic jam was avoided only because a five mile radius evacuation for pregnant women and preschool children was ordered, instead of the 20 mile radius evacuation that had been anticipated.

A particular problem has arisen when different and uncoordinated response plans have been developed for safety and security purposes. For instance, the response to an intruder [101] resulted in essentially locking all the doors in a nuclear power plant, which interfered with the activation of the emergency centres, off-site communications and notifications. Following a terrorist act involving a radioactive source, the objectives of the security services — gathering evidence, etc. — may conflict with the objectives of those concerned with safety — minimizing the exposure of people.

### 4.4.2. Conclusions

These lessons demonstrate the importance of:

- effective coordination of emergency response, which is achieved through appropriate prior planning, including the establishment of an appropriate management structure as discussed in the previous subsection;
- using local emergency planning committees and undertaking joint training programmes, drills and exercises, which will facilitate the process;
- establishing clear handover arrangements, since many emergencies last over many days, even weeks;
- effective coordination of the emergency response plans with those of the security services.

## 4.5. PLANS AND PROCEDURES

The principal requirements on plans and procedures covered in the Safety Requirements publication [1] relate to:

- the establishment of arrangements for coordinating the national response, including the specification of the organization responsible for the arrangements, the responsibilities of the operators and other response organizations, and the description of the coordination with the arrangements for response to a conventional emergency;
- the preparation of plans by each response organization for coordinating their assigned functions;
- the basing of plans for emergency response on the assessment of threats;
- the coordination of the plans with any other plans that may be implemented in an emergency;
- the duties of the responsible authorities for ensuring that emergency plans are prepared, response organizations are involved in the preparation of the emergency plans, the emergency plans take account of the results of any threat assessment and lessons from operating experience and emergencies with similar sources, and the plans are periodically reviewed and updated;
- the content of the emergency plans, covering the allocation of responsibilities, identification of the operating conditions that could lead to the need for intervention, the intervention levels, the procedures, including communication arrangements, the methodology and instrumentation for assessing the emergency and its consequences, the public information arrangements and the criteria for terminating each protective action;
- the preparation of an emergency plan by a facility or practice in threat I, II, III or IV, coordinated with the plans of other organizations;
- the content of the emergency plan of a facility or practice in threat I, II, III or IV;
- the development by operating and response organizations of the necessary procedures, analytical tools and computer programs to perform the necessary functions;
- the testing of the procedures, analytical tools and computer programs;
- the implementation of on-site emergency plans by the operator;
- the implementation of off-site emergency plans and any transboundary plans by the response organizations.

### 4.5.1. Observations

The importance of having clear emergency plans and procedures has already been discussed in this publication. The lack of such pre-established plans and procedures has hampered the response to many emergencies [14, 30, 77].

Problems also arise when emergency plans are developed without the input of those who will actually implement them. The involvement of all the relevant organizations in the development of emergency plans enables the identification of errors in assumptions about response capabilities, increases the understanding of the capabilities of the other response organizations, increases the understanding of what is expected from them and determines the resources needed. It also tends to increase ownership and therefore commitment to successful implementation of the plan.

Well-defined procedures enhance the performance of the difficult tasks that need to be undertaken during an emergency. However, many procedures have been found to be ineffective under emergency conditions because they are poorly designed, needed more time or information than was available, the users did not have the necessary expertise or training, or they were not compatible with other elements of the response system. The effectiveness of procedures can be assessed through testing under realistic emergency conditions during drills and exercises.

Responses to the Chernobyl and Goiânia emergencies demonstrated that decisions concerning the implementation of protective actions affecting the public can be made by public officials who are not radiation specialists, and therefore make their decisions on the basis of their own understanding of both the radiological risk and the societal and political concerns.

The failure to make arrangements to deal with the low probability/high consequence events is obvious from the Chernobyl accident. For example, the failure to promptly restrict consumption of locally produced milk and vegetables when there was a severe core damage accident resulted in radiation-induced thyroid cancers. In addition, many fire fighters and other personnel who responded on site died because of high level exposure. They could not measure the dose rates (which could be fatal in minutes) and were not trained or equipped to operate in the severe conditions caused by the accident.

The accident in Goiânia [13] and one of a similar scale, also involving a radiotherapy source, in Juarez, Mexico [29, 93] provide examples of low probability radiological events that have resulted in high consequences in the public domain. These emergencies occur in unpredictable locations and have unpredictable consequences. Similarly, the location and consequences of an event involving the use of a radiological dispersal device by terrorists cannot be predicted.

For many years, the UK has had an integrated all hazards emergency response framework [94]. The lessons from Three Mile Island were an input to its development, as equally were experiences from floods, chemical fires, etc. The threat of possible terrorist attacks using CBRN agents has reinforced the need for an all hazards integrated approach. Whatever the emergency affecting the public sector, the police take the lead role. If it is a serious emergency, they will establish a Strategic Coordinating Group (SCG), which they chair. The SCG will have senior representatives from the emergency services, the National Health Service, local authorities, utilities and scientific/ regulatory bodies. Whilst these organizations provide advice, and have their own defined responsibilities, the police are in command of the response. If the emergency is of national importance, such as a large area flooding or multiple sited terrorist attacks, then the police remain in command locally, but national coordination and policy issues would be dealt with by the government through a group known as the Civil Contingencies Committee (CCC) located in dedicated crisis management facilities, the Cabinet Office Briefing Room (COBR). For each type of emergency, there is a designated lead government department, who would chair the CCC, unless the Prime Minister chooses to do so.

This framework has been used to deal with a variety of emergencies: it is also regularly exercised for nuclear sites and possible terrorist attacks. So on 7 July 2005, when four terrorist bombs were detonated in the London transport system, the various responding organizations were clear about their respective roles and responsibilities, and there was a clear command and control structure through the police [102]. These arrangements were also used during the polonium-210 incident in London in 2006 and worked well. Both incidents involved many responding agencies, each of whom had representatives, or were represented by their parent government department, at SCG and CCC. Experience from a variety of previous emergencies has shown the need to also have some key crosslinks with advisers from one agency, embedded within the response structure of another which close working was necessary. This does place demands on senior staff resources, but has to be factored into organizational plans and relevant training programmes.

There have also been serious radiological emergencies involving overexposures caused by operators (e.g. radiographers) of portable dangerous sources trying to recover from, or mitigate, abnormal conditions. These overexposures occurred because of inadequate procedures, training and tools, and a lack of understanding of the basic principles of radiation safety and the operating principles of the devices they were using [30].

### 4.5.2. Conclusions

These lessons demonstrate the importance of:

- pre-established plans for emergency response, which need to be written down, shared with all those concerned, cover the full spectrum of possible emergencies including low probability/high consequence events, integrated into an all-hazards emergency management programme and supplemented by written procedures;
- particular consideration being given to the integration of emergency response plans with the arrangements to respond to terrorist and other criminal threats involving radioactive material;
- the development of generic plans and procedures that can provide a command and control infrastructure, and the ability to deploy expertise and resources for emergencies involving activities in threat category.

## 4.6. LOGISTICAL SUPPORT AND FACILITIES

The principal requirements on logistical support and facilities covered in the Safety Requirements publication [1] relate to:

- the provision of adequate tools, instruments, supplies, equipment, communication systems, facilities and documentation;
- for facilities in threat category I or II, the designation of emergency facilities for coordination of on-site response action, the coordination of local off-site response actions, the coordination of national response actions, the coordination of public information, and the coordination of off-site monitoring and assessment;
- for facilities in threat category I, the provision of an on-site emergency control centre;

- the designation of laboratories to perform analysis of environmental and biological samples and measurements of internal contamination;
- the designation of a national emergency facility or facilities for the coordination of response actions and public information;
- the arrangements for obtaining support from the organizations responsible for providing such support.

### 4.6.1. Observations

The resources for use in response to the Goiânia accident were located either in Rio de Janeiro or in San Paulo, over 1300 km away. This posed severe logistical problems. In the event, Brazil mobilised all of its relevant resources and drew on international assistance under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency [13, 51]. Areas in which expertise were required were in the medical treatment of patients, the deployment and maintenance of monitoring capability, logistics, bioassay, personal dosimetry, and environmental sample analysis. At its peak, over seven hundred staff were deployed to deal with decontaminating the environment. Staff had to be trained in the use of monitoring equipment and there was a need on site for support facilities such as: facilities to repair monitoring equipment, a dedicated laundry to deal with contaminated items, a transportable whole body monitor, and a facility to manufacture waste containers.

There were cases when facility control rooms have been used to support emergency response and operational functions simultaneously. For instance, during the TMI accident, there were over 40 people in the control room at one point. The resulting noise and congestion interfered with the control room staff’s response to the accident [9, 53]. In the same event, the control room received over 4000 phone calls within the first few days of the event. This blocked the phone lines and prevented receipt of important information related to the management of the response [9]. In the same event, technical assistance provided to operators was inadequate because the facilities, tools and training were not designed for use during response to a severe accident [53].

Overloading and sometimes the breakdown of the public telephone systems in the vicinity of an event has happened shortly after the public become aware of an event that they perceive as significant. This prevented the regulatory body from maintaining communications with the site during the TMI accident and hampered many other aspects of the official emergency response.

Experience shows that routine use of emergency facilities, equipment, and other resources provides cost savings, familiarizes emergency responders with the resources they will use and ensures equipment that will be used is properly maintained. However, these benefits will not be realized unless controls are in place to ensure the availability of these resources during the emergency.

During many emergencies, problems have been caused by incompatibilities of communication equipment and/or radiofrequencies among the various response organizations.

During response to emergencies [13], environmental monitoring and other equipment failed or were found to be unusable under the prevailing environmental and work conditions such as high temperatures, strong sunlight, rain, rapid temperature changes, high humidity or rough treatment. The reason for this was the equipment had been selected on the basis of its adequacy under laboratory conditions and not its suitability for fieldwork.

During the response to emergencies, problems have arisen when equipment was too complex for use by personnel with limited training and experience in real emergency conditions. In addition, during emergencies involving many organizations, problems have arisen when each organization conducts environmental monitoring using its own equipment without regard to harmonization of calibration and procedures.

Under normal circumstances, local agencies such as police, fire, and public workers use radios tuned to different frequencies in order to avoid overloading the communications network and interfering with each other's operations. However, this can pose a problem in emergency situations because there may be a need for communication between the various agencies. This was a critical problem in the 9/11 World Trade Center attacks in New York City because sources close to the police department rapidly assessed the imminent collapse of the towers. Unfortunately, this information could not be transmitted to fire department crews in time for them to evacuate the building. The lack of communications interoperability contributed to the responding fire crews' death toll [103].

### 4.6.2. Conclusions

These lessons demonstrate the importance of:

- identifying the demands that a spectrum of events would place on response organizations for resources;
- making sure that emergency teams are familiar with the facilities and equipment designed to be used in an emergency;
- making sure that the equipment is readily available in the event of an emergency and fit for purpose in the environments in which it will be used;
- ensuring the continued availability of communications channels, including diverse and redundant systems for telephone communications and compatibility of radio communication frequencies.

## 4.7. TRAINING, DRILLS AND EXERCISES

The principal requirements on training, drills and exercises covered in the Safety Requirements publication [1] relate to:

- the identification by the operator and the response organizations of the knowledge, skills and abilities necessary to perform the required functions and the making of arrangements to ensure that the personnel have the requisite knowledge, skills, abilities, equipment and procedures and other arrangements to perform their assigned response functions;

- for facilities in threat I, II or III, the instruction of those on site of the arrangements to notify them in the event of an emergency and the actions to be taken when so notified;
- for a facility or practice in threat I, II or III, the conducting of exercise programmes for emergency response and all organizational interfaces, and, for threat categories IV or V, the testing of the national level programmes;
- the participation of staff responsible for critical response functions in training exercises or drills;
- the training of off-site officials responsible for making decisions on protective actions and their participation in exercises;
- for facilities in threat category I, II or III, the evaluation of the performance of exercises against established response objectives.

### 4.7.1. Observations

Research and operational experience shows that communities respond more effectively in disasters if they receive training in the implementation of emergency plans and procedures, conduct drills to assess individual performance, carry out annual exercises to assess the effectiveness of the plans, procedures, and training, and hold critiques to identify areas of needed improvement [56, 98].

Another common problem is that those who fill senior positions (e.g. a leader of the national or local government) in the response organization often do not attend trainings or exercises and thus do not know what to do when called on under stressful response conditions.

Non-existent or inadequate training are often mentioned as one of the lessons in reviews of response to emergencies. The main reason that training in emergency response was not provided because it was regarded as a low priority matter. Other problems with training are:

- it was not designed to provide the specific knowledge, skills and attitude that responders needed to perform their assigned response tasks during an emergency;
- there was no follow-up (refresher) training;
- the training was not undertaken under conditions that simulate those of an emergency;
- the training focused on the individual rather than on building teams;
- the training did not include all the people and organizations that would be involved in an actual response;
- there were no evaluations to ensure that the training had been properly received.

Research and experience show that drills as a team are effective in developing and testing team skills. Exercises involving all the response teams are, however, needed to integrate the team into the emergency response organization [104].

Research also shows that effective job performance requires training to develop knowledge, skills and attitude so that individuals know the proper response to a given situation. In addition, it is also important to develop expertise in problem solving, evaluating strategies in terms of their prospects for success, and judging the time required to successfully complete a task [104].

One of the problems with refresher training is that it is often repetitive and uninteresting, resulting in a reluctance to participate and to treat it seriously. This problem is reduced if the refresher training concentrates on tasks that are critical, difficult and infrequently performed and involve trying new strategies and learning from experience [104].

Often exercises are designed around unrealistic scenarios to ensure that all the response functions are activated and demonstrated within normal working hours. As such, they do not simulate many important aspects of real emergencies and therefore, can lead to false expectations that may be harmful during the response to a real emergency.

### 4.7.2. Conclusions

These lessons demonstrate the importance of:

- ensuring that all persons and organizations that have a role in an emergency are properly trained to respond;
- training programmes being designed to develop skills in problem solving and team work;
- refresher training being designed to challenge responders in order to trigger their participation;
- ensuring that coordinated training programmes, drills and exercises involving all persons and organizations having a role in an emergency are undertaken;
- exercises being designed around realistic scenarios.

## 4.8. QUALITY ASSURANCE PROGRAMME

The principal requirements of a quality assurance programme covered in the Safety Requirements publication [1] relate to:

- for the operator of a facility, practice or source in threat category I, II, III or IV and the off-site response organizations, the establishment of a quality assurance programme;
- for the operator of a facility, practice or source in threat category I, II, III or IV and the off-site response organizations, the establishment of arrangements to review and evaluate responses in emergencies and in drills and exercises in order to make the necessary improvements.

### 4.8.1. Observations

During the response to some emergencies, equipment, supplies, and facilities required for the response were not always available or were inadequate because they:

(a) had not been procured in advance;

(b) were not located where needed;

(c) had been borrowed and not returned to the emergency stores;

(d) were not operational when needed;

(e) were not properly maintained or calibrated;

(f) had exceeded their recommended life.

This is primarily because emergencies are rare events and therefore equipment, facilities and resources designated solely for emergency response are not normally used and there is not an adequate programme to ensure that these resources are maintained. Experience also shows that outdated call lists, procedures and other documentation have hindered emergency response.

In addition, training programmes, staffing levels and emergency procedures may not have been maintained and implemented to a specified standard.

Drills and exercises are effective ways of determining if the plan, organization, staffing, procedures, training, facilities, equipment and resources are adequate. However, in many cases there were no provisions in place to identify and take account of the lessons.

Lessons identified in the review of the responses to real emergencies, such as those given in various IAEA publications [11–31], can provide useful information which can be taken into account in improving emergency arrangements. For this reason, the IAEA has encouraged States to request a review to be carried out following a serious emergency and for results of that review to be made widely available. Evaluations and external peer review of the emergency arrangements performed at the preparedness stage have also been found to be effective in identifying where improvements can be made.

### 4.8.2. Conclusions

These lessons demonstrate the importance of:

- establishing a quality assurance programme relating to the emergency response arrangements;
- making use of feedback information from drills, exercises and real emergencies in order to improve the emergency response arrangements — plans, procedures, equipment, resources, etc.;
- internal and external audits and evaluations in order to identify weaknesses in the emergency arrangements.

## 5. CONCLUSIONS

The lessons from these incidents and emergencies confirm the requirements given in the IAEA Safety Requirements publication [1]. Actual implementation of the Safety Requirements in the area of emergency preparedness and response assists in establishing an adequate level of preparedness and response for a radiation emergency in a State. Their implementation also assists in minimizing the consequences for people, property and the environment of any radiation emergency [1].

# APPENDIX I
# DESCRIPTION OF TEN SELECTED DOCUMENTED EMERGENCIES

## 1. THE THREE MILE ISLAND (TMI) NUCLEAR POWER PLANT ACCIDENT

As with most reactors, the TMI reactor had three barriers that must fail in order for there to be a major release of radioactive material resulting in public exposure. There are the fuel pins (first barrier), that form the core where the nuclear reaction takes place. The core is surrounded by a cooling system (second barrier), that is intended to always keep the core covered with water. The cooling system includes pumps that automatically replace any water that may be lost. The core and cooling system are within a very large and strong structure, called the containment (third barrier), which is intended to prevent any radioactive material released from the core and cooling system from being released into the atmosphere. The core must always be kept covered with water, otherwise it will heat up and pins holding the fuel can begin to fail, and the fuel can begin to melt shortly thereafter. If the core did melt, it would release vast amounts of radioactive material into the containment. A melting of the core can also produce conditions that cause the containment to fail unpredictably. The plant was designed to prevent a core from melting, but not designed to prevent a release if the core were to melt.

The accident began on 28 March 1979 at about 04:00 when a pump that fed water to the boiler stopped. This was not a serious event and should have been easily handled by the plant safety system. The safety system operated as intended and shutdown the plant (stopped the nuclear reaction). During the shutdown a valve failed to close allowing water to be released from the cooling system. This loss of water was detected by the safety system which started pumps to inject water to replace what was being lost, and thus ensure the core was kept covered with water. At this point, one instrument in the control room incorrectly showed that there was too much water in the cooling system. The operators, according to their procedures and training, turned off some of the safety system pumps that were replacing the water being lost. Within a few hours the core became uncovered and began to melt and within minutes had released, into the containment, about 40% of all the radioactive material it contained. This was about the same amount of radioactive material that was released into the atmosphere by the Chernobyl accident. The radiation within parts of the plant and containment rapidly increased to 1000 or more times the normal level. However, the operators still failed to understand that the core was not being cooled, even with these indisputable indications of a melted core. After several hours, the operators started a sufficient number of pumps to cover the melted core with water. It took several hours before the mass of melted core cooled. The containment, while not designed for these conditions, remained essentially intact and only a very small fraction of the radioactive material was released into the atmosphere, and consequently the exposure of the public was small. It was several days before it was realized that the danger of a major release had passed. It was several years before it was discovered the core had melted.

As discussed earlier, two days after the core had melted pregnant women and children of preschool age were advised to leave the area within a five mile radius [63]. However, the NRC inquiry found it would have been prudent to recommend precautionary evacuation at about the time the core was being damaged because ‘the containment building was … filling with intensely radioactive gas and vapours, leaving the nearby public protected by only one remaining barrier, the containment, a barrier with a known leak rate that needed only internal pressure to drive the leakage’ [66]. In addition, the advisory calling for a few thousand pregnant women and preschool children to evacuate, resulted in entire families evacuating, and it is estimated that over 100,000 people evacuated from areas within 40 kilometres of the plant.

## 2. THE CHERNOBYL NUCLEAR POWER PLANT ACCIDENT

The accident occurred at the Chernobyl nuclear power plant in northern Ukraine on 26 April, 1986 and resulted in the release into the atmosphere of a large amounts of radioactivity, primarily radioactive isotopes of caesium and iodine. These releases contaminated large areas of Belarus, the Russian Federation and Ukraine, and other countries to a lesser extent. These releases caused sizable populations to receive internal and external radiation doses.

The Chernobyl accident caused the deaths of 30 power plant employees and firemen within a few days or weeks (including 28 deaths that were due to radiation exposure). In addition, about 240,000 recovery operation workers (also called ‘liquidators’ or ‘clean up workers’) were called upon in 1986 and 1987 to take part in major mitigation activities at the reactor and within the 30 km zone surrounding the reactor. Residual mitigation activities continued on a relatively large scale until 1990. Altogether, about 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators, according to laws promulgated in Belarus, the Russian Federation, and Ukraine [32, 39].

In addition, massive releases of radioactive materials into the atmosphere brought about the evacuation of about 116,000 people from areas surrounding the reactor during 1986, and the relocation, after 1986, of about 220,000 people from Belarus, the Russian Federation, and Ukraine.

The accident at the Chernobyl nuclear power plant occurred during a low-power engineering test of the Unit 4 reactor. Improper, unstable operation of the reactor allowed an uncontrollable power surge to occur, resulting in successive steam explosions that severely damaged the reactor building and completely destroyed the reactor.

The radionuclide releases from the damaged reactor occurred mainly over a ten day period, but with varying release rates. From the radiological point of view, $^{131}$I and $^{137}$Cs are the most important radionuclides to consider, because they are responsible for most of the radiation exposure received by the general population. The releases of $^{131}$I and $^{137}$Cs are estimated to have been 1,760 and 85 PBq [90], respectively (1 PBq = $10^{15}$ Bq). It is worth noting, however, that the doses were estimated on the basis of environmental and thyroid or body measurements, and that knowledge of the quantities released was not needed for that purpose.

The three main areas of contamination, defined as those with $^{137}$Cs deposition density greater than 37 kBq m$^{-2}$ (1 Ci km$^{-2}$), are in Belarus, the Russian Federation and Ukraine; they have been designated the Central, Gomel-Mogilev-Bryansk and Kaluga-Tula-Orel areas. The Central area is within about 100 km of the reactor, predominantly to the west and northwest. The Gomel-Mogilev-Bryansk contamination area is centred 200 km to the north-northeast of the reactor, at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the Russian Federation. The Kaluga-Tula-Orel area is located in the Russian Federation, about 500 km to the northeast of the reactor. Altogether, as shown in Ref [39, Annex J; 56, Appendix A], territories with an area of approximately 150,000 km$^2$ were contaminated in the former Soviet Union. About five million people reside in those territories.

Outside the former Soviet Union, there were many areas in northern and eastern Europe with $^{137}$Cs deposition density in the range of 37–200 kBq m$^{-2}$. These regions represent an area of 45,000 km$^2$, or about one third of the contaminated areas found in the former Soviet Union.

The highest doses were received by the approximately six hundred emergency workers who were on the site of the Chernobyl power plant during the night of the accident. The most important exposures were due to external irradiation, as the intake of radionuclides through inhalation was relatively small in most cases. Acute radiation sickness was confirmed for 134 of those emergency workers. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with doses between 2.2 and 4.1 Gy, 22 between 4.2 and 6.4 Gy, and 21 between 6.5 and 16 Gy. The skin doses from beta exposures evaluated for eight patients with acute radiation sickness ranged from 10 to 30 times the whole body doses from external irradiation.

The thyroid doses received by the evacuees varied according to their age, place of residence and date of evacuation. For example, the residents of Pripyat, who were evacuated essentially within 48 hours after the accident, the population-weighted average thyroid dose is estimated to be 0.17 Gy, and to range from 0.07 Gy for adults to 2 Gy for infants. For the entire population of evacuees, the population-weighted average thyroid dose is estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid were, on average, much smaller.

Following the first few weeks after the accident when $^{131}$I was the main contributor to the radiation exposures, doses were delivered at much lower dose rates by radionuclides with much longer half-lives. Since 1987, thprotvinoe doses received by the populations of the contaminated areas have resulted essentially from external exposure from $^{134}$Cs and $^{137}$Cs deposited on the ground, and internal exposure due to contamination of foodstuffs by $^{134}$Cs and $^{137}$Cs. Other, usually minor, contributions to the long term radiation exposures include the consumption of foodstuffs contaminated with $^{90}$Sr and the inhalation of aerosols containing isotopes of plutonium. Both external irradiation and internal irradiation due to $^{134}$Cs and $^{137}$Cs result in relatively uniform doses in all organs and tissues of the body. The average effective doses from $^{134}$Cs and $^{137}$Cs that were received during the first ten years after the accident by the residents of contaminated areas are estimated to be about 10 mSv. The median effective dose was about 4 mSv and only about 10,000 people are estimated to have received effective doses greater than 100 mSv. The lifetime effective doses are expected to be about 40% greater than the doses received during the first ten years following the accident [105].

## 3. THE TOKAIMURA, JAPAN, CRITICALITY ACCIDENT

In 1999 at Tokaimura, Japan, a criticality accident occurred in a fuel conversion plant, involving the processing of highly enriched fuel for an experimental fast reactor. Using unauthorized procedures, the workers poured 16.6 kg of 18.8% enriched uranium into a precipitation tank, resulting in the critical excursion.

Three workers (A, B and C) received doses ranging from 10 to 20 Gy, from 6 to 10 Gy and from 1.2 to 5.5 Gy, respectively. The workers (A and B) receiving the highest doses later died, the first at 83 days and the second at 211 days after the accident. Of the radiation workers recruited to work under conditions of managed radiation exposure, 21 of them were engaged in the operation to drain water from the cooling jacket; their range of estimated doses (gamma plus neutrons) was 0.04–119 mGy. Six of them were engaged in the operation to feed boric acid into the precipitation tank; the range of estimated doses (gamma plus neutrons) was 0.034–0.61 mGy. For 56 other workers at the site, the range of estimated doses (gamma plus neutrons) was 0.1–23 mGy. For three Tokaimura emergency service workers who took the three exposed workers (A, B and C) to hospital, the range of estimated doses (gamma plus neutrons) was 0.5–3.9 mGy. Seven local workers assembling scaffolding on a construction site had a range of estimated doses (gamma plus neutrons) of 0.4–9.1 mGy [12].

Although the Tokaimura criticality accident presented some consequences to nearby populations, no significant long term effects are expected. Of the approximately two hundred residents who were evacuated from within 350 m radius, about 90% received doses <5 mSv, and, of the remainder, none received >25 mSv. While there was measurable contamination from deposition of airborne fission products off the site, this contamination did not last long and maximum readings were less than 0.01 mSv $h^{-1}$ [77].

Several criticality accidents have occurred over the past fifty years. These accidents release a large amount of radiation in a very short space of time. They have often resulted in fatal doses to those in the vicinity; they do not, however, release sufficient radioactive material into the atmosphere or emit sufficient radiation to be a health threat beyond 1 km from the event (in most cases it is within much smaller distances).

## 4. THE GOIÂNIA ACCIDENT

The accident in Goiania was one of the most serious radiological accidents to have occurred to date. It resulted in the death of four persons and the injury by radiation of many others; it also led to the radioactive contamination of parts of the city.

Goiânia, a city of one million, is the capital of Goias state in Brazil. In 1985 there was an acrimonious break up of a private medical practice that ran a clinic containing a radiotherapy unit with a very dangerous radioactive source (50.9 TBq caesium-137). When the clinic facility was no longer being used, no one took responsibility for a radiotherapy unit containing the dangerous source. The closing of the facility had been precipitated by the land owner wanting to redevelop the site. During preparation of the site for redevelopment, the clinic was partly demolished but the developer ran out of money. As a result, the radiotherapy unit was left abandoned in an abandoned building.

Two local people hearing rumours that equipment had been left in the abandoned clinic went to the abandoned building. They found a radiotherapy unit, and not knowing what the unit was, but thinking it might have some scrap value, removed the dangerous radioactive source assembly from the head of the unit. This they took home and tried to dismantle, and in the process the source capsule was ruptured. The radioactive material in the capsule was in the form of caesium chloride salt, which is highly soluble and readily dispersible. After the source capsule was ruptured, the remnants of the source assembly were sold for scrap to a junkyard 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, resulting in external exposure and ingestion of the caesium chloride salt. This proceeded for five days, resulting in the contamination of a large area and severe exposure of a number of people who were showing symptoms: namely nausea and vomiting, and later skin lesions.

Within a few days, one of those suffering from symptoms when to a doctor, but the symptoms were not recognized as being due to irradiation and he was sent home. About two weeks later, after many people had fallen ill, one person became convinced that the glowing powder from the source assembly was causing the sickness. She put the remnants of the source assembly in a bag. She took the bag by bus to a local doctor and placed the bag on his desk and told him that it was "killing her family". The doctor became worried and removed the bag to a courtyard where it remained for one day.

At about the same time, one of the doctors treating the victims became suspicious that the skin lesions had been caused by radiation. This resulted in a call to the doctor that had received the bag with parts of the source, who then decided to have the suspicious bag monitored to see if it was radioactive. When a medical physicist went to the office of the doctor with the suspicious bag, he immediately deflected full scale readings on his dose rate monitor, irrespective of the direction in which he pointed it. He assumed the meter was defective and fetched a replacement. When the replacement was switched on, it also showed very high dose rates in all directions, which convinced him that it was a major source of radiation.

The medical physicist and doctor immediately evacuated some of the local people and reported the situation to the local authorities, who in turn reported it to the national authorities in Rio de Janeiro. There were, however, no local or national emergency arrangements to deal with such an accident, and all resources were located in Rio and Sao Paolo both over 1300 km away.

The local authorities evacuated residents from the contaminated areas to a football stadium to await triage by experts, who started to arrive early the next day. It took five days to gain control of the emergency.

A monitoring service for people and objects was carried out at the Olympic Stadium of Goiânia. In total, about 110,000 persons reported to the Olympic Stadium for monitoring. Of these, 249 were shown to be contaminated. Those with only external contamination were decontaminated, but 129 people were found to also have internal contamination and were referred for medical care. Seventy-nine persons with low whole body doses, as determined by cytogenetic methods, were managed as outpatients. Fifty persons required close medical surveillance; thirty of them remained under medical observation at the primary care unit, and the other 20 were hospitalized at a secondary care unit.

Fourteen of these patients required intensive medical care and were sent to the tertiary care unit in Rio de Janeiro. Four persons died within one month of the event from complications of acute radiation syndrome, including bleeding and infection [13].

About 150 persons who were exposed and/or contaminated are being followed up; the health effects that have occurred within this group have been reported in [13]. The estimated collective doses were 56.3 person Sv for external exposure and 3.7 person Sv from internal exposure, including 14.9 person Sv (external) and 2.3 person Sv (internal) for the four persons who died [106].

Initially, contaminated sites were identified based on information provided by the persons being examined. Some places had a high contamination level. In total, 85 residences were found to have significant levels of contamination and 41 were evacuated [13]. Seven houses have been demolished. In addition to residences, 45 public places (including streets, squares and shops) were decontaminated. Contamination was also found on approximately 50 vehicles. The implementation of decontamination programme lasted six months. The total volume of waste removed was 3,500 $m^3$ [13]. Lack of initial agreement as to where to locate the temporary waste repository almost brought the programme to a stop. It took the personal intervention of the Brazilian president to overcome the problem. The building of the final repository was accomplished in 1997, almost ten years after the accident.

Altogether, 755 professionals were involved in the accident response and subsequent decontamination. In addition, international assistance was supplied through bilateral arrangements and under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

## 5. THE SAN JOSÉ, COSTA RICA ACCIDENT

The start of the event occurred at the San Juan de Dios Hospital in San José on 22 August 1996, when a $^{60}$Co radiation therapy source was replaced. When the new source was calibrated, an error was made in calculating the dose rate. This miscalculation resulted in the administration to patients of significantly higher radiation doses than those prescribed. This was a major radiation accident; it appears that 115 patients being treated for neoplasms by radiotherapy were affected. The error was recognized on 27 September 1996, and treatments stopped. Officially, the radiotherapy machine was closed down on 3 October 1996.

Measurements on the machine in question, and a review of patient charts confirmed that, the exposure rate had been greater then assumed by about 50–60%. Examination and evaluation were carried out on seventy of the seventy-three patients who remained alive at the time of the IAEA review in July 1997. It was concluded at the time that four patients were suffering from severe consequences and a further 16 patients were experiencing major adverse effects resulting from overexposure and would be at high risk in the future. Twenty-six patients showed effects that were not severe, but could be at some risk of suffering effects in the future. Twenty-two patients had no discernible effects and were considered to be at low risk of future effects, because many had undergone only a small part of their therapy with the replaced source. At least two patients were underexposed. Three patients were not examined.

Forty-two of the patients had died as of 7 July 1997, i.e. within nine months of the accident. Data on thirty-four of these patients were reviewed. It was concluded at that time, when the final answers from full autopsies and a review of the clinical records were still in process of being completed, that three patients may have died as a direct result of overexposure and another four patients were considered to have died with radiation overexposure probably as a major contributory cause of death. Twenty-two patients appeared to have died as a result of their disease rather than radiation exposure, while information on the other five deaths was either inconclusive or unavailable. The findings from examination of the patients and records are summarized in Table 2.

TABLE 2. FINDINGS OF MEDICAL REVIEW [20]

| Number of patients | Adverse effects in surviving patients |
|---|---|
| 4 | Severe effects |
| 16 | Marked effects, with high risk of future effects |
| 26 | Radiation effects that were not severe at the time of examination; some risk of future effects |
| 22 | No definite effects of significance at the time of examination; low risk of future effects |
| 2 | Underexposed patients as therapy was discontinued (when the error was discovered) |
| 3 | Could not be seen; one possibly at risk of future effects |
| Total 73 | |
| **Number of fatalities** | **Findings in deceased patients** |
| 3 | Exposure as the major factor in causing death |
| 4 | Exposure as a substantial contributory factor |
| 22 | Death related to a tumour or cause other than exposure |
| 5 | Not enough data to judge |
| 8 | Data on patients were not reviewed |
| Total 42 | |

## 6. THE SAN SALVADOR ACCIDENT

An accident occurred in February 1989 at an industrial irradiation facility near San Salvador, El Salvador. Pre-packaged medical products were sterilized at the facility by irradiation of a $^{60}$Co source in a movable source rack. The accident happened when this source rack became stuck in the irradiation position. The operator (worker A) bypassed the irradiator’s already degraded safety systems and entered the radiation room. On his first entrance, Worker A tried to fix the rack. Unable to free the rack by himself, he left the radiation room about five minutes after his initial entry. Soon afterwards, he returned with two workers (B and C) from another department, who had no experience with the irradiation facility, to help him to free the source rack manually [14].

The $^{60}$Co source elements were contained in doubly encapsulated stainless steel source pencils approximately 45 cm long, with solid stainless steel end caps approximately 1 cm in diameter. Fourteen active source pencils and forty inactive dummy pencils (stainless steel spacer rods) were loaded into each of the two source modules. When the source was installed in June 1975, the total radioactivity of the $^{60}$Co gamma source was 4.0 PBq (108 kCi). By the time of the accident its radioactivity had declined to 0.66 PBq (18 kCi).

The next day, the company became aware of the receipt of sick notes for the absent workers A, B and C; however, these notes stated that the men were suffering from food poisoning. The company remained unaware that the accident had caused any radiological injury to the workers until contacted by medical staff from the hospital on day 4. The significance of the injuries was still not appreciated at that time.

For the remainder of the week, the facility was operated more or less normally, with a typical number of shutdowns for repairs, usually requiring entry to the radiation room. It is believed that the source rack was damaged in the first event, which led to a second event later in the week, in the course of which the pencils were all knocked out of the upper source module. One active source pencil was later found to have remained in the radiation room; the others all fell into the water pool.

The elevated radiation level in the radiation room (due to the active source pencil) was detected on day 6. In response to the company's request for help, the supplier sent two of its personnel, who eventually located the active source pencil and moved it into the pool. It was initially believed that this second event had not resulted in the exposure of any personnel. However, cytogenetic tests made in the course of the accident investigation indicated that four workers had received doses in excess of occupational exposure limits.

At the facility, the dose rate monitor was mounted on the wall of the radiation room and interlocked with the personnel access door to prevent access to the radiation room if there were abnormal radiation levels. In order to enter the radiation room, the operator must first press the monitor test button. However, more than five years before the accident, the monitor probe had failed and the probe assembly had been removed, with its cabling remaining in place. Removal of the monitor probe should have disabled the irradiator; but it was discovered that access could be gained to the radiation room by depressing the monitor test switch and repeatedly cycling the buttons on the panel of the radiation monitor. This method of gaining access became the ‘usual’ procedure. Thus, one major safety feature of the design was bypassed [14].

The practice of using the dose rate monitor outside the closed personnel access door to the radiation room was a crucial factor in the exposure in the second event of at least four workers (the maintenance manager and workers X, Y and Z). The dose rate outside the door would have been at least thirty times lower than the dose rate just inside the entrance maze. Whereas a full (or even half full) source rack in the raised position was detectable with the monitor held outside the closed door, the single active source pencil could only be detected when the monitor was held inside the entrance maze.

None of the workers had worn personal dosimeters. Their exposures were discovered only later, after cytogenetic tests were performed on all workers who might have been exposed as a result of the accident. The estimated doses for these four workers ranged from 0.09 to 0.22 Gy. Had the elevated radiation level in the radiation room due to the active source pencil gone undetected, operating personnel could have accumulated much higher, possibly even lethal, doses through continual uncontrolled exposure.

The three workers (A, B, and C) who were exposed to high radiation doses developed acute radiation syndrome. Their hospital treatments in San Salvador (and subsequently more specialized treatment in Mexico City) were effective in countering the acute effects. However, injuries to the legs and feet of two of the three men were so severe that amputation was required. Worker A, who had received the highest exposure, died six and a half months after the accident, death being attributed to residual lung damage due to irradiation exacerbated by injury sustained during treatment.

For worker B, after amputation, the need for psychological support became the most important factor in his further progress. For Patient C, further rehabilitation therapy was commenced to relieve residual chronic effects, particularly in his more exposed foot [14].

## 7. THE BHOPAL, INDIA HAZARDOUS MATERIALS RELEASE

The Indian subsidiary of the Union Carbide Corporation had a facility located in Bhopal that used methyl icocyanate (MIC) to manufacture a pesticide. MIC is highly toxic, flammable and water soluble. Despite strong sales projections, the market for the pesticide proved to be weak, so plant operation was unprofitable. To save money, the company cut back funds for safety training and maintenance. During one night in 1984, an accident at the plant led to an uncontrolled release of MIC that bypassed engineered safety features. These included a flare tower that could have incinerated the escaping gas and a water curtain that could have dissolved it, causing it to fall harmlessly into an on-site collection pool. Instead, the gas cloud drifted downwind over a shanty town where thousands of people lived. Worse, a siren that sounded during the accident attracted a crowd that moved *toward* the plant to see what was wrong. The MIC attacked people’s eyes, mucous membranes, and lungs, killing an estimated 2,000 and severely injuring another 20,000. The poor quality of the shanty housing precluded effective sheltering, but at least partial evacuation of the impact area should have been possible. Moreover, local knowledge of MIC’s water solubility would have reduced victims’ exposures had they covered their faces with wet towels [81].

## 8. HURRICANES KATRINA AND RITA

Hurricane Katrina killed nearly 1500 people, making it the deadliest U.S. hurricane in eighty years and the third deadliest in U.S. history. Most of the deaths occurred in New Orleans after some of the levees that protected the city collapsed. The hurricane also caused approximately $75 billion in damage, the costliest disaster in U.S. history. The total economic effect, which includes indirect losses due to business interruption, is about twice as high.

Hurricane Rita struck an area on the Louisiana/Texas border, but caused fewer deaths because evacuations were initiated earlier and compliance with instructions was higher than for Katrina. Rita caused less destruction (about $10 billion) because it struck a less densely developed area [62]. A preliminary assessment of the information follows.

### *Emergency assessment*

The function of emergency assessment for hurricanes is performed mostly by the National Weather Service, especially the National Hurricane Center (NHC) and its local forecast offices. Both storms were tracked well and information was disseminated in a timely manner to federal, state, and local authorities and to the news media. For Hurricane Katrina, the NHC issued a *Hurricane Watch* at 10:00 on 27 August 2005 and a *Hurricane Warning* at 22:00 that night. The hurricane eye made landfall on the Louisiana/Mississippi border about 11:00 on 29 August. For Hurricane Rita, the NHC issued a *Hurricane Watch* at 16:00 on 21 September 2005 and a *Hurricane Warning* at 11:00 22 September. The hurricane eye made landfall near Sabine Pass, on the Texas/Louisiana border about 04:00 on 24 September.

### *Population protection*

Local authorities in New Orleans were extremely late in issuing an evacuation order for Hurricane Katrina — 28 August, the day before landfall — even though they had decided to order the evacuation nearly 30 hours earlier. The delay appears to have been caused by issues that should have been resolved by preplanning. Many households evacuated successfully, in part because some of them left before the official evacuation order. However, many households remained in the city because they lacked transportation. Indeed, approximately one-third of the households in New Orleans either had no personal vehicle, or lacked one that was reliable enough for a trip out of town. After the city flooded, many of those who remained were forced out of their homes into the Superdome and Convention Center. These facilities were not stocked with food and water and did not have emergency generators.

U.S. Coast Guard helicopters were immediately active in search and rescue operations, which later continued with the support of Urban Search and Rescue (USAR) teams from other States. As victims emerged from the impacted area, they were transported to mass care facilities throughout the country. The distribution of evacuees was extremely variable, with tens of thousands sent to Houston, Dallas, and San Antonio. Other households were sent as far as Minneapolis and Salt Lake City — thousands of miles from home. Some households were separated and it took weeks to reconnect family members. Medical care was a serious problem during the storm and immediately afterward. The staff of some nursing homes abandoned their patients before the hurricane struck and some of these patients drowned when the city flooded. A few hospitals remained in operation during the emergency, but few people in the city could reach them. Access into New Orleans and other impacted areas was tightly controlled following the storm. Even counties with minimal damage (St. Charles and Jefferson, west of New Orleans) prohibited re-entry until a week later.

Evacuation orders for Hurricane Rita began to be issued on 21 September — three days before landfall. Houston's Mayor urged residents of 'low lying areas' to evacuate, but this was an ambiguous instruction given the city's very flat terrain. Evacuation traffic management was extremely problematic because the number of evacuees (estimated to be 1.6 million) greatly exceeded projections (about 0.5 million). The high traffic volume led to severe traffic jams and led to delays in the evacuation of the area where the hurricane eventually made landfall. These traffic problems were resolved when inbound freeway lanes were reversed to carry outbound traffic. The large number of evacuees placed a considerable strain on accommodation resources. Search and rescue efforts after the hurricane were small but successful because of the small population in the impact area. Medical care was generally better than in Katrina because hospitals and nursing homes were evacuated before the storm, but 24 nursing home residents died when their bus caught fire.

*Hazard operations*

Repair of New Orleans' damaged levees started as soon as the flooding began. In addition, a massive amount of extra-community resources flowed to the impact area to clear debris and restore infrastructure (electric power, water, sewer, transportation, and telecommunications). Similar activities were initiated in damaged areas of Mississippi and Alabama. Unfortunately, these operations were slowed by poor coordination. In one case, the Federal Emergency Management Agency (FEMA) rejected useful personnel and equipment from another federal agency.

*Incident management*

Perhaps the greatest failings in the management of both hurricanes were inadequate staffing of police, inadequate numbers of evacuation buses in New Orleans and airport baggage checkers in Houston, logistics, external coordination, communication and documentation. Agencies at local, state, and federal levels did not have accurate information about the situation, or the response of other organizations. The mayor of New Orleans claims to have requested federal assistance on 29 August, but assistance did not even begin to arrive until four days later. The delay appears to have been due, in part, to disputes between the state and federal governments about which level of government was in charge. Within the federal government, FEMA (the agency usually in charge of disaster operations) was replaced by the military. Public information was generally good, mostly because the news media provided extensive coverage of both hurricanes. Indeed, television coverage seems to have been a major source of information to emergency response organizations. Reporters accurately described the deplorable living conditions in the New Orleans Superdome and Convention Center, as well as the massive traffic jams out of Houston. However, they also transmitted unsubstantiated rumours about violence and grossly exaggerated the amount of crime in New Orleans [62].

## 9. LONDON BOMBINGS 7 JULY 2005

On the morning of 7 July 2005, four separate but inter-connected explosions occurred in central London when suicide bombers detonated bombs on the public transport system. Three explosions occurred on the underground system and one on a bus, leading to fifty-two deaths and approximately seven hundred injured. Each of these events was a serious incident in its own right, and the cumulative effect was a significant challenge for the emergency response arrangements implemented against the unknown of whether or not further attacks were imminent.

Early on, the first responders were able to confirm that there was no radiation or other CBRN component to the attack. Nevertheless, by this time all the organizations that would have been involved if there had been a CBRN component had initiated their alerting of emergency response capabilities. This in itself was valuable experience, added to by the fact that many of these organizations also had other roles in a conventional emergency. For example, the lead radiation protection organization, the Health Protection Agency (HPA) also had other divisions providing advice on a range of public health issues, such as potential exposure to chemicals in the London Underground following the explosion, and prevention of the spread of infections from blood and bodily fluids. Overall, the emergency response arrangements worked well, but inevitably there were lessons to be learned; many of which were pertinent to radiation protection preparedness arrangements [102, 107].

At the time of the bombings, the HPA was a relatively new organization that had brought together a number of mature organizations, each with their own background in dealing with emergencies. Whilst progress had been made in unifying the arrangements, it was clear that improvements needed to be made in the command and control arrangements, and in clarifying responsibilities. This was achieved over the next year or so, with further refinements from the experience of dealing with Avian Influenza emergencies, which was crucial in the effectiveness of the response to the polonium-210 incident in London.

One of the effects of the bombings during the rush hour was to paralyse the public transport systems, meaning that many people could not get to work. As a consequence of this experience, HPA modified its Emergency Plans so that its National Emergency Coordination Centre (NECC) function could be undertaken at any of its four main sites in similarly equipped dual purpose facilities that could be meeting rooms/training facilities or an Emergency Operations Centre. In the event the NECC was at the HPA headquarters in London with the Emergency Operations Centre in the Radiation Protection Division also operational.

One of the issues identified in this, and the later Buncefield petroleum fire (December 2005), [108] was difficulties in quickly accessing environmental monitoring data in order to make risk assessments and provide a sound basis for advice to responders and the government. As a consequence of this, response arrangements were modified so that during the event, HPA staff were embedded with scientific advisers to the police who carried out monitoring within the multiple crime scenes. This facilitated the two-way flow of monitoring data and other relevant information, from both the crimes scenes, and the environmental monitoring of public places carried out by HPA.

## 10. POLONIUM-210 INCIDENT IN LONDON, 2006

On 23 November 2006, Alexander Litvinenko died in London allegedly from poisoning by $^{210}$Po, an almost pure alpha particle emitter. The spread of radioactive contamination, arising from the poisoning and the events leading up to it, involved many locations in London. The potential for intakes of $^{210}$Po arising from contamination posed a public health risk and generated considerable public concern. The scale of the event required a multiagency response, including top level government emergency response management arrangements. The Health Protection Agency (HPA) had a leading role in coordinating and managing the public health response, which had to deal with thousands of concerned individuals [33].

In parallel to this, the London Metropolitan Police Service (MPS) were undertaking a criminal investigation. As the investigation progressed it identified many locations where there was a potential for the presence of radioactive contamination. In order to manage and prioritise the monitoring and other emergency response resources in a rapidly changing situation, good liaison with the police and other agencies was essential. Polonium-210 contamination was found in tens of locations, including hospitals, hotels, offices, restaurants, bars and transportation. In some cases, it was possible to carry out simple decontamination procedures at the time of monitoring, and release the location as being safe for public access. However, there were some locations where this was not possible and the levels of contamination were such that public access had to be prohibited until appropriate remediation or decontamination work had been undertaken. The acute phase of the response lasted into January 2007, with the recovery phase lasting into the summer.

### *Hospitalization and recognition*

As in many other incidents, it took some time for radiation exposure to be identified as the cause. On 3 November, a few days after the poisoning may have taken place, Mr. Litvinenko was admitted to a north London general hospital with vomiting, diarrhoea and abdominal pain. His condition deteriorated and he was transferred to a specialist hospital in London. It was reported that, in a broadcast interview with him, he claimed he had been poisoned. Various possible causes of illness were investigated, including chemical poisoning and the effects of ionising radiation. With respect to the latter, contamination and dose rate measurements had been made of him and his surroundings in the hospital, but the presence of radiation was not detected. Crucially, alpha contamination is not expected in a medical environment and the monitors used were not designed to detect alpha contamination.

A few days before Mr. Litvinenko died, the MPS in following up his claim of poisoning requested the assistance of their scientific advisers and the HPA in identifying what could have caused the clinical picture. Tests established that Mr. Litvinenko had a significant quantity of $^{210}$Po in his body. Initial assessments by HPA indicated that an intake in excess of one GBq of $^{210}$Po would have been required to explain the clinical course [109]. Further, exposure to both his body fluids and any residual source material (which was likely to have spread) could pose a significant public health risk. Also, it was not known if this was a single event or whether there had been other related events, with more than one source of radioactive material.

*Public health response strategy*

To address the hazards associated with the incident, the HPA developed key objectives for the public health response, in brief:

- To prevent further exposure of the public:
  - work closely with the police to aid their criminal investigation and identify sites and individuals that might be contaminated;
  - develop an environmental monitoring strategy to support this;
  - assess and advise on public access and remediation of contaminated sites.
- To assess risks to those potentially exposed:
  - develop and implement risk assessment criteria;
  - offer, implement and report on personal monitoring though urine analysis.
- To provide advice and reassurance to those exposed and the general public.

The activities necessary to achieve these objectives included identifying where contamination might be, or have been, since the poisoning; obtaining environmental monitoring information and a knowledge of the activities undertaken at these locations, assessing the possible patterns and magnitudes of intake of $^{210}$Po, and then identifying and prioritising those that might need to undergo a clinical examination or individual monitoring.

*Managing the response*

The incident required a multiagency response within the UK Emergency Response Framework [94]. The government's dedicated crisis management facilities, the Cabinet Office Briefing Rooms (COBR) were activated from where the Civil Contingencies Committee (CCC) provided overall management of the response. Underneath this, the Strategic Coordinating Group (SCG) chaired by the police, covered coordination of the multiagency activities to meet directions made by the CCC. Overall, the response arrangements worked well. Although the scenario of the incident was radically different from those in the nuclear and counterterrorism sectors, the integrated response clearly benefited from the experience of the substantive programme of exercises in these sectors.

It was clear within the first day or so that the incident would have a significant recovery phase, and consequently the SCG took an early decision to establish a subgroup, the Recovery Working Group (RWG) chaired by Westminster City Council (WCC), who were acting on behalf of the various London Local Authorities in which the contaminated locations were situated. During the early response phases, the RWG developed a framework strategy and processes for remediation and clearance of locations [94]. This was important in providing clarity on responsibilities and the protocols and procedures to be used.

*Environmental monitoring and assessments*

One of the early deployments of the environmental monitoring teams was to the hospitals where Mr. Litvinenko had been treated. There was a clear potential risk that body fluids from him were a source of contamination. Low levels of contamination were found at the hospitals; however, with an aggressive hospital cleaning policy in place it is likely the contamination levels at the time of treating Mr. Litvinenko would have been significantly higher. Therefore, it was considered necessary to carry out individual monitoring of staff that had come into contact with him. Some intakes were detected but were relatively low, partly due to the routine use of Personal Protective Equipment (PPE) and procedures to avoid infection.

The criminal investigation quickly gathered pace identifying the movements of relevant persons and locations that could be potentially contaminated. Over the next few weeks, more than forty locations were identified that had to be monitored and assessed either as crime scenes by the police and their specialist scientific advisers or as public health risks by the HPA. For the latter, parts of the national response arrangements for civil and military nuclear emergencies were used, with HPA coordinating the monitoring programme using resources from several organizations across the UK. At the incident's peak there were seventy monitoring staff working in shifts. A key observation from this was that the contamination was not uniformly distributed, but in discrete patches, and on hard surfaces it was largely fixed to the surface, not readily removable and therefore not readily available to be taken into the body.

Using modelling techniques, and the flow of environmental monitoring data, estimates were made of the ranges of potential radiation doses to people in restaurants, bars, offices, hotels, hospitals, cars, and transportation identified as having areas contaminated with $^{210}$Po, and to those who came into contact with individuals potentially contaminated with $^{210}$Po. Intakes of $^{210}$Po into the body via ingestion, inhalation or wounds were considered from various objects and surfaces contaminated either directly or through body fluids. These assessments provided the underpinning to the triage questionnaires used to identify those who should have individual monitoring. The potential radiological impacts of the discharges of $^{210}$Po to sewers from the two hospitals and from the incineration of clinical wastes were also considered, as were the potential implications of the burial or cremation of Mr. Litvinenko's body.

*Public health response*

On 25 November, following a risk assessment, the HPA made a request via the media asking members of the public who were in potentially contaminated locations in a specified period to call NHS Direct (a 24 hour National Health Service helpline). To support this, a questionnaire was developed to assist the collection of key information from callers. The details of any callers associated with relevant locations were forwarded to the HPA for further health assessment and follow-up. Overall, there were 3,837 calls to NHS Direct with 1,844 questionnaires going to HPA for follow-up. In addition to this group, there were the staff and known visitors to the various locations arising from the police investigation.

A public health team was assigned to each of the main locations and site-specific risk assessments and questionnaires developed to identify those at risk and requiring monitoring using an alpha spectrometry technique on 24 hour urine samples. Throughout this, it was necessary to explain the process and respond to the many concerns of the staff and management at the affected locations. A complicating factor was that for many hotel staff, English was not their first language. Individuals identified from any source who reported symptoms which could be associated with radiation effects, or were seriously concerned, were triaged by a clinical assessment team. Of the 186 reviewed in this way, a total of 29 were referred to a special clinic for a clinical examination. None were suffering any acute radiation effects.

*Individual monitoring programme*

Early on it was clear that the number of people requiring urine analysis would be many hundreds and possibly thousands. To deal with this, and the rate at which they were identified, the HPA quickly developed a monitoring technique and protocols that were used at three laboratories across the UK. Contingency arrangements were also made with other laboratories in Europe and with the IAEA should the need arise to use them.

Overall, urine samples from 752 persons were processed and assessed [110]. It was necessary to develop a reporting protocol that put the results into dose bands. Polonium-210 is naturally occurring and some is found in everybody's urine. The minimum Reporting Level (RL) was set at 30 millibecquerels per 24 hour sample to ensure that any result above RL was likely to be due to the event. Where the intakes were above the RL, an assessment was made of the committed effective dose. Aggregated individual monitoring data was routinely reported in the HPA press releases. Overall, there were 86 individuals with the $^{210}$Po levels in urine above RL, however, their doses were below 1 mSv. For 36 individuals doses were in the range ≥1 mSv and < 6 mSv; and for 17 individuals doses were ≥ 6 mSv. Of the highest dose group, 14 were staff and visitors to a bar of one hotel, two were staff from another hotel, and one was a family member caring for Mr. Litvinenko before he went into hospital. The highest assessed dose was for the family member at about 100 mSv.

*Following up foreign visitors*

In addition to UK residents, a large number of those potentially exposed to $^{210}$Po were overseas visitors who had stayed in, or visited, one of the hotels or other locations involved in the incident. These people had to be followed up through diplomatic and public health channels. To address this, the HPA established an Overseas Advice Team. Making appropriate contacts in the various countries proved to be difficult. The IAEA were able to help in this process. In total, attempts were made to follow up 664 individuals from 52 countries and territories. Significant difficulties were encountered in obtaining feedback on results, due to data protection legislation and medical-in-confidence issues. Nevertheless, results were received for about a quarter of the identified individuals. None had doses in excess of 6 mSv, 5 had doses in the range ≥ 1 mSv to < 6 mSv. 8 individuals had $^{210}$Po levels in urine above the Reporting Level but their doses were below 1 mSv [102].

*Communicating with the public and media*

Throughout the incident, there was a determination to be as open as possible with the media and the public, whilst ensuring that the confidential nature of police investigations, as well as the sensitivities of those individuals involved in the incident, are respected. The first press conference on 24 November was vital in setting the tone. At this, HPA announced that tests on Mr. Litvinenko had detected a significant quantity of $^{210}$Po, explained the nature of alpha radiation and how $^{210}$Po was only a hazard if it was ingested, inhaled or absorbed through wounds. The proactive monitoring that was being carried out at the locations identified by the police was also covered.

During those first few days and weeks, many interviews were given on radio and TV, and HPA released press statements each day in the weeks leading up to Christmas, as well as responding to thousands of media calls and ensuring the website was up-to-date with information. Significant effort was put into liaising with others involved in the response to ensure that the public received a coherent picture of what was happening.

# APPENDIX II
# DESCRIPTION OF DIFFERENT TYPES OF RADIATION EMERGENCIES

Appendix II provides standardized summary description of different types of radiation emergencies, as well as their statistics. Emergencies are grouped according to the type of practice. Tables 3-11 are primarily adapted from Ref. [32].

TABLE 3. NUCLEAR CRITICALITY EMERGENCIES

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1945 | USA | New Mexico (Los Alamos) | Nuclear research | 2 exposed: 1 died | 0.5–5.1 Gy | NA | Unsafe procedure; during critical assembly experiment scientist's hand slipped, allowing a tungsten carbide brick to fall into assembly | [77] |
| 2 | 1946 | USA | New Mexico (Los Alamos) | Nuclear research | 8 exposed: 1 died | 0.37–21 Gy | NA | Unsafe procedure; a critical assembly reflected by beryllium was being demonstrated; reflector slipped, allowing critical excursion | [77] |
| 3 | 1952 | USA | Illinois (Argonne) | Nuclear research | 4 exposed | 0.1–1.6 Gy | NA | Failure to follow operating procedure during replacement of control rod | [77, 111] |
| 4 | 1953 | USSR | Chelyabinsk (Mayak Complex) | Nuclear research and reprocessing | 2 exposed: 1 with severe ARS and amputation of legs | 1–10 Gy | NA | Poor design; unfavourable geometry used for mixing, dilution, storage, etc. of plutonium nitrate products | [112] |
| 5 | 1957 | USSR | Chelyabinsk (Mayak Complex) | Nuclear research and reprocessing | 6 exposed: 1 died, 5 others had ARS | 3–30 Gy | NA | Poor design; accumulation of uranyl oxalate in unsafe geometry in a glove box | [77, 111, 112] |
| 6 | 1958 | USSR | Chelyabinsk (Mayak Complex) | Nuclear research and reprocessing | 4 exposed: 3 died, 1 further away survived | fatalities 60 Gy<br>other person 6 Gy | NA | Unsafe geometry during draining of uranium solution; neutron reflector contributed to criticality | [77, 111, 112] |
| 7 | 1958 | USA | Tennessee (Oak Ridge) | Nuclear processing | 8 exposed | 0.69–3.65 Gy | NA | Valve leakage led to an unplanned transfer of enriched uranium solution to a 55-gallon (208-litre) drum.<br>Unsafe geometry resulted in a criticality | [113] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 1958 | USA | New Mexico (Los Alamos) | Nuclear research | 3 exposed: 1 died | 45 Gy (fatality): 1.34 and 0.53 Gy (survivors) | 120 Gy to upper torso | Unsafe geometry occurred when plutonium solids were washed from 2 vessels into 1 | [77, 111] |
| 9 | 1958 | Yugoslavia | Vinca | Zero power reactor | 6 exposed: 1 died 5 suffered ARS | 2.07–4.36 Gy | NA | Equipment failure (controls) caused nuclear excursion: detectors at saturation value and not showing increase in power level | [77, 111] |
| 10 | 1961 | USA | Idaho | Reactor research | 10 exposed: 3 died. 2 men were killed instantly from a steam explosion and a third man died from head injury. 7 others were exposed | up to 3.5 Gy | NA | Evidence suggests control rod was manually pulled out too fast, causing power rise | [77] |
| 11 | 1961 | USSR | Siberia | Chemical processing | 1 exposed | 2 Gy | NA | Criticality controls were not in place during condensing and evaporation of uranium hexafluoride | [77, 111, 112] |
| 12 | 1962 | USA | Washington (Hanford) | Chemical processing | 2 exposed | 0.43–1.1 Gy | NA | Improper control of solutions led to unfavourable geometry | [77, 111] |
| 13 | 1962 | USA | Richland | | 2 exposed | | | | [114] |
| 14 | 1963 | USSR | Sarov (Arzamas) | Nuclear weapons research | 2 exposed: suffered ARS | 3.7–5.5 Gy | NA | Violation of operating procedures | [77, 111] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 15 | 1964 | USA | Rhode Island (Wood River Junction) | Chemical processing | 3 exposed: 1 died | fatality: 100 Gy.<br>others 0.6–1.0 Gy | NA | Human factors; labelled bottle indicated high concentration of U; transferred to vessel and unsafe geometry resulted | [77, 111, 115] |
| 16 | 1965 | Belgium | Mol | Experimental reactor | 1 exposed<br>Non uniform exposure of body, left foot amputated | 5 Gy | 3–40 Gy | Failure to follow safety procedures | [77, 111,116, 117] |
| 17 | 1966 | USSR | | Experimental reactor | 5 exposed | 3.0–7.0 Gy | – | – | [114] |
| 18 | 1968 | USSR | Chelyabinsk-70 | Reactor | 2 died | 20–40 Gy and 5–10 Gy | 700 Gy to left hand of highest exposed | Violation of procedure; failure to reposition a reflector | [77, 111] |
| 19 | 1968 | USSR | Chelyabinsk-40 | Plutonium extraction | 2 exposed: 1 died survivor had ARS plus amputation of legs and a hand | fatality 24.5 Gy: other 7 Gy | NA | Inadequate design leading to unfavourable geometry of plutonium solution | [111, 112] |
| 20 | 1968 | USSR | | Experimental reactor | 4 exposed | 1.0–1.5 Gy | – | – | [114] |
| 21 | 1969 | USSR | | Experimental reactor | 1 exposed | 5.0 Gy | – | – | [112, 114] |
| 22 | 1971 | USSR | Kurchatov Institute | Power reactor research facility | 4 exposed: 2 died<br>2 with ARS and long term health effects | fatalities: 20 and 60 Gy<br>Others 8–9 Gy | NA | Faulty construction of the fuel assembly in the reactor; fuel rods fell into highly supercritical geometry | [77, 111, 118] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 23 | 1971 | USSR | Kurchatov Institute | Power reactor research facility | 3 exposed | 3 Gy | 20 Gy to legs | Violation of operating procedure; control rods not actuated when water was added to tank containing fuel rods | [77, 111, 118] |
| 24 | 1978 | USSR | Siberia | Plutonium<br>processing | 8 exposed, 1 died<br>1 person with amputation at elbow: 7 others exposed | 0.05–2.5 Gy | 70 Gy | Violation of procedures. Unfavourable geometry of larger than allowed plutonium ingots during packaging; deficient glove box design | [77, 111, 112] |
| 25 | 1983 | Argentina | Buenos Aires | Criticality facility | 1 died | 17 Gy (neutron) and 20 Gy (gamma) | NA | Failure to follow procedure in removing water from tank containing fissile material | [77, 119] |
| 26 | 1997 | Russian Federation | Kremler (Sarov) | Nuclear weapons research | 1 died | 45 Gy (neutrons) + 3.5 Gy (gamma) | up to 250 Gy to hands | Criticality; experimenter violated safety requirements | [11, 77] |
| 27 | 1999 | Japan | Tokaimura | Small fuel preparation plant | 3 exposed: 2 died | 10–20 Gy,<br>6–10 Gy<br>1–5 Gy | NA | Human error and unauthorised modification of procedures that bypassed criticality safe geometry | [12, 120] |

TABLE 4. EMERGENCIES IN NUCLEAR OPERATIONS

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1951 | USSR | Chelyabinsk-40 | Nuclear research and reprocessing | 5 exposed; 1 died, others suffered ARS and/or local injury | – | – | – | [117] |
| 2 | 1952 | USSR | Chelyabinsk-40 | Nuclear research and reprocessing | 2 died: internal contamination with tritiated water | – | – | – | [117] |
| 3 | 1954 | USSR | Sarov (Arzamas) | Nuclear weapons | 1 died: Po-210 internal exposure | – | – | – | [117] |
| 4 | 1955 | USA | Washington (Hanford) | Research processing | 1 exposed intake of Pu-239 | – | – | – | [114] |
| 5 | 1957 | USSR | Kyshtym (Mayak complex) | Radiochemical plant | release of 740 PBq of radioactive products | – | – | Overheating, resulting in explosion of a storage tank | [106] |
| 6 | 1957 | UK | Cumbria (Windscale) | Graphite reactor | release of 740 TBq 131I; other radionuclides also released | – | < 0.1 Gy to child thyroid | Overheating and fire | [106] |
| 7 | 1975 | Germany (GDR) |  | Research reactor | 1 exposed (localized exposure) | – | 20–30 Gy | – | [114] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 1976 | USA | Washington (Hanford) | Research processing | 1 exposed<br>explosion trauma and intake of Am-241 (~40 MBq) | NA | 8.6 Gy to bone marrow | Chemical explosion of an ion exchange column in glove box | [121] |
| 9 | 1977 | Argentina | Atucha | Nuclear reactor | 1 person exposed: wound contaminated with 3800 Bq, surgically removed after 8 years | – | 364 Gy to localised area over 8 years | Worker not wearing lead gloves | [32, 39] |
| 10 | 1979 | USA | Pennsylvania, (Three Mile Island) | Commercial nuclear power plant | Reactor severely damaged: 550 GBq I-131 released to atmosphere: no significant exposure | <1 mSv | – | Pump failure triggered shut down, but a further pump failure and incorrect instrumentation readings caused operators to take actions that led to low water levels in reactor. This led to severe damage to fuel elements | [106] |
| 11 | 1985 | Czechoslo-vakia | Petrvald |  | 1 person exposed: intake through wound of 600 Bq of 241Am | – | – | Carelessness and inadequate equipment | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 12 | 1986 | USA | Oklahoma (Gore) | Uranium processing | 1 died of trauma, workers and 7 members of public with low level internal contamination | – | – | Accidental rupture of a 14-ton cylinder of UF6 | [122] |
| 13 | 1986 | USSR | Ukraine (Chernobyl) | Nuclear power plant | 237 significant exposures: 30 deaths<br>destruction of the reactor.<br>30 deaths (including 2 from trauma): 207 others with significant doses. A significant release of radionuclides into the environment, including 1760 PBq of I-131 and 86 PBq of Cs-137 | up to16 Gy | – | Violation of safety procedures combined with a flawed design resulted in a steam explosion, fire, and destruction of the reactor. | [38] |
| 14 | 1993 | Russia | Siberia (Tomsk) | Reprocessing | Release of Pu-239 and mixed fission products | – | – | Buildup of gases in vessel followed by explosive rupture and an explosion of flammable cloud | [19] |

TABLE 5. TRANSPORT EMERGENCIES

| No. | Year | Country | Vehicle type | Location | Identifying name | Cause and consequences | Ref. |
|---|---|---|---|---|---|---|---|
| | | | | **Sea** | | | |
| 1 | 1961 | USSR | Nuclear submarine | NW Atlantic | K-19 | Leakage in heat transfer circuit with fuel overheating; submarine towed to base | [123] |
| 2 | 1963 | USA | Nuclear submarine | Atlantic (unspecified) | Thresher | Unknown cause; lost at sea with entire crew. The estimated total amount of radioactivity released was < 0.04 GBq | [123] |
| 3 | 1968 | USSR | Diesel submarine | Pacific near Hawaii | K-129 | Submarine sank carrying 2 nuclear warheads that were subsequently recovered | [123] |
| 4 | 1968 | USA | Nuclear submarine | Atlantic (unspecified) | Scorpion | Unknown cause; lost at sea with entire crew | [123] |
| 5 | 1970 | USSR | Nuclear submarine | Bicay Bay | K-8 | Fire; rubber seals in hull failed and seawater entered; sank NW of Spain | [123] |
| 6 | 1978 | Unspecified | Surface vessel | SE Barents Sea | Nikel | Lighter carrying encapsulated waste was lost at sea during storm | [123] |
| 7 | 1984 | France | Surface vessel | North Sea | Mont Louis | Collision of vessel and ferry; ship carrying 30 containers of <1% Zeebrugge enriched UF6 sank; all containers recovered | [123] |
| 8 | 1985 | USSR | Nuclear submarine | Chazma Bay | K-431 | Explosive criticality occurred during refuelling; environmental contamination in Russia resulted | [123] |
| 9 | 1986 | USSR | Nuclear submarine | NE Atlantic | K-219 | Fire and explosion damaged hull; towed to 6 000 m depth and sunk (Bermuda) | [123] |
| 10 | 1989 | USSR | Nuclear submarine | Norwegian Sea | K-278 | Fire in the stern compartment while submerged; submarine sank | [123] |

| No. | Year | Country | Vehicle type | Location | Identifying name | Cause and consequences | Ref. |
|---|---|---|---|---|---|---|---|
| 11 | 1989 | USSR | Nuclear submarine | Ara Bay | Unknown member of North Fleet | Unknown problem; largest reported release of radioactive material | [123] |
| 12 | 1997 | Panama | Surface vessel | Atlantic, Azores | MSC Carla | 3 type B packages containing 137Cs involved | [123] |
| 13 | 2000 | Russia | Nuclear submarine | Barents Sea | Kursk | Cause unknown: 2 seismic events occurred the day of the accident; the submarine sank with 118 crew members onboard; subsequently, the reactors onboard were found to be intact | [123] |
| | | | | **Air** | | | |
| 14 | 1965 | USA | Aircraft | Near Okinawa, Japan | Skyhawk Jet | Jet carrying nuclear weapon rolled off aircraft carrier | [123] |
| 15 | 1966 | USA | Aircraft | Palomares, Spain | Bomber (B-52) | Aircraft collision during refuelling; 4 nuclear weapons involved with 2 recovered intact, 2 destroyed on impact with land; significant ongoing plutonium contamination of the environment resulted | [123] |
| 16 | 1968 | USA | Aircraft | Thule, Greenland | Bomber (B-92) | Aircraft crashed; 4 nuclear weapons destroyed, spreading plutonium contamination over large area of marine environment | [123] |
| 17 | 1987 | USSR | Aircraft | Sea of Okhotsk | – | Helicopter emergency resulted in drop of RTG* equipped with 90Sr source (12.95–25.3 PBq) at sea in 30 m of water; attempts to locate it have been unsuccessful | [123] |
| 18 | 1997 | Russia | Aircraft | Sea of Okhotsk | – | Helicopter emergency resulted in disposal of RTG containing 1.3 PBq 90Sr | [123] |

| No. | Year | Country | Vehicle type | Location | Identifying name | Cause and consequences | Ref. |
|---|---|---|---|---|---|---|---|
| **Space vehicle** | | | | | | | |
| 19 | 1964 | USA | Spacecraft | West Indies Ocean | SNAP-9A<br>Transit-5BN3 | Satellite containing 630 TBq of 238Pu failed to achieve orbit and vaporized during re-entry in the southern hemisphere | [123] |
| 20 | 1968 | USA | Spacecraft | Santa Barbara, California | Nimbus BI | Spacecraft failed to achieve orbit; 2 RTGs recovered intact | [123] |
| 21 | 1970 | USA | Spacecraft | South Pacific | Apollo 13 | Malfunction in oxygen supply led to emergency return to earth in the lunar landing module; an RTG onboard entered intact and is at a depth of not less than 6000 m in the Tonga Trench | [123] |
| 22 | 1978 | USSR | Spacecraft | Northern Canada | Cosmos 954 | Research satellite carrying small nuclear reactor re-entered atmosphere and spread radioactive fragments over wide area | [123] |
| 23 | 1983 | USSR | Spacecraft | South Atlantic | Cosmos 1402 | Satellite failed to boost nuclear reactor into higher orbit after completion of mission; reactor core and fission products re-entered atmosphere east of Brazil | [123] |
| 24 | 1996 | USA | Spacecraft | Pacific Ocean | Mars 96 | Unsuccessful burn of booster resulted in re-entry of earth's atmosphere west of Chile; 18 RTGs onboard with total 238Pu activity of 174 TBq | [123] |

TABLE 6. EMERGENCIES IN INDUSTRIAL USES: RADIOACTIVE SOURCES

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1968 | Argentina | La Plata | Industrial radiography | 0.5 TBq<br>Cs-137 | 1 with both legs amputated | 0.5 Gy | 17000 Gy, max to thigh | Worker carried the source in pocket for 18 hours | [124] |
| 2 | 1968 | India | | Industrial radiography | Ir-192 | 1 with skin ulceration | – | 130 Gy, max | Worker picked up a source that fell out of a camera and kept it in his pocket for 2 hours | [125] |
| 3 | 1968 | Germany (FRG) | | Industrial radiography | Ir-192 | 1 with localised injury to pelvis and thigh | 1.0 Gy | 40–60 Gy | Worker carried source in jacket pocket | [126] |
| 4 | 1969 | UK | Scotland | Industrial radiography | 900 GBq<br>Ir-192 | 1 person: original incident | 450 mSv | 2.15 Sv to hip | Source in unlocked container on front passenger seat of car. Rotated to ‘exposure position’ and exposed driver | [127] |
| | | | | | | 8 months later, serious lesion on chest wall | 0.6 Gy | 20–200 Gy | Self-inflicted exposure | |
| 5 | 1971 | UK | | Industrial radiography | 185 GBq<br>Ir-192 | 1 person with localised exposure | < 0.1 Gy | 30 Gy | Source directly handled | [114] |
| 6 | 1972 | China | Sichuan | Irradiation | 265 TBq<br>Co-60 | 3 exposed | 0.5–1.5 Gy | – | Accidentally entered room | [128, 129] |
| 7 | 1973 | USSR | Moscow region | Irradiation | 4.2 PBq<br>Co-60 | 1 with ARS | 4 Gy | – | Failure of safety device, improper entry | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 1974 | USA | New Jersey, Parsippany | Irradiation | 4.4 PBq Co-60 | 1 exposed | 4.1 Gy | – | Failure to use survey meter before entering irradiation room | [130] |
| 9 | 1975 | Italy | Brescia | Irradiation | 1.33 PBq Co-60 | 1 death | 12 Gy | organ doses 12–24 Gy | Lack of training and safety systems on product conveyor entry point | [32, 39]<br>[116] |
| 10 | 1975 | USSR | Kazan | Industrial radiation facility | 0.7 PBq Co-60 | 2 with ARS and hands injury | 3–5 Gy | 30–50 Gy to hands | Very similar to San Salvador 1989 | [32, 39] |
| 11 | 1976 | USA | Pennsylvania (Pittsburgh) | Industrial radiography | Ir-192 | 1 localised injury to hand | – | 10 or 15 Gy | – | [32, 39] |
| 12 | 1977 | Czechoslovakia | Pardubice | Industrial radiography | Ir-192 | 1 localised injury to hand | 5 mGy | – | Technical failure of the equipment. Improper actions to bring source back under control | [32, 39] |
| 13 | 1977 | USA | New Jersey (Rockaway) | Irradiation | 18.5 PBq Co-60 | 1 exposed | 2 Gy | – | Construction in the facility, lack of safety precautions and interlock failure | [130] |
| 14 | 1977 | UK |  | Industrial radiography | 815 GBq Ir-192 | 1 localised injury to ends of 3 fingers | < 0.1 Gy | – | Operator working in a confined area held source for 90 seconds while conducting radiography on a weld | [32, 39] |
| 15 | 1977 | Hungary | Győr | Industrial radiography | Ir-192 | 1 exposed, mild radiation disease | 1.2 Gy | – | Failure of equipment to withdraw source into its container | [32, 39, 131] |
| 16 | 1977 | UK |  | Tritium light source production | 11 -15 TBq H-3, released, unsealed | 2 exposed, internal contamination | 0.62 Gy and 0.64 Gy | – | Broken inlet manifold led to the release and escape of tritium | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 17 | 1977 | South Africa | Transvaal (Sasolburg ) | Industrial radiography | 260 GBq Ir-192 | 1 with amputation of 2 fingers, plus removal of rib | 1.16 Gy | 100 Gy | Faulty operation of pneumatically operated container and monitor; carelessness of operator | [32, 39] |
| 18 | 1977 | Peru | Zona del Oleoducto | Industrial radiography | Ir-192 | 3 with localised effects to hands, 2 with finger amputations | 2 Gy max | 160 Gy max | Untrained personnel and lack of supervision; equipment neither registered nor authorized | [32, 39] |
| 19 | 1978 | Argentina | Buenos Aires | Industrial radiography | Ir-192 | 1 with localised injury to hand | – | 12–16 Gy | Manual handling of sources | [32, 39] |
| 20 | 1978 | USA | Louisiana (Monroe) | Industrial radiography | 3.7 TBq Ir-192 | 1 with amputation of a finger | < 0.1 Gy | – | Selection of incorrect range on dose rate monitor for checking withdrawal of source into safe position | [132] |
| 21 | 1979 | Czechoslovakia | Sokolov | Industrial radiography | Ir-192 | 1 localised injury to hand | 5 mGy | – | Technical failure of the equipment and inadequate monitoring during and after work | [32, 39] |
| 22 | 1980 | USSR, Russia | Leningrad | Irradiation | 22.2 PBq Co-60 | 1 death | > 12 Gy | – | Failure of safety device, improper entry | [118] |
| 23 | 1980 | Russia | Uyzhno-Sahalinsk | Industrial radiography | 25 Ci Ir-192 | 1 death and 1 other exposed | – | > 15 Gy to abdomen (child) | Orphan source, a victim child | [118] |
| 24 | 1980 | China | Shanghai | Irradiation | 1.96 PBq Co-60 | 1 with ARS and localised exposure | 5.2 Gy | – | Entry into the irradiation chamber during power failure and with defective interlocks | [32, 39, 133] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 1980 | USSR | Smolensk | Industrial radiography | 25 Ci<br>Ir-192 | 1 with localised injury | < 0.5 Gy | 30 Gy to thigh , 12 Gy to hand | Failure of radiography apparatus | [32, 39] |
| 26 | 1981 | Argentina | Buenos Aires | Industrial radiography | Ir-192 | 2 with localised hand injury | – | – | Source became detached and lodged in the delivery tube | [32, 39] |
| 27 | 1982 | Norway | Kjeller | Irradiation | 2.43 PBq<br>Co-60 | 1 death | 22 Gy | – | Failure of safety device and failure to follow procedures | [40, 41] |
| 28 | 1982 | USSR, Azerbaijan | Bacu | Military used source | 50 Ci<br>Cs-137 | 5 deaths and 22 others exposed | < 0.5 Gy - > 10 Gy | 20–50 Gy to hands 150–500 Gy to thigh | Improper storage of sources | [118] |
| 29 | 1982 | Indonesia | Badak, East Borneo | Industrial radiography | Ir-192 | 1 exposed | 0.77 Gy | 0.64 Gy to Gonads, 11.7 Gy to hands | Repair of the source by the operator | [32, 39] |
| 30 | 1982 | India | Vikhroli, Bombay | Unknown | Ir-192 | 1 exposed | 0.4–0.6 Gy | 1.535 Gy to groin | Failure of security during transport of source; source lost and found by railway worker | [32, 39] |
| 31 | 1983 | UK | – | Industrial radiography | – | 1 exposed | 0.56 Gy | – | Inadvertent exposure to radiographer | [32, 39] |
| 32 | 1983 | Germany | Schwarze Pumpe | Industrial radiography | Ir-192 | 1 with localised effect to hand | – | 5 Gy | Technical defect and inappropriate handling | [32, 39] |
| 33 | 1983 | India | Muland, Bombay | Industrial radiography | Ir-192 | 1 with amputation of 4 fingers | 0.6 Gy | 20 Gy? | Operation by untrained personnel | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | 1984 | Hungary | Tiszafured | Industrial radiography | 1.11 TBq Ir-192 | 1 with localised effect to 3 fingers of left hand | 46 mGy | 20–30 Gy | Failure of equipment and careless handling of source | [32, 39] |
| 35 | 1984 | Argentina | Mendoza | Industrial radiography | Ir-192 | 1 with localised effect to fingers | 0.11 Gy | 18 Gy | Operator pushed source into camera using a finger | [32, 39] |
| 36 | 1985 | India | Yamunanager | Industrial radiography | Ir-192 | 2 each with 2 fingers amputated | – | 8–20 Gy | Violation of safe working practices associated with power failure in the workplace | [32, 39] |
| 37 | 1985 | India | Visakhapatnam | Industrial radiography | Co-60 | 2 exposed, with 1 finger amputation | 0.18 Gy | 10–20 Gy | Violation of safe working practices and lack of maintenance | [32, 39] |
| 38 | 1986 | China | Henan | Irradiation | 0.3 PBq Co-60 | 2 exposed | 2.6 and 3.5 Gy | – | Power loss occurred and source was manually raised; workers entered room with source unshielded | [32, 39, 128, 134] |
| 39 | 1986 | China | Beijing | Irradiation | 0.2 PBq Co-60 | 2 exposed | 0.7–0.8 Gy | – | Workers entered irradiation room when source was unshielded; failed drive system; door open | [32, 39, 128, 135] |
| 40 | 1987 | China | Zhengzhou City | Irradiation | 3.29 PBq Co-60 | 1 exposed | 1.35 Gy | – | Accidental exposure for about 1.5–2 minutes | [133] |
| 41 | 1988 | China | Liaoning | Industrial radiography | 1.1 TBq Ir-192 | 6 with localised exposure | – | 0.1–12.6 Gy | Workers directly handled source when removing it from failed equipment | [128, 136] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 1988 | Czechoslovakia | Prague | Am-241 foil production | Am-241, unsealed | 1 with intake | (Dose from 50 kBq inhalation intake) | – | New rolling methods untested; poor radiation protection practice | [32, 39] |
| 43 | 1988 | China | Zhao Xian | Irradiation | Co-60 | 1 exposed | 5.2 Gy | – | Accidentally entered into irradiation room for about 40 seconds | [32, 39] |
| 44 | 1989 | India | Hazira Gujarat | Industrial radiography | Ir-192 | 1 exposed, amputated fingers | 0.65 Gy | 10 Gy | Failure of safety management and improper maintenance | [32, 39] |
| 45 | 1989 | South Africa | Transvaal (Witbank) | Industrial radiography | Ir-192 | 3 exposed, one had amputation of leg and fingers | 0.09–0.78 Gy | – | Detached source; negligence of radiographer (source improperly attached) and failure of portable monitor to register detached source | [32, 39] |
| 46 | 1989 | China |  | Industrial radiography | Ir-192 | 1 with localised dose | – | 18.37 Gy | – | [32, 39] |
| 47 | 1989 | Bangladesh |  | Industrial radiography | Ir-192 | 1 exposed | 2.3 Gy | – | – | [32, 39] |
| 48 | 1989 | China | Beijing |  | Co-60 | 2 exposed | 0.61 and 0.87 Gy | – | Accidental exposure to source for about 4 minutes | [32, 39] |
| 49 | 1989 | El Salvador | San Salvador | Irradiation | 0.66 PBq Co-60 | 1 death and 2 others exposed, including amputations | 2.9–8.1 Gy | > 30 Gy | Lack of training and severe deterioration of safety systems due to lack of maintenance over long period | [14] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 1990 | South Africa | Transvaal (Sasolburg) | Industrial radiography | Co-60 | 6 exposed, 3 with localized injuries, one had amputation of hand | 0.55 Gy | – | Source left behind after radiography work; loss undetected because of inadequate monitoring, source handled by 6 people | [32, 39] |
| 51 | 1990 | China | Shanghai | Irradiation | 850 TBq Co-60 | 2 deaths and 5 other exposures | 2.0–12 Gy | – | Entry into the irradiation chamber, without dose rate meter, during power failure and with defective interlocks | [128, 137] |
| 52 | 1990 | Israel | Soreq | Irradiation | 12.6 PBq Co-60 | 1 death | 10–20 Gy | – | Improper entry and maintenance | [15] |
| 53 | 1991 | Belarus | Nesvizh | Irradiation | 30 PBq Co-60 | 1 death | 11–18 Gy | – | Improper entry with source exposed | [16] |
| 54 | 1992 | UK | Scotland | Industrial radiography | Various sealed sources (likely to be mostly Ir-192) | 1 exposed chronically, whole body and localized | 10 Gy | 100 Gy | Chronic series of incidents and poor practices over 14 years | [32, 39, 138] |
| 55 | 1992 | China | Wuhan | Irradiation | Co-60 | 4 exposed | – | – | Power loss and safety interlocks out of order | [128] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 1992 | Hungary | Budapest | Industrial irradiation | 5.4 PBq Co-60 | No person injured | 1–2 mSv for persons participating in rescue | – | Malfunction of the actuating device | [131] |
| 57 | 1992 | Switzerland |  | Industrial radiography | 700 GBq Ir-192 | 1 with localised exposure | – | 3.5–10 Gy | Jammed source, released by hand | [32, 39] |
| 58 | 1993 | UK |  | Industrial radiography | 700 GBq Ir-192 | 1 with localised exposure of hand | < 0.1 Gy | 10 Gy | Improper procedures, handled stuck source | [32, 39] |
| 59 | 1998 | China | Harbin | Irradiation | – | 1 exposed | – | – | Safety equipment failure | [128] |
| 60 | 1998 | Japan | Nakasaki | Industrial radiography | 120 GBq, Co-60 | 1 worker exposed right hand and whole body | 5.5 mSv | 43 Sv | Error in retracting source and worker directly handled source for 30–60 seconds | [139] |
| 61 | 1999 | Perú | Yanango, San Ramón Junín | Industrial radiography | 1370 GBq Ir-192 | 2 exposed with injuries to leg, hands and back | 0.4–0.8 Sv | 0.5 - > 100 Gy | Worker picked up a source that fell out of a camera and kept it in his pocket for 6 hours | [22] |
| 62 | 1999 | Hungary | Paks | Lost radiography source | 70 GBq Ir-192 | No person injured | 0.1–6 mSv to 12 persons | NA | Malfunction of the device | [131] |
| 63 | 1999 | Hungary | Százhalom-batta | Industrial radiography | 300 GBq Ir-192 | 3 persons exposed, no injuries | 0.6–2.7 mSv | NA | Inappropriate dismantling of radiography source | [131] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 64 | 2000 | Brazil | Rio de Janeiro | Industrial radiography | Co-60 | 1 exposed with injuries to hand | – | – | Exposure during routine service | [140] |
| 65 | 2001 | Hungary | Dunaújváros | Industrial radiography | 800 GBq Ir-192 | No person injured | 10–300 µSv to rescue staff | NA | Source jammed, later according to the procedures the device was repaired | [131] |
| 66 | 2004 | China | Shandong Jining | Irradiation | 38 kCi, Co-60 | 2 deaths | 20.0 Gy and 8.8 Gy | – | Workers entered irradiation room when source was unshielded because of electrical failure. | [141, 142] |
| 67 | 2005 | Chile | Concepción/ Nueva Aldea | Gamma radiography | 3.33 TBq Ir-192 (90 Ci) | 1 worker with lesion on his left buttock;<br>1 worker with lesion on his right hand;<br>1 worker with lesion on his right foot | 0.54–1.03 Gy<br>0–0.42 Gy<br>< LD | – | Non-compliance with regulatory requirements and safety rules | [143] |
| 68 | 2006 | Belgium | Fleurus | Irradiation | 312 TBq Co-60 | 1 exposed | 4.4–4.8 Gy | – | Malfunction of a command/control hydraulic system and failure of safety system | [144] |

## TABLE 7. EMERGENCIES IN INDUSTRIAL USES: ACCELERATORS AND X RAY DEVICES

| No | Year | Place: country | Province/ Town | Type of use | Source descript-tion* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1960 | USA | New York (Lockport) | Irradiation | Klystron tube | Non-uniform exposures: 2 seriously injured; 5 with less severe damage | – | up to 12 Gy | Shielding not in place during maintenance/repair | [145] |
| 2 | 1965 | USA | Illinois (Rockford) | Irradiation | Accelerator (10 MeV electrons) | 1 with amputations | 0.05 Gy | 290 Gy to ankle, 420 Gy to hand | – | [146, 147] |
| 3 | 1967 | USA | Pennsylvania (Pittsburg) | Irradiation | Linear accelerator | 1 with ARS and multiple amputations, 2 with ARS | 6, 3 and 1 Gy | 27 to 59 Gy | Failure of safety interlock system | [146, 148] |
| 4 | 1974 | USA | Illinois | Analysis | Spectrometer | 3 with localized exposure | – | 2.4-48 Gy | – | [114] |
| 5 | 1975 | Germany (FDR) | | Analysis | X ray fluorescence unit | 1 with erythema to fingers | – | 30 Gy | Carelessness and technical faults during repair | [32, 39] |
| 6 | 1975 | Germany (FDR) | | Industrial Radiography | X ray equipment | 1 exposed | – | 2 Gy to torso | Carelessness and technical defects | [32, 39] |
| 7 | 1976 | Germany | | – | X ray equipment | 1 with erythema | 1 Gy | – | Inexpert handling of equipment | [32, 39] |
| 8 | 1977 | Argentina | La Plata | Crystallography | X ray equipment | 1 with localized injury to | – | 10 Gy | Shutter removed from crystallography set | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Source descripttion* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | fingers | | | | |
| 9 | 1979 | Germany | Freiberg | Analysis | X ray fluorescence unit | 1 person exposed | 0.2–0.5 Gy | 10–30 Gy to right hand | Violation of safe working practice | [32, 39] |
| 10 | 1980 | Germany | Bohlen | Analysis | Analytical X ray unit | 1 with localized exposure | – | 15–30 Gy to left hand | Violation of safe working practice | [32, 39] |
| 11 | 1980 | Germany | | – | ‘Radiogram’ unit | 1 person exposed | 0.2 Gy | 23 Gy to hand | Defective equipment | [32, 39] |
| 12 | 1981 | Germany | | Analysis | X ray fluorescent device | 1 with localized injury | – | 20–30 Gy to right thumb | Violation of safe working practice | [32, 39] |
| 13 | 1983 | Germany | | – | X ray equipment | 1 with partial body exposure | – | 6–12 Gy | Defective equipment | [32, 39] |
| 14 | 1985 | China | Shanghai | Irradiation | Accelerator | 1 with localized injury | – | 25–210 Gy | Entered irradiation area while main motor was running | [128, 149] |
| 15 | 1987 | Indonesia | Cirebon, West Java | Industrial radiography | X ray machine | 1 exposed on hand | – | 10 Gy | Repair of shutter while machine was in operation | [32, 39] |
| 16 | 1991 | USA | Maryland (Baltimore) | Irradiation | Accelerator | 1 with most fingers amputated | – | 55 Gy | Exposure to dark current during maintenance | [150] |

| No | Year | Place: country | Province/ Town | Type of use | Source descript-tion* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 17 | 1991 | France | Forbach | Irradiation | Accelerator | 1 with localized severe skin lesions, 2 with less serious injury | < 1 Gy | 40 Gy | Exposure to accelerator dark current | [32, 39] |
| 18 | 1992 | Italy | | Analysis | X ray spectrometer | 1 with injuries to fingers on both hands | – | about 20 Gy | Improper procedure during maintenance | [151] |
| 19 | 1993 | UK | | Radiography | 160 kV X ray unit | 1 with injury to fingers of one hand | – | 60 Gy | Improper procedures and failure in warning systems | [152] |
| 20 | 1994 | Mexico | Lazarus Cardenas | Analysis | X ray spectrometer | 1 with injury to one finger | – | – | Failure to de-energize device prior to repair | [153] |
| 21 | 1995 | Brazil | | Analysis | X ray diffraction unit | 1 with injury to hand | – | – | Poor maintenance of device allowing open back window | [154] |
| 22 | 1999 | USA | | Irradiation | Electron beam device | 1 with injury to hand | – | 50 Gy | Residual beam exposed operator’s hand during manufacture testing (chronic exposure over 1 month) | [155] |
| 23 | 2000 | Japan | Yokaichiba | Irradiation | X ray machine | 3 with injury to hand | – | 50–100 Gy | Workers intentionally unlocked safety device | [156] |
| 24 | 2001 | China | Leshan | Detector | X ray flaw detector | 2 exposed with whole body and localized | – | 50 mGy to gonad and 0.045 mGy to abdomen | Flaw detector operation was on while workers were present | [157] |

TABLE 8. EMERGENCIES IN RESEARCH: RADIOACTIVE SOURCES

| No | Year | Place: country | Province/ Town | Type of use | Source description * | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1960 | USA | Madison | Irradiation of samples | 7 TBq Co-60 | 1 student exposed | 2.5–3 Gy | 30 Gy | Source detached during irradiation of samples | [158] |
| 2 | 1962 | USSR | Moscow | Irradiation | 1.9 PBq Co-60 | 1 person exposed | 2.5-3 Gy | 12 Gy | Violation of safe working practices, improper entry to irradiation room | [159] |
| 3 | 1971 | USA | Tennessee | Irradiation | 285 TBq Co-60 | 1 researcher exposed | 1.3 Gy | 12 Gy to hand | Equipment malfunction and operational error | [160] |
| 4 | 1978 | Sweden | Nykoping | – | Research reactor | 1 with localized injury to hand | – | 30 Gy | Instructions for work not followed | [32, 39] |
| 5 | 1979 | Germany | Rossendorf | Neutron activation | Research reactor | 1 with localized injury to hand | – | 20–30 Gy to right hand | Underestimation of level of activation | [32, 39] |
| 6 | 1980 | Germany | Rossendorf | Radiochemical laboratory | P-32, unsealed | 1 person: hand contaminated | – | 100 Gy | Defect in protective glove led to contamination | [32, 39] |
| 7 | 1983 | Germany | Leipzig | Radiochemical laboratory | Am-241, unsealed | 1 person with intake | 0.076 Gy | – | Explosion of vial containing Am-241 solution | [32, 39] |

TABLE 9. EMERGENCIES IN RESEARCH: ACCELERATORS AND X RAY

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main Cause of Accident | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1972 | UK | | Analytical X ray | X ray crystallography | 1 with localized injury to 2 fingers | – | 15–20 Gy | Shutter was removed prior to, and during, servicing | [161] |
| 2 | 1975 | Germany | | Analytical X ray | X ray fluorescence unit | 1 with localized injury to fingers | – | – | Violation of safe working practice | [32, 39] |
| 3 | 1977 | USA | California (Berkeley) | Sample irradiation | 30 kV X rays | 1 with localized exposure: amputation of 2 fingers on one hand and 1 on the other | – | 70 Gy to hand | Safety interlock failure | [32, 39] |
| 4 | 1977 | USSR | Kiev | Research | Proton accelerator 40 MeV | 1 with localised injury to a hand | < 0.5 Gy | 12–30 Gy to hands | Violation of safety rules | [32, 39] |
| 5 | 1978 | USSR | Leningrad | Research | Electron accelerator | 1 with localised injury to a hand, the second with chest | 0.5–1.2 Gy | 30 Gy to hand<br>>20 to Chest | Violation of safety rules | [32, 39] |
| 6 | 1978 | USSR | Protvino | Research | Proton accelerator 70 GeV, deam 1 mm just a needle | – | – | Could not been measured | Operators error | [159] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main Cause of Accident | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 1981 | Germany | Berlin | Analytical X ray | – | 1 with localised injury to left hand | – | 5 Gy | Violation of safe working practice | [32, 39] |
| 8 | 1982 | Germany | Berlin | Analytical X ray | – | 1 with localised injury to finger | – | 6–18 Gy | Violation of safe working practice | [32, 39] |
| 9 | 1984 | Peru | Lima | Analytical X ray | X ray diffraction equipment | 6 persons with injury to fingers | – | 5–40 Gy | Fault of supervision, deliberate exposure from lack of knowledge of risk; equipment not registered with authorities | [32, 39] |
| 10 | 1988 | Germany | Trustetal | Analytical X ray | – | 2 with injury to hands | – | 4 Gy | Technical defect | [32, 39] |
| 11 | 1988 | Germany | Jena | Analytical X ray | – | 1with localized injury to hand | – | 3 Gy | Violation of safe working practice | [32, 39] |
| 12 | 1992 | Vietnam | Hanoi | Sample irradiation | Research accelerator (15 MeV) | 1 with localized injury to fingers and 1 with hand amputated | 1–2 Gy | 10–50 Gy | Poor design and improper entry to adjust sample in beam | [17] |
| 13 | 1994 | USA | California (Davis) | Analytical X ray | X ray diffraction equipment (45 kV) | 1 with localized injury to both hands | – | – | Bypass of safety interlock to effect repair | [162] |

## TABLE 10. EMERGENCIES WITH ORPHAN RADIOACTIVE SOURCES

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1960 | USSR | Moscow | Industrial radiography | 7.5 TBq<br>Cs-137 | 1 person died | 14.8 Gy | 1650 Gy | A person placed the source on strap of trousers and rotated it around the body more than 15 hours — suicide | [32] |
| 2 | 1962 | Mexico | Mexico City | Industrial radiography | 0.2 TBq<br>Co-60 | Mother, 2 children and grandmother died. Father (highest dose) survived due to fractionation of exposure over 4 months (periods out of the house working) | 28–120 Gy | – | Unsecured source left in the yard of a house. Taken by boy to his house where it remained for 4 months | [44] |
| 3 | 1963 | China | Sanli’an (Hefei City) | Agricultural research | 0.43 TBq<br>Co-60 | Farmer and brother died. 4 others with high exposure | 2–80 Gy | – | Abandoned source taken to farmer’s home, where it remained for 10 days | [128, 134, 163] |
| 4 | 1971 | Japan | Ichihara City, Chiba | Industrial radiography | 194 GBq<br>Ir -192 | 6 exposed: 3 with ARS and local injuries | 0.15–1.5 Gy | up to 90 Gy | Failed to confirm source retraction and disconnected cable allowing source to fall to ground in shipyard. Picked up by worker | [164] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 1973 | Mexico | Tula, Hgo | | Cs-137 | 1 person with amputation of left leg | – | 1400 Gy | Source fell out of its container in truck (wooden ‘plug’ shaken out) and was picked up and put in pocket. | [165] |
| 6 | 1977 | South Africa | Pretoria | Industrial radiography | 260 GBq Ir-192 | 1 person with injury to hands and chest, 5 others also exposed | 1.1 Gy | 50–100 Gy | Source became detached from winding cable. Picked up from factory floor and taken home | [166] |
| 7 | 1978 | China | Henan | | 54 GBq Cs-137 | 29 persons | 0.01–0.53 Gy | – | Unused source was taken to worker’s home | [32, 39, 128, 167] |
| 8 | 1978 | Algeria | Sétif | Industrial radiography | 925 GBq Ir-192 | 1 death and 6 others significantly exposed. | – | – | Source fell out of truck and was picked up by 2 boys and taken to the family home | [45, 168] |
| 9 | 1979 | USA | California (Los Angeles) | Industrial radiography | 1.0 TBq Ir-192 | 1 person with injury to right buttock; 4 others with minor skin injuries | 0.75–1 Gy | 800–4000 Gy to most exposed | Failure of radiographer to check source storage led to source falling out and being picked up by a worker | [169] |
| 10 | 1982 | China | Hanzhong | | 1.0 TBq Co-60 | – | 0.42–3 Gy | – | Source was stolen | [128, 170, 171] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 11 | 1983 | Mexico | Ciudad Juarez | Radiotherapy | 16.6 TBq Co-60 made of ~ 6000 pellets, each 2.77 GBq | 10 exposed<br>Some intact pellets and smelted ones incorporated in metal products caused chronic exposure of a significant number of the public, but no acute effects | 0.25–5.0 Sv for 10 most exposed | – | Device placed in unsecure long term storage. Illegally removed to sell for scrap: source ruptured: some source pellets in public domain and rest smelted | [92, 172] |
| 12 | 1984 | Morocco | Casablanca | Industrial radiography | 0.6 TBq Ir-192 | Protracted exposures resulted in deaths of 4 adults and 4 children | – | – | Source became disconnected; no monitoring. Found by member of public and taken home; kept in family bedroom; source discovered after 80 days | [46, 173] |
| 13 | 1985 | China | Mudanjiang |  | 370 GBq Cs-137 | Protracted exposures of 3 people: 1 death | 8–10 Gy | – | Source was found and taken home, where it remained for 150 days | [133, 174] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 1987 | Brazil | Goiânia | Radiotherapy | 50.9 TBq Cs-137 (soluble caesium chloride in capsule) | 129 exposed: 4 died.<br>Intakes and external exposure led to 21 persons receiving doses above 1 Gy, 19 had skin lesions and 129 had intakes of activity (highest 4 GBq, one of whom died) | up to 7 Gy | | Abandoned device containing caesium source: disassembled | [13, 175] |
| 15 | 1988 | China | | Radiography | 220 GBq Ir-192 | 1 exposed | 0.5–1 Gy | – | The source fell to the ground, and worker picked up and placed in his home for about 50 hours | [176] |
| 16 | 1988–1992 | USSR | Ukraine | | 2.6 TBq Cs-137 | 2 boys who slept in the bedroom died | – | – | Source found embedded in bedroom wall | [46] |
| 17 | 1992 | China | Xinzhou | Irradiation | 400 GBq Co-60 | 3 died and 11 others significantly exposed | fatalities > 8 Gy | – | Disused irradiator left with source. Farmer working on the site demolishing facility picked up source; it went with him to the hospital | [128, 177] |
| 18 | 1993–1998 | Turkey | Istanbul | Radiotherapy | 3.3 TBq Co-60 | 18 persons with ARS, 1 with lesions on 1 hand | 3 Gy | 10–20 Gy | Poor source security over a protracted period led to the source containers being sold for scrap and dismantled | [21] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 1994 | Estonia | Tammiku | Irradiation | 1.6 TBq Cs-137: part of an irradiator | 6 persons exposed, 1 died, 2 with localised injury | 4 Gy | 1800 Gy | Source originally found in scrap metal. Then insecurely stored: stolen and taken to house | [18] |
| 20 | 1994 | Georgia |  | Radiotherapy |  | 1 died | – | – | Accident occurred with abandoned radiotherapy source | [178] |
| 21 | 1995 | Russia | Moscow |  | 48 GBq Cs-137 | 1 person died (chronic exposure) | 7.9 Gy | 65 Gy | Source located in door pocket of truck for approximately 5 months | [179, 180] |
| 22 | 1995 | France |  | Radiography | 1 TBq Ir-192 | 1 person with localised injury | – | > 30 Gy | Direct handling of source | [32, 39] |
| 23 | 1996 | Iran | Gilan | Industrial radiography | 185 GBq Ir-192 | 1 person with ARS and local injury to chest | 4.5 Gy | 40 Gy | Failure of lock on radiography container allowed source to fall out, no monitoring and poor procedures left source to be found and picked up by worker | [26] |
| 24 | 1996–1997 | Georgia | Lilo | Military training | Multiple sources, mostly Cs-137, 0.01 to 164 GBq | 11 persons chronically exposed over various periods, local injuries and some systemic effects | 4.5 Gy | 10–30 Gy | Abandoned sources at a military training center | [23] |
| 25 | 1999 | China | Henan | ‘Ex-service’ therapy source | 101 TBq Co-60 | 7 people exposed | 1–6 Gy | Up to 20 Gy | Source found in residence of farmer | [181] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 2000 | Thailand | Samut Prakarn | Radiotherapy | 15.7 TBq<br>Co-60 | 3 died and 7 others received significant exposures (5 of the 10 also had localized injuries) | > 6 Gy ( fatalities)<br>1–6 Gy (others) | – | 3 old therapy units left in an insecure parking lot. Source container of one removed to scrap yard and dismantled | [25] |
| 27 | 2000 | Egypt | Meet Halfa | Industrial radiography | 1.85 TBq<br>Ir-192 | Father and son died, 5 others exposed | 5–8 Gy (fatalities)<br>3–4 Gy (others) | – | Source lost by worker testing pipe welds was found by farmer and taken home | [182, 183] |
| 28 | 2000 | Russia | Samara Oblast | Industrial radiography | 9 TBq<br>Ir-192 | 3 radiographers exposed, 1 with hand injury | 1–3 Gy | 30–70 Gy | Poor procedures, lack of batteries in doserate meters and insufficient safety training of radiographers | [184] |
| 29 | 2000 | China | Henan |  | Co-60 | 1 exposed | 1.44 Gy | – |  | [185] |
| 30 | 2000 | China | Henan |  | Gamma internal overexposure | 1 exposed | 0.15 Gy | – |  | [185] |
| 31 | 2000 | Japan | Wakayama | Unknown | 230 MBq, Cs-137, 1.8 GBq, Am-Be Neutron source | No person injured | – | – | Two radiation sources were found in a scrap container imported from the Philippines | [156] |
| 32 | 2000 | Japan | Hyogo | Medical treatment | Radium needle | No person injured | – | – | Four Radium needles were found in a scrap container. | [156] |

| No | Year | Place: country | Province/ Town | Type of use | Source description* | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 33 | 2000 | Japan | Okayama | | Depleted Uranium | No person injured | – | – | Depleted Uranium was found in a scrap yard | [156] |
| 34 | 2000 | Japan | Kawasaki | | 1 MBq and 3 MBq, Radium | No person injured | – | – | Source was found in a scrap yard | [156] |
| 35 | 2001 | Japan | Shinnanyo | | 5.5 GBq, Cs-137 | No person injured | – | – | Source was found in a container imported from Taiwan at the scrap yard | [156] |
| 36 | 2001 | Georgia | Lia | RTG (Radioisotope Thermal Generator) | 2.6 PBq Sr-90 | 3 persons exposed, 2 developed severe localised injuries | 1–4 Gy | 20 Gy | Lumberjacks found thermally hot objects (2 abandoned sources) and used them for heaters | [186] |
| 37 | 2002 | China | South China | | Ir-192 | More than 70 | – | – | Individual hurt others intentionally | [187] |

TABLE 11. EMERGENCIES IN MEDICAL APPLICATION

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1967 | India | | Co-60 teletherapy | 1 worker, hand injury | – | 80 Gy | Source gain during transfer | [188] |
| 2 | 1968 | USA | Wisconsin | Nuclear medicine, Au-198 | 1 patient death | 4–5 Gy | 70–90 Gy to liver | Higher than prescribed dose administered (7.4 GBq instead of 7.4 MBq) | [189, 190] |
| 3 | 1966 | USSR | Kaluga | Medicine radiography,<br>X ray 50kV | 1 with localized exposure of head | 1.5 Gy | > 20 Gy to forehead | Operator's rough error | [114] |
| 4 | 1970 | Australia | | X rays | 2 with localized exposure | – | 4–45 Gy | | [114] |
| 5 | 1972 | China | Wuhan | Co-60 radiotherapy | 20 patients and 8 workers exposed | 0.5–2.45 Gy | – | Source fell from holder and was unnoticed for 16 days; design of device did not meet international standards | [128, 168, 191] |
| 6 | 1974–1976 | USA | Ohio (Riverside) | Co-60 radiotherapy | 426 patients overexposed | 10–45 % higher | – | Use of incorrect decay curve, lack of periodic calibration of output | [155] |
| 7 | 1975 | Germany | | X ray equipment | 1 worker exposed, head and upper torso | – | > 1 Gy | Probable violation of safe working practice in maintenance | [32, 39] |
| 8 | 1975 | Argentina | Tucuman | Co-60 teletherapy | 2 workers exposed, injuries to fingers | – | – | Failure of source mechanical mechanism | [32, 39] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 9 | 1975 | USSR, Russia | Sverdlovsk | 460 PBq Co-60 | 1 death and 2 with effects | 3.0–7.0 Gy | 3.0–7.0 Gy | Accidental fallout of source transported from container | [118] |
| 10 | 1977 | Germany | | Ir-192 radiogram unit | 1 worker with localized injury | 0.01 mGy | 5 Gy | Defective equipment | [32, 39] |
| 11 | 1977 | UK | | Nuclear medicine I-125 | Intake by 2 workers, significant thyroid exposure of 1 | – | 1.7 Gy | Accidental contamination of laboratory workers | [32, 39] |
| 12 | 1979 | Argentina | Parana | Diagnostic radiology | 1 worker exposed | 0.94 Gy | – | Faulty wiring led to emission of X rays when the top of the fluoroscope was open | [32, 39] |
| 13 | 1980 | India | Ludihana | Radiotherapy | 3 workers or patients, no adverse health effects | 0.25, 0.4 and 0.5 Gy | – | Defective equipment (mercury leaked out through shutter) | [32, 39] |
| 14 | 1981 | France | Saintes | 137 TBq Co-60 teletherapy | 3 workers with amputation of hands | – | > 25 Gy | Direct hand contact with source during source loading | [192] |
| 15 | 1981–1991 | UK | | Radiotherapy | 1045 (492 patients developed a local recurrence, possibly as a result of the underdosage) | – | 5–30 % underdosage | Inappropriate commissioning of a computerised radiotherapy treatment planning system. | [178] |
| 16 | 1982 | Argentina | La Plata | X ray therapy facility | 1 worker with cataracts | 0.12 Gy | 5.8 Gy | Operator looked through tube window while changing tubes without recognizing system was energized | [193] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 17 | 1985 | USA | Georgia (Marietta) | Radiotherapy Therac-25 accelerator | 1 patient with injury to arm and shoulder | Much higher than prescribed dose | – | Problem of integration of hardware and software of system | [193] |
| 18 | 1985 | Canada | Ontario (Hamilton) | Radiotherapy Therac-25 accelerator | 1 patient with severe injury to hip | Much higher than prescribed dose | – | Problem of integration of hardware and software of system | [193] |
| 19 | 1985 | UK | | Nuclear medicine I-125 | 1 worker with intake and exposure of thyroid | – | 400 Gy | Technician cut his finger while wearing a glove contaminated with 125I; sucked cut finger | [32, 39] |
| 20 | 1985 | China | | Injections of Au-198 | 3 patients, 1 died | Much higher than prescribed dose | – | Mistake in treatment | [114] |
| 21 | 1986 | UK | | 130 TBq Co-60 radiotherapy | 1 worker with hand injury | < 0.1 Gy | 15 Gy | Exposure during source changing. Misalignment of tubes prevented source from being pushed into safe position | [32, 39] |
| 22 | 1986 | USA | Texas (Tyler) | Therac-25 accelerator | 1 patient died | Much higher than prescribed dose | – | Problem of integration of hardware and software of system | [193] |
| 23 | 1986–1987 | Germany | | Co-60 radiotherapy | 86 patients | – | – | Co-60 dose calculations based on erroneous dose tables (varying overdoses) No independent determination of the dose rate | [178] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 24 | 1987 | USA | Washington (Yakima) | Therac-25 accelerator | 1 patient overexposed | Much higher than prescribed dose | 90–100 Gy to chest | A problem of integration of hardware and software of system and operator error | [193] |
| 25 | 1987–1988 | USA | Maryland | Co-60 therapy | 33 exposed: 20 died | NA | 75 % > than prescribed | Treatment planning, computer file was not updated after source change | [178] |
| | | | | | 33 patients with high doses to brain | | | | |
| 26 | 1988 | Netherlands | Rotterdam | Sagittaire accelerator | 1 patient with injury to upper body and head | – | 10–20 Gy | Leakage of radiation during therapy | [194] |
| 27 | 1988 | UK | | Co-60 radiotherapy | 207 patients | – | 25 % overdose | Error in the calibration of a Co-60 therapy unit (25% overdose). No independent calibration of the beam | [178] |
| 28 | 1988–1989 | UK | | Cs-137 branchytherapy source | 22 patients | – | 75 % overdose | Error in the identification of Cs-137 branchytherapy sources (dosimetry errors between -20 % and +10 %). No independent determination of source strength | [178] |
| 29 | 1990 | Spain | Zaragoza | Linear accelerator | 27 patients overexposed, 15 died. | 2–7 times higher than prescribed | – | No post maintenance testing done. Assumption that meter on control panel was stuck; but was operating at max energy (36 MeV electron beam) irrespective of energy selected | [155, 178, 195] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 1992 | USA | Pennsylvania (Indiana) | Brachytherapy source (16 GBq, Ir-192 wire) | 1 patient died: source remained in person for 4 days, 94 others exposed. Source fell out of patient and disposed in biohazard waste; discovered but monitored at incinerator | – | 16,000 Gy at 1 cm instead of 18 Gy | Source dislodged; failure to check for source’s return to shielded holder | [155, 178, 196] |
| 31 | 1994 | USA |  | HDR brachytherapy | Patient given dose to wrong area | NA | 12 Gy | Treatment planning errors | [197] |
| 32 | 1995 | Peru | Arequipa | Co-60 teletherapy | 1 exposed with injuries to hand | 0.7 Sv | > 30 Gy | Non-qualified worker tried to repair a cobalt unit and touch the source with his right hand for a less than one second | [32, 39] |
| 33 | 1996 | Costa Rica | San José | Co-60 teletherapy | 63 patients overexposed: 17 died | 50–60 % higher than prescribed | – | Error in calculating dose rate | [20, 178] |
| 34 | 1998 | Japan | Okinawa | Radiotherapy, 296 GBq, Ir-192 | 2 workers exposed | – | no health effects | Carelessness to touch the source whilst changing it | [156] |
| 35 | 1999–2000 | Japan | Tokyo | LINAC | 23 patients overexposed | 1.23 times higher than prescribed | – | Error in inputting dose to computer which controls therapeutic dose | [156] |

| No | Year | Place: country | Province/ Town | Type of use | Consequences | Received effective dose | Received equivalent dose | Main cause | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 36 | 2000–2001 | Panama | Panama City | Co-60 teletherapy | 23 patients overexposed: 5 died, others with significant injuries | 2 times higher than prescribed | – | Misuse of a treatment planning system | [24, 198] |
| 37 | 2001 | Poland | Bialystok | Linear accelerator | 5 patients with injuries | significantly higher than prescribed | – | Power failure causing damage to the dose monitoring and safety systems | [27] |
| 38 | 2001 | Japan | Tokyo | Linac-CT | 1 worker exposed | < 200 mSv | – | A worker was above the ceiling and accidentally exposed by radiation generation testing | [156] |
| 39 | 2002 | China | Henan | Co-60 radiotherapy | 1 exposed to whole body and right hand | 1–2 Gy | > 20Gy | Carelessness during maintenance | [199] |
| 40 | 2004 | France | Epinal |  | 23 patients overexposed: 4 died | 20 % higher than prescribed | – | Errors in treatment planning. Operator’s instructions not in language understood | [200] |
| 41 | 2006 | UK | Scotland (Glasgow) | Linear accelerator | 1 patient overexposed | 58 % higher than planned | – | Inexperienced treatment planner. Critical error made in data used during treatment delivery | [201] |
| 42 | 2007 | USA | Michigan (Detroit) | Gamma knife radiotherapy | 1 patient with wrong treatment area | NA | 18 Gy | Image reversal on MRI led to wrong side of brain treated | [202] |

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# ABBREVIATIONS

| | |
|---|---|
| CBRN | Chemical, Biological, Radiological or Nuclear material incidents |
| CCC | Civil Contingencies Committee |
| FEMA | Federal Emergency Management Agency (USA) |
| HPA | Health Protection Agency |
| IAEA | International Atomic Energy Agency |
| ICS | Incident Command System |
| MIC | Methyl icocyanate |
| MPS | Metropolitan Police Service (London, UK) |
| NHC | National Hurricane Center |
| NHS | National Health Service (UK) |
| NRC | Nuclear Regulatory Commission (USA) |
| OILs | Operational Intervention Levels |
| PAZ | Precautionary Action Zone |
| PPE | Personal Protective Equipment |
| RWG | Recovery Working Group |
| SCG | Strategic Coordinating Group |
| TMI | Three Mile Island |
| UPZ | Urgent Protective Action Planning Zone |
| WCC | Westminster City Council (UK) |

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